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Governor
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# The Characterization of Reclaimed Asphalt Pavement for HMA Surface Courses in Massachusetts

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16. Abstract

The goal of this study was to understand the properties of the reclaimed asphalt pavement (RAP) sources available in Massachusetts and develop guidelines or recommendations for using RAP in new hot-mix asphalt surface course mixtures. MassDOT specifications allow up to 15% RAP by dry weight in surface mixtures without using a softer-grade virgin binder or using blending equations to determine the appropriate virgin binder grade.

RAPs from 13 sources located geographically across the state were tested to determine important properties such as binder content, recovered RAP binder grade, and maximum theoretical specific gravity. The typically specified PG 64-28 asphalt binder used in the state was obtained from regional suppliers of this grade and tested to confirm the performance grade. Analyses were conducted to evaluate each recommended RAP specification method, and accuracies of these methods were investigated by evaluating the performances of actual mixtures incorporating different RAPs and virgin binder sources.

The MassDOT specification allowing up to 15% RAP by dry weight of mixture was found to be not valid and, in many cases, not stringent enough. The findings supported that a specification change is warranted. It is suggested that these changes include requiring testing of critical RAP and virgin binder properties for all mixtures; utilization of blending chart equations to estimate blended binder properties; and subsequent mixture performance testing to ensure adequate performance.

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# Characterization of Reclaimed Asphalt Pavement (RAP) for HMA Surface Courses in Massachusetts

Final Report

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# Disclaimer

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# Executive Summary

This study of “Characterization of Reclaimed Asphalt Pavement (RAP) for HMA Surface Courses in Massachusetts” was undertaken as part of the Massachusetts Department of Transportation (MassDOT) Research Program. This program is funded with Federal Highway Administration (FHWA) State Planning and Research (SPR) funds. Through this program, applied research is conducted on topics of importance to the Commonwealth of Massachusetts transportation agencies.

The overall goal of this study was to understand the properties of the reclaimed asphalt pavement (RAP) sources available in Massachusetts and, based on these properties, to develop guidelines or recommendations for using RAP in new hot-mix asphalt (HMA) surface course mixtures.

The main constituents of any RAP stockpile are asphalt and aggregates; hence, it provides an environmentally conscious alternative source for the main materials used in producing new HMA mixtures. Using larger RAP contents conserves natural resources and can also lead to significant economic savings. The potential drawback to using more RAP is it contains a highly aged/oxidized asphalt binder, which is stiffer and more brittle as compared to a virgin binder. Using more of this stiff and brittle binder has raised concerns that these mixtures will be less durable and more prone to distress. Therefore, being able to accurately specify the correct amount of RAP to use in a mixture without sacrificing performance is of utmost importance.

The amount of RAP to be used in a mixture is typically specified by state transportation agencies following the guidance of the American Association of State Highway and Transportation Officials (AASHTO), which recommends various methods: (1) percent RAP by the dry weight of the mixture; (2) RAP binder ratio (RAPBR); and (3) binder blending charts. The current MassDOT specification allows up to 15% RAP by dry weight of the mixture and requires the typical performance grade (PG 64-28) virgin asphalt binder to be used. Higher percentages of RAP are currently not allowed in surface mixtures. This limitation is based on the specification objective to use as much RAP as practical while simultaneously maintaining the typical binder grade required for the mixture. Using RAP amounts above 15% would likely reduce the binder grade at the intermediate and low temperatures in the resultant mixture to an unacceptable level (i.e., warmer than the typical temperatures for a PG 64-28). Only by evaluating these recommended specification methods, using the properties of the materials available in Massachusetts, can the validity of the MassDOT specification be determined. This evaluation should indicate whether more or less RAP can be specified for surface mixtures.

Thirteen RAP stockpiles were sampled from various locations around Massachusetts from 2017 to 2019. Each stockpile was tested to determine important properties of the RAP, including binder content, recovered binder performance grade, maximum theoretical specific gravity, recovered aggregate gradation, and recovered aggregate specific gravity. Similarly, the typical virgin asphalt binder used in Massachusetts (PG 64-28) was obtained from four

supply sources in the state and tested to determine the samples' properties. These RAP and virgin binder properties were then used to determine the accuracy of the AASHTO-recommended RAP specification methods, using the actual properties of materials located in Massachusetts. Moreover, mixtures were developed and evaluated using a balanced mixture design (BMD) procedure by incorporating specific RAP stockpiles and virgin binders exhibiting the extremes in available properties. Appropriately aged mixtures were developed with 15% RAP, 25% RAP, and 35% RAP and evaluated for their stiffness (dynamic modulus) and performance characteristics (rutting, moisture susceptibility, intermediate-temperature cracking, and low-temperature cracking), using a suite of laboratory tests.

Analysis of the RAP property testing data indicated that no geographic trends in properties could be made. Significant variations were noted in the performance grades of the recovered RAP binders and the RAP binder contents. Year-to-year testing of the same RAPs also indicated variance in the performance grades of the recovered RAP binders. Finally, high variability in aggregate gradation results for specific RAP stockpiles were also noted.

Virgin binder testing indicated one of the four sources tested had intermediate- and low-temperature continuous grades close to the specification criterion. This virgin binder can potentially have less capacity to accommodate RAP in any mixture, because adding even small amounts of aged RAP binder might not maintain the blended binder in the mixture at a PG 64-28.

The current MassDOT specification, which allows up to 15% RAP in surface mixtures by dry weight of the mixture without using a softer-grade virgin binder or blending equations, was not valid based on blended binder properties. Analyses using AASHTO blending equations and laboratory-determined RAP and virgin binder properties indicated that 28.9% of the time, the required PG 64-28 would not be maintained. The disparity between the estimated amounts of allowable RAP that would maintain a PG 64-28, ranging from 3.1% to 46.8%, shows the high influence of RAP source and virgin binder sources on the amount of RAP that can be added to a mixture. Utilizing the RAPBR for specifying RAP in lieu of the percent by dry weight of the mixture produced similar results. Therefore, a specification change for MassDOT is warranted.

All mixtures incorporating up to 35% RAP passed the rutting and moisture susceptibility performance tests. Statistical analysis of the mixture cracking performance test data indicated universally that virgin binder source significantly impacted all cracking performance measures. RAP source and percent RAP also had a significant effect on the intermediate cracking measure. However, there was inconsistency among all of the cracking performance tests except that virgin binder source has a significant effect. Although the low- and intermediate-temperature mixture test results often showed that RAP source, virgin binder source, and percent RAP had a significant effect, the lack of pass-fail criteria for these tests precluded stating exactly which mixtures were balanced or unbalanced.

In an attempt to quantify the amount of blending of the RAP and virgin binders, a microscopic technique was used to evaluate actual RAP mixtures, simulating real-world blending conditions. The microscope technique used was energy dispersive X-ray spectroscopy (EDS) scanning electron microscopy. EDS mapping allows for the determination of the distribution and proportion of the elements at specific locations within the specimen. Since an asphalt binder is elementally composed of carbon and sulfur, a tracer element, titanium dioxide, was added to the virgin binder so it could be distinguished from the RAP binder in the sample. The tracer element was blended with the virgin binder prior to specimen fabrication. Therefore, in the mixture sample, virgin binder was identified as areas with both carbon and titanium. RAP binder alone, that did not blend with the virgin binder, was identified by carbon only, without titanium. Partially blended RAP and virgin binders consisted of both carbon and titanium, but at lower concentrations than the purely virgin binder areas. Aggregate areas of the specimens were composed primarily of silica, so they were dissimilar from the binder areas in terms of elemental composition. Overall the blending analysis using EDS suggested that the assumption of 100% blending between RAP and virgin binders is inaccurate. Furthermore, the analysis illustrated that the degree of blending in a mixture is a function of RAP content, source, and properties.

The data and analysis showed that one specific RAP percentage cannot be specified for all surface course mixtures in Massachusetts, as the properties of RAP and virgin binder are functions of the source of the materials. Several specification recommendations are presented for using RAP in new surface mixtures. These recommendations address required RAP property testing and frequency, testing of the virgin binders, selection of a method to determine RAP aggregate specific gravity, and RAP aggregate gradation variability. Overall, a three-tiered approach is suggested to properly specify RAP in a mixture, even at RAP contents ≤15%:

- The properties of the RAP (including binder content, recovered binder grade, etc.) and virgin binder properties must be determined.
- AASHTO blending charts equations need to be utilized to estimate the RAP amount at which the desired blended binder properties of the mixture are obtained, which in turn will assist in properly limiting the amount of RAP.
- After the appropriate RAP content is determined, the actual mixture to be produced must be tested to ensure adequate performance after appropriate aging that is related to the in-service aging experienced.

Using this type of three-tiered approach should help ensure that quality mixtures are produced, and the amount of RAP utilized is appropriate to maintain performance.

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# List of Acronyms

| Acronym | Expansion |
|---|---|
| AASHTO | American Association of State Highway and Transportation Officials |
| AMPT | Asphalt Mixture Performance Test |
| ANOVA | Analysis of Variance |
| APA | Asphalt Pavement Analyzer |
| ASTM | American Society for Testing and Materials |
| BMD | Balanced Mixture Design |
| CG | Continuous Grade |
| DC(T) | Disk-Shaped Compact Tension |
| DSR | Dynamic Shear Rheometer |
| EDS | Energy Dispersive X-ray Spectroscopy |
| ESAL | Equivalent Single Axle Load |
| FE | Fracture Energy |
| FHWA | Federal Highway Administration |
| FI | Flexibility Index |
| FIT | Flexibility Index Test |
| $G_{mm}$ | Maximum Theoretical Specific Gravity |
| HMA | Hot Mix Asphalt |
| HWTT | Hamburg Wheel Tracking Test |
| IDEAL | Indirect Tensile Asphalt Cracking Test |
| IDT | Indirect Tension Test |
| $J_{nr}$ | Non-recoverable Creep Compliance |
| LAS | Linear Amplitude Sweep |
| MassDOT | Massachusetts Department of Transportation |
| MSCR | Multiple Stress Creep Recovery |
| NAPA | National Asphalt Pavement Association |
| NCHRP | National Cooperative Highway Research Program |
| $N_f$ | Number of Cycles to Failure |
| NMAS | Nominal Maximum Aggregate Size |
| PG | Performance Grade |
| RAP | Reclaimed Asphalt Pavement |
| RAPBR | RAP Binder Ratio |
| $RAPBR_{max}$ | Maximum RAP Binder Ratio |
| SCB | Semicircular Bend |
| SEM | Scanning Electron Microscopy |
| SGC | Superpave Gyratory Compactor |
| SIP | Stripping Inflection Point |
| SPR | State Planning and Research |
| VFA | Voids Filled with Asphalt |
| VMA | Voids in Mineral Aggregate |

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# 1.0 Introduction and Objectives

This study of the Characterization of Reclaimed Asphalt Pavement (RAP) for HMA Surface Courses in Massachusetts was undertaken as part of the Massachusetts Department of Transportation (MassDOT) Research Program. This program is funded with Federal Highway Administration (FHWA) State Planning and Research (SPR) funds. Through this program, applied research is conducted on topics of importance to the Commonwealth of Massachusetts transportation agencies.

## 1.1 Background

Similar to other state transportation agencies and the asphalt mixture industry, the Massachusetts Department of Transportation (MassDOT) is working concurrently to achieve two significant goals: Optimize the use of reclaimed asphalt pavement (RAP) in asphalt mixtures, and design mixtures that have balanced performance in regard to certain pavement distresses, such as low- and intermediate-temperature cracking and high-temperature rutting.

The main constituents of RAP are asphalt and aggregates; hence, it provides an environmentally conscious alternative source for the main materials used in producing new asphalt mixtures. Recycling RAP in this way undoubtedly conserves natural resources. Optimizing the amount of RAP used in asphalt mixtures, especially when using RAP contents greater than 25% by the weight of mixture, can also lead to significant economic savings *(1)*.

RAP use has been largely limited due to concerns associated with the aged asphalt binder contained in the RAP, which is highly oxidized due to years of in-service aging. This aging provides drastically different binder properties as compared to a virgin binder, with the RAP binder being stiffer and more brittle. Using larger amounts of a stiff and brittle binder in a mixture has raised concerns that these mixtures will be less durable and more prone to distress. Many approaches have been employed in order to qualitatively analyze the impact of using more RAP in a mixture design, with all of them centering upon some sort of performance measure. More recently, this process has been formalized into what is now known as a balanced mix design (BMD) approach. Under this approach, a mixture is tested and evaluated to ensure that adequate performance is achieved. This is contrary to approaches undertaken in the past that relied heavily on volumetric measures to ensure an adequate mixture design. These approaches would likely not be able to distinguish the true mixture performance ramifications resulting from using more RAP in a mixture, thus potentially leading to subpar performing mixtures being produced and placed. The Federal Highway Administration (FHWA) BMD Task Force defined a BMD as “Asphalt mix design using performance tests on appropriately conditioned specimens that address multiple modes of distress, taking into consideration mix aging, traffic, climate, and location within the pavement structure” *(2)*.

RAP use in a mixture is typically specified by state transportation agencies following the guidance of the American Association of State Highway and Transportation Officials (AASHTO). AASHTO M 323-17 "Standard Specifications for Superpave Volumetric Mix Design" *(3)* provides two guidelines for incorporating RAP into an asphalt mixture. The first guideline as presented by Table 2 of AASHTO M 323 *(3)* shows how to specify the percent RAP by the dry weight of the mixture, which is how state transportation agencies have historically specified RAP. This specification method does not account for differences in RAP source properties, like RAP binder content, which could lead to different amounts of aged RAP binder being added to a mixture because of varying RAP binder contents. The second guideline as presented by Table 3 of AASHTO M 323 *(3)* shows how to specify RAP according to the RAP binder ratio (RAPBR). This specification accounts for different RAP sources contributing different amounts of aged binder to a mixture by controlling the amount of RAP binder being used. For a given RAPBR, less RAP will be used in a mixture when its binder content is high, and more when its binder content is low. Hence, using this specification method might provide greater control over the resultant performance grade (PG) of a blended asphalt binder in a mixture incorporating RAP, especially when using high RAP contents. AASHTO M 323 suggests using Equation 1, as follows, to calculate RAPBR. Once an RAPBR is specified by an agency, the percent RAP by dry weight of the mixture (PRAP) can then be calculated.

$$RAPBR = \frac{(Pb_{RAP})(P_{RAP})}{100(Pb_{Total})} \tag{1}$$

Where:
RAPBR = RAP binder ratio.
$Pb_{RAP}$ = Binder content of RAP.
$P_{RAP}$ = Percent RAP by dry weight of mixture.
$Pb_{Total}$ = Total binder content of the mixture.

In addition to the two guidelines for specifying RAP, AASHTO M 323 also provides blending equations *(3)* that account for variations in RAP binder properties in terms of their PGs at high, intermediate, and low temperatures. These equations are used to maintain a specific resultant binder PG in the final mixture. When these equations are not used, typically at smaller amounts of RAP, the source of the RAP binder and its variations in properties are considered to have an insignificant impact on the resultant blended binder in the mixture. Because of this, no analysis of or adjustment to the virgin binder grade is made. It is important to note that both methods for specifying RAP assume that there will be 100% blending of the aged RAP binder with the virgin binder in the mixture.

Ultimately, determining how much RAP can be added into a mixture and how to accurately specify RAP use is a direct function of the performance of the resultant mixture. Because RAP stockpiles can have varying properties such as binder content, binder PG, gradation, etc., a BMD approach is a critical tool to evaluate that a RAP mixture will perform acceptably without premature failure. This evaluation can be used to help validate that the means of specifying RAP, either the percent dry weight of mixture or RAPBR, is accurate. If a RAP mixture does not meet the BMD performance criteria, the state transportation agency could then adjust its specification method by lowering either the percent RAP by dry weight of the mixture or the RAPBR until the desired mixture performance criteria is attained. If a RAP mixture has performance that exceeds expectations, it may be possible to adjust the specification to include more RAP.

Any specification for using RAP in mixtures needs to be sensitive to the variability of the materials used to produce said mixtures. For instance, RAP binder properties may vary by geographic location within a state because the different environmental conditions at these locations may have imparted different amounts of in-service aging. Another factor to consider is that studies have illustrated that virgin asphalt binders having the same PG but obtained from different sources will not always lead to mixtures that perform the same *(4)*. Since virgin binders used in most states can be obtained from different sources, it is critical for an agency to investigate the combinational effects of both RAP source and virgin binder source on mixture performance. Using a BMD approach will help account for these factors and ultimately help shape and refine a specification for the use of RAP that more accurately reflects performance as it relates to the properties of the available materials.

## 1.2 Problem Statement

MassDOT specification currently requires a PG 64-28 to be used in surface mixtures and up to 15% RAP by dry weight of the mixture. Higher percentages of RAP are not allowed in surface mixtures. Since no change in virgin binder selection is required, this specification assumes that the required intermediate-temperature PG of 22°C and the low-temperature PG of -28°C will be met, regardless of the RAP binder content or the intermediate- and low-temperature PGs of the aged RAP binder. Thus, for example, even if the PGs of the aged RAP binders being used vary with the geographical location because of different degrees of in-service aging, it is assumed that none of these PGs will require a change in virgin binder selection when using low RAP contents up to 15%.

The specification also assumes that the performances of a RAP mixture will be independent of the source of the virgin PG 64-28 asphalt binder that is used. However, several research studies have illustrated that virgin binders having the same PG but obtained from different sources will not always lead to mixtures that perform the same *(4)*. Additionally, the industry within the state would like to see greater than 15% RAP be allowed in surface mixtures. MassDOT specifications recommend using a softer binder than a PG 64-28 for higher than 15% RAP. Even so, many agencies are reluctant to do this because of the fear that the softer binder will dominate the resultant binder due to lack of blending. This might lead to rutting and other distresses in the field. To begin to address the issue of using higher RAP contents, this study was expanded to determine the effects of using percentages of RAP greater than 15% without using a softer binder or a rejuvenator.

## 1.3 Objectives

The objectives of this study were as follows.

1. Sample the RAP being used throughout Massachusetts and characterize the RAP binder and aggregates.
2. Sample and characterize the properties of the virgin PG 64-28 binder being used throughout Massachusetts to determine its ability to accommodate additional RAP.
3. Determine, by using blended binders, if the MassDOT specification that allows up to 15% RAP in surface mixtures without using a softer-grade virgin binder or blending equations is valid regardless of RAP source and virgin binder source.
4. Determine if the MassDOT specification should be based on RAPBR instead of by dry weight of the mixture, which is being used currently.
5. Use a BMD procedure on a select group of surface mixtures that accounts for RAP source and virgin binder source to validate the previous findings and to determine the effects of using 15%, 25%, and 35% RAP without using a softer binder or a rejuvenator.
6. Using the BMD procedure, determine which mixtures would remain balanced in terms of rutting, moisture susceptibility, fatigue cracking, and thermal cracking.
7. Based on the preceding, determine what changes are needed, if any, to the current MassDOT specification for RAP use in surface mixtures.

# 2.0 Experimental Plan

In order to achieve the objectives of this study, an experimental plan was developed as shown in Figure 2.1. A critical aspect of the plan was to sample and characterize the RAP stockpiles available geographically throughout the state. Equally important to the plan was determining the supply sources for the typically specified asphalt binder (PG 64-28) in the state, and subsequently sampling and characterizing these binders. With the available RAP and binder properties known, the AASHTO recommended methods for specifying RAP discussed previously (dry weight and RAPBR) could then be evaluated with respect to maintaining at least a PG 64-28 binder in the resultant mixture. Because these specification methods rely on mathematical calculations, mixtures needed to be prepared to validate that mixture performance is not different due to RAP source or virgin binder source, even if the blending charts method indicates that PG 64-28 is maintained. Mixture performance testing was conducted with a BMD approach, utilizing tests for assessing rutting, moisture susceptibility, fatigue cracking and thermal cracking. Two RAPs and two virgin binders (PG 64-28) with quite different properties were used for this mixture evaluation. By analyzing the AASHTO recommendations and the actual laboratory mixture performance data, any changes needed to the current MassDOT specification for RAP use in surface mixtures could be determined.

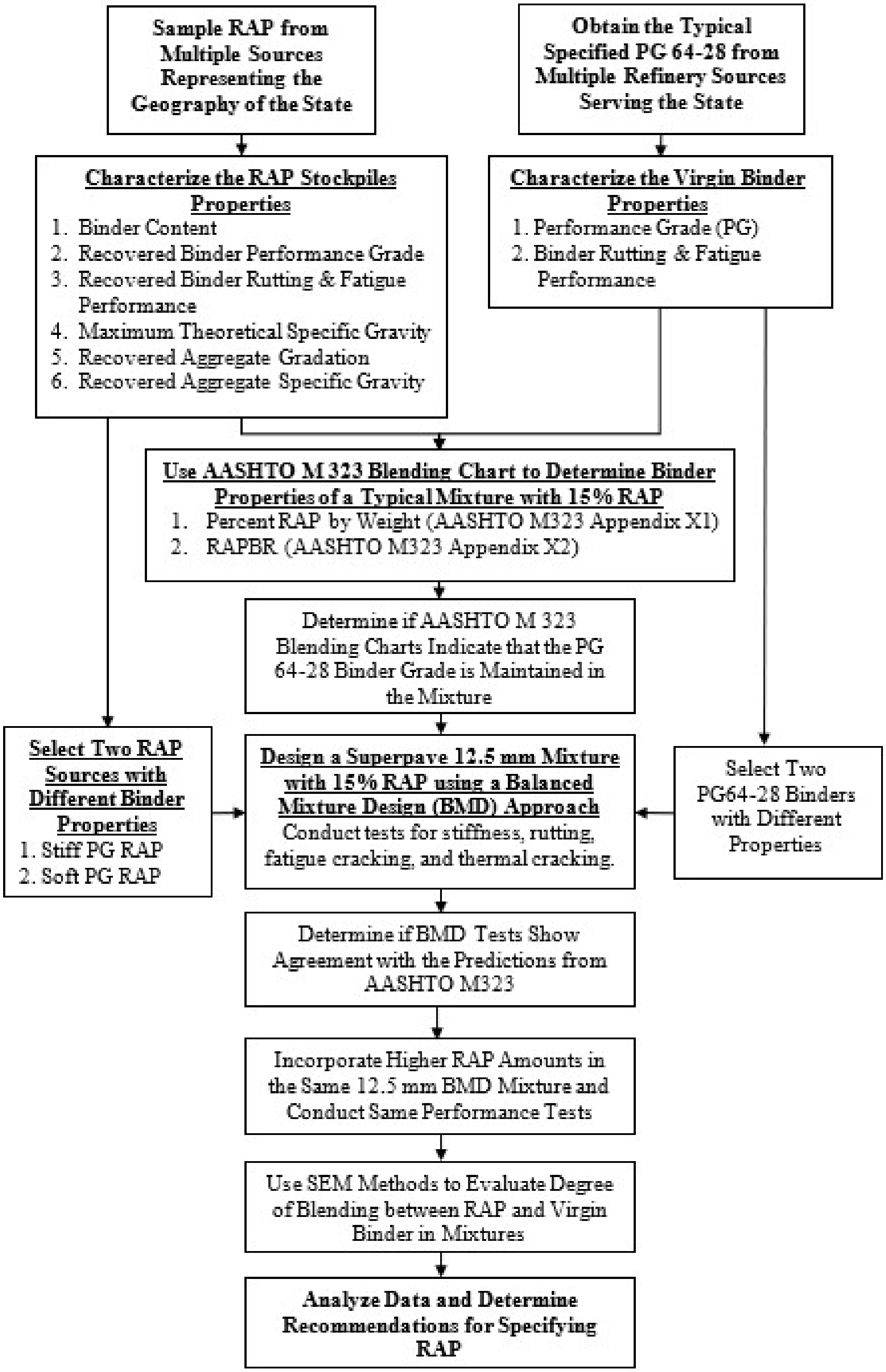

**Figure 2.1: Experimental plan**

# 3.0 Reclaimed Asphalt Pavements

In order to evaluate the AASHTO M 323 recommended methods for specifying RAP in a mixture, the properties of the sampled RAP needed to be determined first. This section outlines the testing for these RAPs.

## 3.1 RAP Sampling and RAP Source

It was important to obtain RAP stockpile material from various sources throughout Massachusetts, as the current RAP specification applies to all mixtures placed within the state. An attempt was made to obtain RAP from each of the six MassDOT districts within the state to cover the geography of the state and characterize the possible RAP stockpiles that could be used in a mixture. As shown in Figure 3.1, eight unique producers were identified representing five of the six districts. A suitable producer could not be identified in District 6. One producer was identified in Cumberland, Rhode Island. This producer regularly serves both District 3 and District 5, so it was included in the study. Note that duplicate samples were collected in the subsequent year for select RAP stockpiles. This was done to identify any year-to-year variability in the RAP properties. A total of 13 stockpiles of RAP were included in the study.

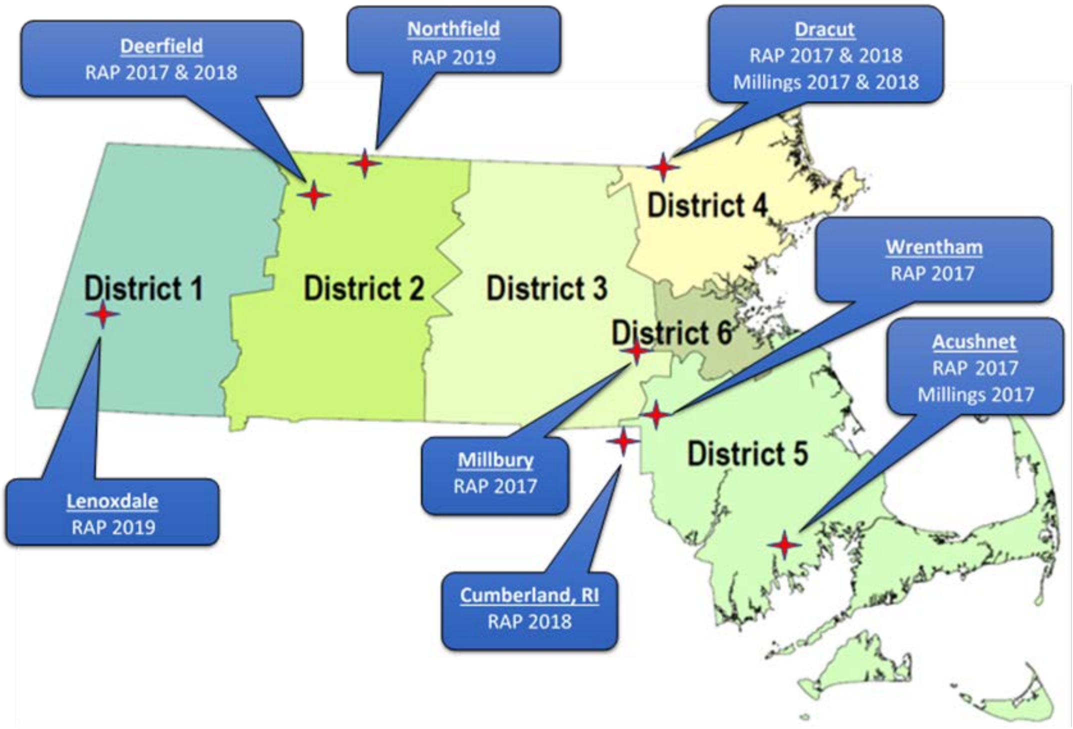

**Figure 3.1: RAP stockpile sampling location, year, and type**

RAP stockpile sampling was conducted using the mini stockpile method outlined in Chapter 3 of NAPA's Quality Improvement Series 129 *(5)*. Mini stockpiles were made by a front-end loader for various locations around the RAP stockpile. A minimum of 20 unique samples were obtained from each stockpile for each RAP source. The stockpile type sampled (RAP or millings) and year obtained are also shown in Figure 3.1. In total, 13 unique RAP stockpiles were sampled and tested. Note that none of the RAP stockpiles was fractionated, as MassDOT does not require it. Also, the maximum particle size noted in any RAP stockpile was 12.5 mm (1/2 inch).

## 3.2 RAP Properties

For this study, it was important to determine specific physical properties of each RAP stockpile. For the calculation of RAPBR, it was essential to know the binder content of each RAP stockpile. To use the AASHTO blending charts, it was important to know the properties of the extracted and recovered RAP binder. The recommendations outlined in NCHRP Report 752, *Improved Mix Design, Evaluation, and Materials Management Practices for Hot Mix Asphalt with High Reclaimed Asphalt Pavement Content (6),* were followed to determine minimum test frequency and suggested maximum standard deviation between measurements for each specific test, as shown in Table 3.1.

**Table 3.1: NCHRP Report 752 proposed RAP sampling and testing guidelines for high RAP content mixes**

| Property | Test Method(s) | Frequency | Minimum Number of Tests per Stockpile | Maximum Standard Deviation |
|---|---|---|---|---|
| Asphalt Content | AASHTO T 164 or AASHTO T 308 | 1 per 1,000 tons | 10 | 0.5 |
| Recovered Aggregate Gradation* | AASHTO T 30 | 1 per 1,000 tons | 10 | 5.0 all sieves<br>1.5 on 75 micron |
| Recovered Aggregate Bulk Specific Gravity | AASHTO T 84 and T 85 | 1 per 3,000 tons | 3 | 0.030** |
| Binder Recovery and PG Grading | AASHTO T 319 or ASTM D5404 and AASHTO R 29 | 1 per 5,000 tons | 1 | n/a |

* Samples for Superpave aggregate consensus properties or other aggregate testing needs may be obtained by combining the tested aggregates following sieve analyses.

**Preliminary value based on limited data and possible impacts to VMA for high RAP content mixes.

### 3.2.1. Binder Content

Each RAP binder content was determined by two methods: ignition oven (AASHTO T 308 "Standard Method of Test for Determining the Asphalt Binder Content of Hot Mix Asphalt by the Ignition Method") and centrifuge extraction (AASHTO T 164 "Standard Method of Test for Quantitative Extraction of Asphalt Binder from Hot Mix Asphalt" – Method A) *(3)*. Per the recommendations of NCHRP Report 752, over 10 random samples were tested in the ignition oven for each stockpile. For centrifuge extraction, due to the amount of chemical solvent involved, only two random samples were tested for each stockpile to compare them to the findings of the ignition oven results. The average results are shown in Table 3.2. The ignition oven determined binder content was generally greater than the centrifuge extraction binder content. This was expected, as no correction factors were used in the ignition oven since the aggregate source in the RAP stockpiles was unknown. For the majority, the ignition oven- and centrifuge-determined binder contents were within ±0.5%.

**Table 3.2: RAP binder content and extracted/recovered RAP binder performance grade**

| Location | Type | Year | Avg. $P_{bI}$ | Avg. $P_{bC}$ | Avg. Binder Continuous Grade High, (Intermediate), Low, °C | Avg. Binder PG |
|---|---|---|---|---|---|---|
| **District 1** | | | | | | |
| Lenoxdale | RAP | 2019 | 6.0 | 6.3 | 92.1 (31.4) -15.4 | PG 88-10 |
| **District 2** | | | | | | |
| Deerfield | RAP | 2017 | 6.6 | 6.1 | 86.7 (30.7) -18.3 | PG 82-16 |
| Deerfield | RAP | 2018 | 6.3 | 5.8 | 85.4 (30.9) -17.9 | PG 82-16 |
| Northfield | RAP | 2019 | 6.0 | 5.5 | 85.8 (30.2) -18.2 | PG 82-16 |
| **District 3** | | | | | | |
| Millbury | RAP | 2017 | 5.8 | 5.4 | 76.8 (23.4) -24.7 | PG 76-22 |
| Cumberland | RAP | 2018 | 5.8 | 5.6 | 91.2 (32.3) -14.3 | PG 88-10 |
| **District 4** | | | | | | |
| Dracut | RAP | 2017 | 5.2 | 4.9 | 84.2 (27.0) -21.2 | PG 82-16 |
| Dracut | RAP | 2018 | 5.4 | 4.8 | 85.8 (29.1) -20.1 | PG 82-16 |
| Dracut | Millings | 2017 | 6.0 | 5.5 | 99.3 (37.7) -11.0 | PG 94-10 |
| Dracut | Millings | 2018 | 6.2 | 5.9 | 80.2 (27.6) -22.2 | PG 76-22 |
| **District 5** | | | | | | |
| Wrentham | RAP | 2017 | 5.1 | 5.5 | 79.1 (25.4) -22.2 | PG 76-22 |
| Acushnet | RAP | 2017 | 4.6 | 4.7 | 83.0 (27.9) -20.3 | PG 82-16 |
| Acushnet | Millings | 2017 | 5.9 | 5.5 | 82.7 (28.2) -21.2 | PG 82-16 |

PbI = Binder content determined by ignition oven.
PbC = Binder content determined by chemical extraction.

### 3.2.2. Extracted/Recovered RAP Binder Performance Grade

Each RAP binder was extracted and recovered for continuous grade and PG determination. Chemical extraction was completed using a centrifuge extractor with toluene as the solvent, in accordance with AASHTO T 164 “Standard Method of Test for Quantitative Extraction of Asphalt Binder from Hot Mix Asphalt” – Method A) *(3)*. Recovery was conducted using a Rotovap device in accordance with ASTM D 5404 “Standard Practice for Recovery of Asphalt from Solution Using the Rotary Evaporator” *(7)*. The recovered RAP binder was then tested to determine its PG in accordance with AASHTO R 29 “Standard Practice for Grading or Verifying the Performance Grade of an Asphalt Binder” and M 320 “Standard Specification for Performance-Graded Asphalt Binder” *(3)*. A minimum of two random samples were tested for each RAP stockpile, although NCHRP Report 752 only recommended one test per stockpile, as shown in Table 3.1. The average continuous grade and PG for each recovered RAP binder are shown in Table 3.2. The recovered binder PG data indicates that the PGs of the RAPs in the state varied from PG 76-22 to PG 94-10.

### 3.2.3. Extracted/Recovered RAP Binder Performance Properties

In addition to determining the PG of the recovered RAP binder, the performance properties of the binder were also measured. Specifically, the binder rutting and fatigue performance were evaluated using two tests performed using the dynamic shear rheometer (DSR).

Rutting performance was measured using the Multiple Stress Creep Recovery (MSCR) test, in accordance with AASHTO T 350 “Standard Method of Test for Multiple Stress Creep Recovery Test of Asphalt Binder Using a Dynamic Shear Rheometer” *(3)*. A minimum of two tests were conducted at 64°C to coincide with the typical binder high PG grade temperature for the state. Values of the nonrecoverable creep compliance ($J_{nr}$) were determined for each binder tested, as shown in Table 3.3. In accordance with AASHTO M 332 “Standard Specification for Performance-Graded Asphalt Binder Using Multiple Stress Creep Recovery Test” *(3)*, values of the nonrecoverable creep compliance at the highest shear stress of 3.2 kPa ($J_{nr3.2}$) are used to determine the traffic loading designations for the binder, “S,” “H,” “V,” or “E,” which correspond to standard, high, very high, or extremely high traffic loading, respectively.

Per AASHTO T 350, the standard designation “S” is for traffic levels fewer than 10 million equivalent single axle loads (ESALs) and more than the standard traffic speed (>70 km/h or 43.5 mph). The high designation “H” is for traffic levels of 10 to 30 million ESALs or slow-moving traffic (20 to 70 km/h or 12.4 to 43.5 mph). The very high designation “V” is for traffic levels of greater than 30 million ESALs or standing traffic (<20 km/h or 12.4 mph). The extremely high designation “E” is for traffic levels of greater than 30 million ESALs and standing traffic (<20 km/h or 12.4 mph) such as toll plazas or port facilities. The data for the recovered RAP binders in Table 3.3 indicate that a majority of the binders were an “E” designation, while one was a “V” designation. The results are not surprising, as the aged RAP binder is expected to be stiff and thereby would exhibit increased rutting resistance.

Fatigue performance was measured using the linear amplitude sweep (LAS) test, in accordance with AASHTO TP 101 “Standard Method of Test for Estimating Fatigue Resistance of Asphalt Binders Using the Linear Amplitude Sweep” *(3)*. A minimum of two tests were conducted at the intermediate-temperature grade of the binder. For the RAP binders, the intermediate temperature from the performance grading tests ranged from 23.4°C to 37.7°C, as shown in Table 3.2. Initial specimens tested at colder temperatures (22°C and 25°C) fractured during testing. Two RAP specimens were able to be tested at a colder temperature of 25°C without fracturing. Thus, through trial and error, the test temperature for the remaining specimens was determined to be 35°C, to keep the specimens from fracturing during testing. The results of the LAS testing are shown in Table 3.4. Generally, increased number of cycles to failure ($N_f$) at a particular strain level indicate better fracture resistance. The results indicate that the fracture resistance of the RAP binders varied based on source.

**Table 3.3: Extracted/recovered RAP binder rutting performance properties (MSCR)**

| Location | Type | Year | MSCR @ 64°C | | |
|---|---|---|---|---|---|
| | | | $J_{nr3.2}$ | $J_{nr\ Diff}$ 75% max. | Traffic Loading Designation |
| **District 1** | | | | | |
| Lenoxdale | RAP | 2019 | 0.05 | 3.4 | E |
| **District 2** | | | | | |
| Deerfield | RAP | 2017 | 0.13 | 5.0 | E |
| Deerfield | RAP | 2018 | 0.16 | 3.4 | E |
| Northfield | RAP | 2019 | 0.16 | 8.7 | E |
| **District 3** | | | | | |
| Millbury | RAP | 2017 | 0.69 | 9.0 | V |
| Cumberland | RAP | 2018 | 0.08 | 23.6 | E |
| **District 4** | | | | | |
| Dracut | RAP | 2017 | 0.20 | 5.9 | E |
| Dracut | RAP | 2018 | 0.16 | 5.5 | E |
| Dracut | Millings | 2017 | 0.03 | 6.8 | E |
| Dracut | Millings | 2018 | 0.45 | 5.2 | E |
| **District 5** | | | | | |
| Wrentham | RAP | 2017 | 0.46 | 7.4 | E |
| Acushnet | RAP | 2017 | 0.24 | 4.7 | E |
| Acushnet | Millings | 2017 | 0.26 | 4.7 | E |

**Table 3.4: Extracted/recovered RAP binder fatigue performance properties (LAS)**

| Location | Type | Year | LAS | | | |
|---|---|---|---|---|---|---|
| | | | Test Temp., °C | $N_f$ @ 2.5% strain | $N_f$ @ 5% strain | $N_f$ @ 10% strain |
| **District 1** | | | | | | |
| Lenoxdale | RAP | 2019 | 35°C | 10,650 | 564 | 30 |
| **District 2** | | | | | | |
| Deerfield | RAP | 2017 | 35°C | 90,496 | 7,020 | 545 |
| Deerfield | RAP | 2018 | 35°C | 65,012 | 5,139 | 407 |
| Northfield | RAP | 2019 | 35°C | 54,217 | 4,142 | 316 |
| **District 3** | | | | | | |
| Millbury | RAP | 2017 | 35°C | 80,306 | 7,409 | 684 |
| Cumberland | RAP | 2018 | 35°C | 20,669 | 1.337 | 87 |
| **District 4** | | | | | | |
| Dracut | RAP | 2017 | 35°C | 86,679 | 7,066 | 576 |
| Dracut | RAP | 2018 | 35°C | 60,311 | 4,693 | 365 |
| Dracut | Millings | 2017 | 35°C | 5,051 | 301 | 18 |
| Dracut | Millings | 2018 | 35°C | 88,014 | 7,569 | 653 |
| **District 5** | | | | | | |
| Wrentham | RAP | 2017 | 25°C | 50,081 | 2,722 | 148 |
| Acushnet | RAP | 2017 | 25°C | 34,499 | 1,655 | 80 |
| Acushnet | Millings | 2017 | 35°C | 42,626 | 3,838 | 346 |

### 3.2.4. RAP Maximum Theoretical Specific Gravity

The maximum theoretical specific gravity ($G_{mm}$) of the dried RAP was determined in accordance with AASHTO T 209 “Standard Method of Test for Theoretical Maximum Specific Gravity and Density of Asphalt Mixtures” *(3)*. Typically, for each stockpile, a minimum of five random samples were tested. The results are presented by district in Tables 3.5 through 3.9. The tables show that the RAP $G_{mm}$ varied between and within the districts.

RAP $G_{mm}$ is commonly used in the mixture design process to estimate the effective specific gravity ($G_{se}$) of the RAP aggregates using equations found in AASHTO R 35 “Standard Practice for Superpave Volumetric Design for Asphalt Mixtures” *(3)*, as shown in Equation 2. This effective specific gravity is then used to estimate the RAP aggregate bulk specific gravity, as outlined in Equation 3. This specific gravity is combined with the virgin aggregate specific gravity in the appropriate mixture blend ratio to calculate the combined mixture aggregate specific gravity, as shown in Equation 4.

**Table 3.5: District 1 RAP recovered aggregate properties**

| **Location** | Lenoxdale |
|---|---|
| **Type** | RAP |
| **Year** | 2019 |
| **Average Maximum Theoretical Specific Gravity – 5 Replicates** | |
| $G_{mm}$ | 2.625 |
| **Average Gradation (After Ignition) – 10 Replicates** | |
| 19.0 mm | 100 |
| 12.5 mm | 99.6 |
| 9.5 mm | 93.9 |
| 4.75 mm (No. 4) | 68.7 |
| 2.36 mm (No. 8) | 51.5 |
| 1.18 mm (No. 16) | 40.2 |
| 600 µm (No. 30) | 30.6 |
| 300 µm (No. 50) | 21.4 |
| 150 µm (No. 100) | 13.6 |
| 75 µm (No. 200) | 9.1 |
| **Average Gradation (After Centrifuge) – 2 Replicates** | |
| 19.0 mm | 100.0 |
| 12.5 mm | 99.7 |
| 9.5 mm | 94.3 |
| 4.75 mm (No. 4) | 69.9 |
| 2.36 mm (No. 8) | 52.4 |
| 1.18 mm (No. 16) | 40.7 |
| 600 µm (No. 30) | 30.7 |
| 300 µm (No. 50) | 21.0 |
| 150 µm (No. 100) | 12.9 |
| 75 µm (No. 200) | 8.3 |
| **Average Combined Aggregate Specific Gravity (After Ignition)** | |
| $G_{sb}$ | 2.733 |

### Table 3.6: District 2 RAP recovered aggregate properties

| **Location** | Deerfield | Deerfield | Northfield |
|---|---|---|---|
| **Type** | RAP | RAP | RAP |
| **Year** | 2017 | 2018 | 2019 |
| **Average Maximum Theoretical Specific Gravity – 5 Replicates** | | | |
| $G_{mm}$ | 2.563 | 2.584 | 2.605 |
| **Average Gradation (After Ignition) – 10 Replicates** | | | |
| 19.0 mm | 100 | 100 | 100 |
| 12.5 mm | 99.9 | 99.9 | 99.6 |
| 9.5 mm | 96.4 | 96.1 | 95.8 |
| 4.75 mm (No. 4) | 69.6 | 68.4 | 65.1 |
| 2.36 mm (No. 8) | 50.9 | 50.8 | 46.5 |
| 1.18 mm (No. 16) | 38.1 | 39.3 | 35.3 |
| 600 µm (No. 30) | 26.7 | 29.4 | 26.1 |
| 300 µm (No. 50) | 18.3 | 20.9 | 18.8 |
| 150 µm (No. 100) | 12.6 | 14.4 | 12.7 |
| 75 µm (No. 200) | 8.9 | 10.1 | 8.7 |
| **Average Gradation (After Centrifuge) – 2 Replicates** | | | |
| 19.0 mm | 100 | 100 | 100 |
| 12.5 mm | 99.9 | 99.8 | 99.9 |
| 9.5 mm | 96.6 | 95.8 | 96.3 |
| 4.75 mm (No. 4) | 70.1 | 67.6 | 66.7 |
| 2.36 mm (No. 8) | 51.4 | 50.1 | 48.2 |
| 1.18 mm (No. 16) | 37.8 | 38.4 | 36.4 |
| 600 µm (No. 30) | 26.3 | 28.5 | 26.9 |
| 300 µm (No. 50) | 17.7 | 20.0 | 18.8 |
| 150 µm (No. 100) | 12.2 | 13.7 | 12.7 |
| 75 µm (No. 200) | 9.0 | 10.0 | 8.6 |
| **Average Combined Aggregate Specific Gravity (After Ignition)** | | | |
| $G_{sb}$ | 2.615 | 2.708 | 2.682 |

**Table 3.7: District 3 RAP recovered aggregate properties**

| **Location** | Millbury | Cumberland |
|---|---|---|
| **Type** | RAP | RAP |
| **Year** | 2017 | 2018 |
| **Average Maximum Theoretical Specific Gravity – 5 Replicates** | | |
| $G_{mm}$ | 2.542 | 2.511 |
| **Average Gradation (After Ignition) – 10 Replicates** | | |
| 19.0 mm | 100 | 100 |
| 12.5 mm | 95.5 | 99.2 |
| 9.5 mm | 88.8 | 93.6 |
| 4.75 mm (No. 4) | 69.2 | 70.0 |
| 2.36 mm (No. 8) | 52.9 | 52.2 |
| 1.18 mm (No. 16) | 41.1 | 40.1 |
| 600 µm (No. 30) | 31.2 | 31.0 |
| 300 µm (No. 50) | 22.5 | 23.6 |
| 150 µm (No. 100) | 14.8 | 16.6 |
| 75 µm (No. 200) | 10.5 | 11.6 |
| **Average Gradation (After Centrifuge) – 2 Replicates** | | |
| 19.0 mm | 100 | 99.7 |
| 12.5 mm | 97.1 | 99.1 |
| 9.5 mm | 91.2 | 93.7 |
| 4.75 mm (No. 4) | 70.2 | 68.8 |
| 2.36 mm (No. 8) | 53.3 | 50.6 |
| 1.18 mm (No. 16) | 40.5 | 38.3 |
| 600 µm (No. 30) | 30.2 | 29.5 |
| 300 µm (No. 50) | 21.2 | 22.3 |
| 150 µm (No. 100) | 13.5 | 15.6 |
| 75 µm (No. 200) | 9.0 | 10.9 |
| **Average Combined Aggregate Specific Gravity (After Ignition)** | | |
| $G_{sb}$ | 2.652 | 2.520 |

## Table 3.8: District 4 RAP recovered aggregate properties

| **Location** | Dracut | Dracut | Dracut | Dracut |
|---|---|---|---|---|
| **Type** | RAP | RAP | Millings | Millings |
| **Year** | 2017 | 2018 | 2017 | 2018 |
| **Average Maximum Theoretical Specific Gravity – 5 Replicates** | | | | |
| $G_{mm}$ | 2.597 | 2.592 | 2.519 | 2.507 |
| **Average Gradation (After Ignition) – 10 Replicates** | | | | |
| 19.0 mm | 100 | 100 | 100 | 100 |
| 12.5 mm | 99.9 | 100 | 98.5 | 98.5 |
| 9.5 mm | 97.3 | 97.2 | 93.7 | 93.3 |
| 4.75 mm (No. 4) | 73.8 | 72.4 | 64.4 | 71.0 |
| 2.36 mm (No. 8) | 54.8 | 53.1 | 42.4 | 52.0 |
| 1.18 mm (No. 16) | 41.1 | 40.2 | 31.6 | 39.6 |
| 600 µm (No. 30) | 30.8 | 30.5 | 23.7 | 29.5 |
| 300 µm (No. 50) | 22.2 | 22.2 | 17.6 | 20.4 |
| 150 µm (No. 100) | 14.6 | 14.7 | 12.3 | 12.9 |
| 75 µm (No. 200) | 9.7 | 9.9 | 8.7 | 8.7 |
| **Average Gradation (After Centrifuge) – 2 Replicates** | | | | |
| 19.0 mm | 100 | 100 | 100 | 100 |
| 12.5 mm | 99.8 | 100 | 98.3 | 98.3 |
| 9.5 mm | 97.7 | 97.8 | 92.6 | 92.5 |
| 4.75 mm (No. 4) | 74.5 | 68.9 | 59.8 | 70.0 |
| 2.36 mm (No. 8) | 55.7 | 49.1 | 37.9 | 51.1 |
| 1.18 mm (No. 16) | 41.7 | 36.5 | 27.3 | 39.0 |
| 600 µm (No. 30) | 31.2 | 27.5 | 20.6 | 29.0 |
| 300 µm (No. 50) | 22.3 | 19.8 | 15.1 | 19.6 |
| 150 µm (No. 100) | 14.6 | 12.8 | 10.3 | 11.8 |
| 75 µm (No. 200) | 9.5 | 8.4 | 6.9 | 7.6 |
| **Average Combined Aggregate Specific Gravity (After Ignition)** | | | | |
| $G_{sb}$ | 2.663 | 2.664 | 2.650 | 2.642 |

Table 3.9: District 5 RAP recovered aggregate properties

| **Location** | Wrentham | Acushnet | Acushnet |
|---|---|---|---|
| **Type** | RAP | RAP | Millings |
| **Year** | 2017 | 2017 | 2017 |
| **Average Maximum Theoretical Specific Gravity – 5 Replicates** | | | |
| $G_{mm}$ | 2.493 | 2.529 | 2.570 |
| **Average Gradation (After Ignition) – 10 Replicates** | | | |
| 19.0 mm | 100 | 100 | 100 |
| 12.5 mm | 98.6 | 98.8 | 97.9 |
| 9.5 mm | 90.9 | 88.1 | 90.6 |
| 4.75 mm (No. 4) | 68.2 | 58.5 | 67.8 |
| 2.36 mm (No. 8) | 51.3 | 41.9 | 51.7 |
| 1.18 mm (No. 16) | 38.5 | 32.7 | 39.4 |
| 600 µm (No. 30) | 28.0 | 25.9 | 30.2 |
| 300 µm (No. 50) | 19.1 | 19.9 | 22.6 |
| 150 µm (No. 100) | 11.8 | 13.6 | 15.2 |
| 75 µm (No. 200) | 7.7 | 9.0 | 10.2 |
| **Gradation (After Centrifuge) – 2 Replicates** | | | |
| 19.0 mm | 100 | 100 | 100 |
| 12.5 mm | 96.0 | 99.2 | 96.3 |
| 9.5 mm | 88.2 | 94.4 | 87.4 |
| 4.75 mm (No. 4) | 66.4 | 71.8 | 64.0 |
| 2.36 mm (No. 8) | 50.9 | 52.3 | 49.4 |
| 1.18 mm (No. 16) | 38.8 | 39.3 | 37.4 |
| 600 µm (No. 30) | 28.8 | 30.1 | 28.9 |
| 300 µm (No. 50) | 19.7 | 22.1 | 22.0 |
| 150 µm (No. 100) | 12.2 | 14.7 | 15.4 |
| 75 µm (No. 200) | 7.9 | 9.8 | 10.1 |
| **Average Aggregate Specific Gravity (After Ignition)** | | | |
| $G_{sb}$ | 2.547 | 2.587 | 2.679 |

This combined specific gravity has direct influence on the calculated mixture voids in mineral aggregate (VMA) and voids filled with asphalt (VFA), as shown in Equations 5 and 6.

$$G_{se} = \frac{100-P_b}{\left[\frac{100}{G_{mm}} - \frac{P_b}{G_b}\right]} \tag{2}$$

Where:
$G_{se}$ = Effective specific gravity of the RAP aggregate.
$P_b$ = Binder content of RAP, %.
$G_{mm}$ = Maximum theoretical specific gravity of the RAP.
$G_b$ = Specific gravity of asphalt binder (typically = 1.03).

$$G_{sbRAP} = \frac{G_{se}}{\left[\frac{P_{ba}\ x\ G_{se}}{100\ x\ G_b}+1\right]} \tag{3}$$

Where:
$G_{sbRAP}$ = Bulk specific gravity of the RAP aggregate.
$G_{se}$ = Effective specific gravity of the RAP aggregate.
$P_{ba}$ = Absorbed asphalt content of RAP (estimated from virgin mixtures =0.5%)
$G_b$ = Specific gravity of asphalt binder (typically = 1.03).

$$G_{sb} = \frac{(P_{RAP}+P_{S1}+P_{S2}+\cdots P_{Sn})}{\left[\frac{P_{RAP}}{G_{sbRAP}}+\frac{P_{S1}}{G_{S1}}+\frac{P_{S2}}{G_{S2}}+\cdots\frac{P_{Sn}}{G_{Sn}}\right]} \tag{4}$$

Where:
$G_{sb}$ = Bulk specific gravity of combined aggregate blend.
$P_{RAP}$= Percent by mass of RAP in the blend.
$G_{sbRAP}$ = Bulk specific gravity of the RAP aggregate.
$P_{S1}$, $P_{S2}$, …$P_{sn}$ = Percent by mass of each individual aggregate stockpile in the blend.
$G_{S1}$, $G_{S2}$, …$G_{sn}$ = Bulk specific gravity of each individual aggregate stockpile in the blend.

$$VMA = 100 - \frac{G_{mb}-P_s}{G_{sb}} \tag{5}$$

Where:
VMA = Voids in mineral aggregate, %.
$G_{mb}$ = Bulk specific gravity of compacted mixture.
$P_s$= Aggregate content, % by mass of mixture.
$G_{sb}$ = Bulk specific gravity of combined aggregate.

$$VFA = 100\left(\frac{VMA-V_a}{VMA}\right) \tag{6}$$

Where:
VFA = Voids filled with asphalt, %.
VMA = Voids in mineral aggregate, %.
$V_a$= Percent air voids in the compacted mixture, %.

Significant variations in the RAP $G_{mm}$ could thereby subsequently lead to a mixture with inadequate VMA and VFA, depending on the amount and type of RAP used. Sample volumetric calculations were completed using the average $G_{mm}$ values shown in Tables 3.5 through 3.9 through the process described above for a typical 12.5 mm Massachusetts surface course mixture containing 15% RAP with 5.5% asphalt binder. The results are shown in Table 3.10.

**Table 3.10: Back calculated RAP aggregate bulk specific gravity from RAP $G_{mm}$ effects on typical 12.5 mm 15% RAP mixture volumetric properties**

| Location | Type | Year | Avg. $P_{bI}$ | Avg $G_{mm}$ | $G_{se}$ | $G_{sb}$ RAP | $G_{sb}$ for Mix | VMA | VFA |
|---|---|---|---|---|---|---|---|---|---|
| **District 1** | | | | | | | | | |
| Lenoxdale | RAP | 2019 | 6.0 | 2.625 | 2.913 | 2.872 | 2.654 | 16.3 | 75.5F |
| **District 2** | | | | | | | | | |
| Deerfield | RAP | 2017 | 6.6 | 2.563 | 2.864 | 2.825 | 2.647 | 16.1 | 75.2 F |
| Deerfield | RAP | 2018 | 6.3 | 2.584 | 2.876 | 2.836 | 2.649 | 16.2 | 75.3 F |
| Northfield | RAP | 2019 | 6.0 | 2.605 | 2.887 | 2.847 | 2.650 | 16.2 | 75.3 F |
| **District 3** | | | | | | | | | |
| Millbury | RAP | 2017 | 5.8 | 2.542 | 2.795 | 2.757 | 2.638 | 15.8 | 74.7 |
| Cumberland | RAP | 2018 | 5.8 | 2.511 | 2.755 | 2.719 | 2.633 | 15.7 | 74.4 |
| **District 4** | | | | | | | | | |
| Dracut | RAP | 2017 | 5.2 | 2.597 | 2.833 | 2.795 | 2.643 | 16.0 | 75.0 |
| Dracut | RAP | 2018 | 5.4 | 2.592 | 2.838 | 2.799 | 2.644 | 16.0 | 75.0 |
| Dracut | Millings | 2017 | 6.0 | 2.519 | 2.775 | 2.738 | 2.636 | 15.7 | 74.6 |
| Dracut | Millings | 2018 | 6.2 | 2.507 | 2.770 | 2.733 | 2.635 | 15.7 | 74.6 |
| **District 5** | | | | | | | | | |
| Wrentham | RAP | 2017 | 5.1 | 2.493 | 2.699 | 2.664 | 2.625 | 15.4 | 74.0 |
| Acushnet | RAP | 2017 | 4.6 | 2.529 | 2.720 | 2.684 | 2.628 | 15.5 | 74.2 |
| Acushnet | Millings | 2017 | 5.9 | 2.570 | 2.836 | 2.797 | 2.644 | 16.0 | 75.0 |

$P_{bI}$ = RAP binder content determined by ignition oven.
**F** = Failed VFA criteria of 65%–75%.

Regardless of the RAP stockpile used, all mixtures met the MassDOT specified VMA of 15% minimum, with values ranging from 15.4% to 16.3%. Conversely, using these VMA values to calculate VFA, four mixtures had values slightly above the acceptable range of 65%–75%, at 75.2% to 75.5%. Thus, the RAP stockpiles could not be used in those mixtures up to 15%. These sample calculations indicate that the $G_{mm}$ has significance on calculated mixture volumetric properties when the RAP aggregate specific gravity is estimated from the $G_{mm}$. These sample calculations show that using selected RAP stockpiles in the same mixture, at the currently specified 15%, may lead to some mixtures failing to meet the required volumetric properties.

### 3.2.5. Recovered RAP Aggregate Gradation

The aggregates remaining after ignition oven and chemical extraction were further tested for aggregate gradation and specific gravity, in accordance with AASHTO T 11 “Standard Method of Test for Materials Finer Than 75-μm (No. 200) Sieve in Mineral Aggregates by Washing”; T 27 “Standard Method of Test for Sieve Analysis of Fine and Coarse Aggregates”; and T 30 “Standard Method of Test for Mechanical Analysis of Extracted Aggregate” *(3)*. Following the recommendations outlined in NCHRP Report 752 shown in Table 3.1, a minimum of 10 random samples were tested for the ignition oven recovered aggregates. Due to the amount of solvent involved in chemical extraction, a minimum of two random samples were tested for centrifuge extraction recovered aggregates.

Tables 3.5 through 3.9 show the aggregate gradation results post-ignition oven and centrifuge extraction for the 13 RAP stockpiles. Nothing definitive can be surmised directly from the gradation data. Generally speaking, the gradations obtained post-ignition oven were finer than the those obtained after chemical extraction. This is likely due to the fact that aggregates will break down during the ignition oven process, thus a finer gradation was expected to be obtained.

From a specification standpoint, it is important to note that the RAP stockpiles must be graded such that they conform to the mixture gradation at the allowable percentage. Typically, RAP contains more fine material (passing No. 200 material) than a typical virgin stockpile. This, along with the differences in binder content, could have an impact on the overall mixture performance.

Another finding from the testing was that 3 of 13 stockpiles (Acushnet RAP 2017, Dracut RAP 2018, and Dracut Millings 2017) did not meet the recovered aggregate gradation standard deviation requirements outlined in NCHRP 752 (5.0% for all sieves except the No. 200, which was 1.5%) as indicated in Table 3.1. An example of this is shown in Table 3.11. This data indicates that some RAP stockpiles had high variability, as some sieve sizes had standard deviations greater than 10%. That shows if the limits proposed in NCHRP Report 752 were to be incorporated into the future specification, then those three stockpiles would not be uniform enough for use. The current MassDOT and AASHTO M 323 “Standard Specification for Superpave Volumetric Mix Design” specification does not address RAP stockpile variability, thus allowing for potentially highly variable stockpiles to be used. This would result in nonconforming mixtures being produced, with potentially reduced volumetric and performance characteristics. Ultimately, it will be up to each state to determine a measure to quantify RAP variability to ensure suitably homogeneous RAP stockpiles are used.

**Table 3.11: Example of replicate post-ignition oven gradation measurements exceeding suggested NCHRP 752 limits**

| | Acushnet RAP 2017 Average Ignition Oven Gradation (10 Replicates) | Standard Deviation of 10 Replicates | Suggested NCHRP 752 Standard Deviation Limits |
|---|---|---|---|
| 19.0 mm | 100 | 0 | < 5.0 |
| 12.5 mm | 98.8 | 0.7 | < 5.0 |
| 9.5 mm | 88.1 | 5.5 F | < 5.0 |
| 4.75 mm (No. 4) | 58.5 | 13.8 F | < 5.0 |
| 2.36 mm (No. 8) | 41.9 | 11.5 F | < 5.0 |
| 1.18 mm (No. 16) | 32.7 | 8.6 F | < 5.0 |
| 600 µm (No. 30) | 25.9 | 6.2 F | < 5.0 |
| 300 µm (No. 50) | 19.9 | 4.1 | < 5.0 |
| 150 µm (No. 100) | 13.6 | 2.6 | < 5.0 |
| 75 µm (No. 200) | 9.0 | 1.8 F | <1.5 |

**F** =Standard deviation of measurements outside suggested NCHRP 752 limits.

### 3.2.6. Recovered RAP Aggregate Specific Gravity

Due to minimum sample size requirements of AASHTO T 84 “Standard Method of Test for Specific Gravity and Absorption of Fine Aggregate” and T 85 “Standard Method of Test for Specific Gravity and Absorption of Coarse Aggregate” *(3)*, additional extracted aggregate material was obtained in the ignition oven. This material was split into coarse (material larger than No. 4 sieve) and fine (material passing No. 4 sieve) fractions for specific gravity testing. NCHRP Report 752 recommended a minimum of three specific gravity tests per stockpile, as shown in Table 3.1. For this project, a minimum of four random samples were obtained and tested for each RAP stockpile. The specific gravity values for each sample were mathematically combined into one overall aggregate specific gravity value, based on the ignition oven sieve analysis results.

Table 3.12 shows the average specific gravity results, which are also presented in Tables 3.5 through 3.9. The values of the measured aggregate specific gravity for the RAP stockpiles were consistently lower than those that were estimated or back calculated from the RAP $G_{mm}$ calculation discussed previously in Section 3.2.4. Using the same sample volumetric calculations discussed in the $G_{mm}$ section (Section 3.2.4), two of the RAP stockpiles would yield mixtures failing the VMA requirement of >15% (14.7% and 14.8%), but all mixtures passed the VFA requirement. Thus, in terms of specifications, it should be decided which method is preferable to MassDOT to determine the specific gravity of the RAP aggregate, as each method will yield mixtures with different volumetric properties, and not all may conform to current volumetric thresholds.

**Table 3.12: Back calculated RAP aggregate bulk specific gravity from $G_{mm}$ vs. measured bulk specific gravity**

| Location | Type | Year | Back Calculated RAP $G_{sb}$ | AASHTO T 84/T 85 Measured RAP $G_{sb}$ | Using Back Calculated RAP $G_{sb}$ | | Using Measured RAP $G_{sb}$ | |
|---|---|---|---|---|---|---|---|---|
| | | | | | VMA | VFA | VMA | VFA |
| **District 1** | | | | | | | | |
| Lenoxdale | RAP | 2019 | 2.872 | 2.733 | 16.3 | 75.5 F | 15.7 | 74.6 |
| **District 2** | | | | | | | | |
| Deerfield | RAP | 2017 | 2.825 | 2.615 | 16.1 | 75.2 F | 15.2 | 73.6 |
| Deerfield | RAP | 2018 | 2.836 | 2.708 | 16.2 | 75.3 F | 15.6 | 74.4 |
| Northfield | RAP | 2019 | 2.847 | 2.682 | 16.2 | 75.3 F | 15.5 | 74.2 |
| **District 3** | | | | | | | | |
| Millbury | RAP | 2017 | 2.757 | 2.652 | 15.8 | 74.7 | 15.3 | 73.9 |
| Cumberland | RAP | 2018 | 2.719 | 2.520 | 15.7 | 74.4 | 14.7 F | 72.8 |
| **District 4** | | | | | | | | |
| Dracut | RAP | 2017 | 2.795 | 2.663 | 16.0 | 75.0 | 15.4 | 74.0 |
| Dracut | RAP | 2018 | 2.799 | 2.664 | 16.0 | 75.0 | 15.4 | 74.0 |
| Dracut | Millings | 2017 | 2.738 | 2.650 | 15.7 | 74.6 | 15.3 | 73.9 |
| Dracut | Millings | 2018 | 2.733 | 2.642 | 15.7 | 74.6 | 15.3 | 73.9 |
| **District 5** | | | | | | | | |
| Wrentham | RAP | 2017 | 2.664 | 2.547 | 15.4 | 74.0 | 14.8 F | 73.0 |
| Acushnet | RAP | 2017 | 2.684 | 2.587 | 15.5 | 74.2 | 15.0 | 73.4 |
| Acushnet | Millings | 2017 | 2.797 | 2.679 | 16.0 | 75.0 | 15.5 | 74.1 |

**F** = Failed criteria.

## 3.3 RAP Property Changes from Year to Year

Determining the year-to-year variability of the RAPs was of interest for this study, as the properties and sources of materials used to generate a RAP stockpile will vary from one production season to the next. If the variation of the RAP is significant from year to year, any specification would have to address this. Three RAP stockpiles were sampled in 2017 and then again in 2018 (Dracut RAP, Dracut Millings, and Deerfield RAP). This comparison is shown in Table 3.13, with the average results being presented.

### Table 3.13: Differences in average RAP stockpile properties, year to year

| **Location** | Dracut | Dracut | Dracut | Dracut | Deerfield | Deerfield |
|---|---|---|---|---|---|---|
| **Type** | RAP | RAP | Millings | Millings | RAP | RAP |
| **Year** | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 |
| **Average Maximum Theoretical Specific Gravity** | | | | | | |
| $G_{mm}$ | 2.597 | 2.592 | 2.519 | 2.507 | 2.563 | 2.584 |
| **Average Binder Content, %** | | | | | | |
| Ignition Oven | 5.2 | 5.4 | 6.0 | 6.2 | 6.6 | 6.3 |
| Centrifuge | 4.9 | 4.8 | 5.5 | 5.9 | 6.1 | 5.8 |
| **Average Gradation (After Ignition)** | | | | | | |
| 19.0 mm | 100 | 100 | 100 | 100 | 100 | 100 |
| 12.5 mm | 99.9 | 100 | 98.5 | 98.5 | 99.9 | 99.9 |
| 9.5 mm | 97.3 | 97.2 | 93.7 | 93.3 | 96.4 | 96.1 |
| 4.75 mm | 73.8 | 72.4 | 64.4 | 71 | 69.6 | 68.4 |
| 2.36 mm | 54.8 | 53.1 | 42.4 | 52 | 50.9 | 50.8 |
| 1.18 mm | 41.1 | 40.2 | 31.6 | 39.6 | 38.1 | 39.3 |
| 600 µm | 30.8 | 30.5 | 23.7 | 29.5 | 26.7 | 29.4 |
| 300 µm | 22.2 | 22.2 | 17.6 | 20.4 | 18.3 | 20.9 |
| 150 µm | 14.6 | 14.7 | 12.3 | 12.9 | 12.6 | 14.4 |
| 75 µm | 9.7 | 9.9 | 8.7 | 8.7 | 8.9 | 10.1 |
| **Average Aggregate Specific Gravity (After Ignition)** | | | | | | |
| Combined $G_{sb}$ | 2.663 | 2.664 | 2.650 | 2.642 | 2.615 | 2.708 |
| **Average RAP Binder Grading Results** | | | | | | |
| Performance Grade | PG82-16 | PG82-16 | PG94-10 | PG76-22 | PG82-16 | PG82-16 |
| Continuous Grade High | 84.2 | 85.8 | 99.3 | 80.2 | 86.7 | 85.4 |
| Continuous Grade Intermediate | 27.0 | 29.1 | 37.7 | 27.6 | 30.7 | 30.9 |
| Continuous Grade Low | -21.2 | -20.1 | -11.0 | -22.2 | -18.3 | -17.9 |

In general, the properties of the RAPs did not vary greatly, except for those of the Dracut millings. The recovered RAP binder grade went from very stiff at PG 94-10 to much less stiff at PG 76-22. This demonstrates that RAP properties must be tested thoroughly every season or when new RAP is processed. Another complication is that sections of a particular stockpile may have RAPs with different properties. Moreover, RAP stockpile properties cannot be accurately determined without knowing the properties of the RAP binder. The current specification does not account for these properties at low RAP contents.

# 4.0 Virgin Asphalt Binders

In order to evaluate the AASHTO M 323 recommended methods for specifying RAP in a mixture, the research team also needed to determine the properties of the typical virgin binders used in Massachusetts. This section outlines the testing for these virgin binders.

## 4.1 Sampling of Virgin Asphalt Binders

It was determined that Massachusetts has four regional suppliers of PG 64-28 asphalt binder that currently serve the state. The typical asphalt binder was obtained from all four sources and graded in accordance with AASHTO M 320 "Standard Specification for Performance-Graded Asphalt Binder" *(3)*. The sources were Deerfield, Massachusetts; Providence, Rhode Island; Newington, New Hampshire; and Montreal, Canada.

## 4.2 Performance Grade

Testing of multiple random replicates for the four binder sources confirmed each of the binders to be PG 64-28. The average continuous grades for each asphalt binder source are shown in Table 4.1. Additionally, the average Delta Tc (ΔTc) of each binder after PAV is provided. Delta Tc is a parameter introduced by Anderson et al. *(8)* that is used to measure the loss of relaxation due to aging, which increases the risk of non-load-associated cracking. A minimum ΔTc of -5.0°C has been suggested as a preliminary criterion *(9)*; therefore, binders with a ΔTc of -5.0°C or more negative are considered unacceptable. None of the virgin binders in this study exhibited ΔTc values outside the acceptable range.

**Table 4.1: Virgin binder performance grade**

| Source | Average Binder Continuous Grade (High, Intermediate, Low)°C | Average Binder PG | Average $\Delta T_C$ |
|---|---|---|---|
| Deerfield | 65.8 (15.8) -30.9 | PG 64-28 | +0.8 |
| Providence | 66.2 (20.4) -28.6 | PG 64-28 | -1.2 |
| Newington | 65.0 (16.3) -30.6 | PG 64-28 | 0.0 |
| Canada | 65.5 (16.8) -30.9 | PG 64-28 | -0.1 |

It is important to note that the Providence source had intermediate- and low-temperature continuous grades warmer than those of the other binders tested. Both of them were close to their respective maximum thresholds for PG 64-28 (22°C intermediate temperature and -28°C low temperature). This will have an impact on the capacity of this virgin binder to accommodate RAP in any mixture, because the aged RAP binder might not make the blended binder PG 64-28.

## 4.3 Virgin Binder Performance Properties

As in the case of the recovered RAP binders, the performance properties of the virgin binder were also measured in addition to determining the PG of the binder. Specifically, the same binder rutting and fatigue performance were utilized.

Rutting performance was measured using the multiple stress creep recovery (MSCR) test, in accordance with AASHTO T 350 “Standard Method of Test for Multiple Stress Creep Recovery Test of Asphalt Binder Using a Dynamic Shear Rheometer” *(3)*. A minimum of two tests were conducted at 64°C, coinciding with the typical binder high PG grade temperature for the state. Values of the nonrecoverable creep compliance ($J_{nr}$) were determined for each binder tested, as shown in Table 4.2. In accordance with AASHTO M 332 “Standard Specification for Performance-Graded Asphalt Binder Using Multiple Stress Creep Recovery Test” *(3)*, values of the nonrecoverable creep compliance at the highest shear stress of 3.2 kPa ($J_{nr3.2}$) are used to determine the traffic loading designations for the binder: “S,” “H,” “V,” or “E,” which correspond to “standard,” “high,” “very high,” or “extremely high” traffic loading, respectively.

**Table 4.2: Virgin binder rutting performance properties (MSCR)**

| | **MSCR @ 64°C** | | |
|---|---|---|---|
| **Source** | **$J_{nr3.2}$** | **$J_{nr\ Diff}$ 75% max.** | **Traffic Loading Designation** |
| Deerfield | 3.5 | 38% | S |
| Providence | 2.8 | 17% | S |
| Newington | 3.8 | 38% | S |
| Canada | 3.7 | 42% | S |

All virgin binder testing results indicated they should be used for traffic loading designation of “S.” The standard designation “S” is for traffic levels fewer than 10 million equivalent single axle loads (ESALs) and more than the standard traffic speed (>70 km/h or 43.5 mph). Since the virgin binders were not modified, it was anticipated the traffic designation was standard, as the binders are likely to be less stiff and have relatively less rutting resistance than a modified binder.

Fatigue performance was measured using the linear amplitude sweep (LAS) test in accordance with AASHTO TP 101 “Standard Method of Test for Estimating Fatigue Resistance of Asphalt Binders Using the Linear Amplitude Sweep” (*3*). A minimum of two tests should be conducted at the intermediate temperature grade of the binder. For the virgin binders, the next-coldest intermediate temperature for all binders was 15°C, based on the intermediate continuous grade of each binder as shown in Table 4.1. The results of the LAS testing are shown in Table 4.3. Generally, increased number of cycles to failure ($N_f$) at a particular strain level indicate better fracture resistance. The results indicate that the fracture resistance of the virgin binders varied based on source, with the one binder exhibiting a reduced fatigue performance as compared to the remaining binders tested.

Table 4.3: Virgin binder fatigue performance properties (LAS)

| | LAS | | | |
|---|---|---|---|---|
| **Source** | **Test Temp., °C** | **$N_f$ @2.5% strain** | **$N_f$ @5% strain** | **$N_f$ @10% strain** |
| Deerfield | 15°C | 152,867 | 7,885 | 407 |
| Providence | 15°C | 68,355 | 3,102 | 141 |
| Newington | 15°C | 213,170 | 10,712 | 538 |
| Canada | 15°C | 156,477 | 6,901 | 304 |

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# 5.0 Analysis of Methods to Specify RAP in a Mixture

As noted previously, guidelines are provided by AASHTO M 323 “Standard Specification for Superpave Volumetric Mix Design” for specifying RAP in a mixture by both percentage of dry weight of mixture and RAP binder ratio (RAPBR). Specifically, AASHTO M 323 provides recommendations for the amount of RAP, or a RAPBR, that can be used in a mixture without requiring a change to the virgin binder grade. The specification also provides recommendations on how to select an appropriate binder grade if the RAP amount or RAPBR exceeds specific levels. These recommendations are shown in Table 5.1, and the current Massachusetts specification closely follows AASHTO guidance. This section addresses a major project objective, which was to determine if the MassDOT specification, which allows up to 15% RAP by dry weight of a mixture without using a softer-grade virgin binder or blending equations, is valid regardless of the RAP source or virgin binder source. It will also address the objective of determining if the MassDOT specification should be based on RAPBR instead of by dry weight of the mixture.

**Table 5.1: AASHTO M 323 guidance on how to specify RAP use in Superpave asphalt mixtures**

| **Percent Dry Weight of Mixture Method** | |
|---|---|
| Recommended Virgin Asphalt Binder Grade | RAP Percentage |
| No Change in Binder Selection | <15% |
| Select Virgin Binder One Grade Softer than Normal | 15 to 25% |
| Follow Blending Chart Recommendations (AASHTO M 323 Appendix X1) | >25% |
| **RAP Binder Ratio (RAPBR) Method** | |
| Recommended Virgin Asphalt Binder Grade | RAPBR |
| No Change in Binder Selection | <0.25 |
| Follow AASHTO Procedures for Estimating the Properties of Blended RAP and Virgin Binders (AASHTO M 323 Appendix X2) | >0.25 |

## 5.1 Percent Dry Weight of Mixture Method

As detailed in Table 5.1, at RAP percentages <15%, AASHTO recommends no PG change for the binder used in a mixture. If PG 64-28 is desired, a PG 64-28 binder should be used. This specification implies that the RAP source utilized will have a negligible impact on the overall properties of the blended binder in the mixture. It is blind to the properties of the RAP binder (binder content, PG, etc.) and the virgin binder. The only way to confirm this is to utilize the blending chart procedure that is typically used for >25% RAP. For this study, the properties of the recovered RAP and virgin binder sources were already determined, as shown in Tables 3.2 and 4.1, respectively. The blending chart procedure suggested by AASHTO utilizes these known properties to give an estimate of the percentage of RAP that can be used via its Equation X1.12, shown here as Equation 7.

$$\% \, RAP = \frac{T_{Blend} - T_{Virgin}}{T_{RAP} - T_{Virgin}} \tag{7}$$

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).

Theoretically, if the <15% limit is correct, the results of this analysis should indicate that at least 15% RAP can be used regardless of RAP source or virgin binder source, while maintaining a PG 64-28 blended binder in the mixture. Using Equation 7 and the measured recovered RAP and virgin binder properties already determined, this analysis was completed at high, intermediate, and low temperature with a $T_{Blend}$ of 64°C high temperature, 22°C intermediate temperature, and -28°C low temperature. The low temperature requirement was the limiting case for all combinations.

The results are presented in Table 5.2. The analysis shows that 15% RAP could not be used in 15 of 52 combinations (29%). This indicates that the current MassDOT specification allowing up to 15% RAP by percent of dry weight may not achieve the goal of maintaining PG 64-28. Interestingly, it was also found for the remaining combinations that from 16% to 46.8% RAP could be used while maintaining PG 64-28, depending on the RAP source and virgin binder source. The disparity between the estimated amounts of allowable RAP presents the high influence of the RAP source and virgin binder source on the amount of RAP that can be added to the mixture. Under the current specification, this type of analysis is not completed when up to 15% RAP is used in a surface mixture; the influence of RAP is considered negligible. Clearly, this analysis demonstrates otherwise.

Also noteworthy is that the current percent by dry weight specification at low RAP percentages does not account for differences in RAP binder content. This means that two producers could make a similar mixture, but one will be using less virgin binder as its RAP contains more binder. This may also mean that the performances of the resultant mixtures may be different, as the ratio of virgin to RAP binder in the mixture will be different.

**Table 5.2: Predicted allowable percent RAP by dry weight of mixture to maintain blended PG 64-28 binder in mixture**

| | **Virgin Binder Source** | | | |
|---|---|---|---|---|
| **Location** | **Deerfield** | **Providence** | **Newington** | **Canada** |
| **District 1** | | | | |
| Lenoxdale RAP 2019 | 18.7 | 4.5 F | 17.1 | 18.7 |
| **District 2** | | | | |
| Deerfield RAP 2017 | 23.0 | 5.8 F | 21.1 | 23.0 |
| Deerfield RAP 2018 | 22.3 | 5.6 F | 20.5 | 22.3 |
| Northfield RAP 2019 | 22.8 | 5.8 F | 21.0 | 22.8 |
| **District 3** | | | | |
| Millbury RAP 2017 | 46.8 | 15.4 | 44.1 | 46.8 |
| Cumberland RAP 2018 | 17.5 | 4.2 F | 16.0 | 17.5 |
| **District 4** | | | | |
| Dracut RAP 2017 | 29.9 | 8.1 F | 27.7 | 29.9 |
| Dracut RAP 2018 | 26.9 | 7.1 F | 24.8 | 26.9 |
| Dracut Millings 2017 | 14.6F | 3.4 F | 13.3 F | 14.6 F |
| Dracut Millings 2018 | 33.3 | 9.4 F | 31.0 | 33.3 |
| **District 5** | | | | |
| Wrentham RAP 2017 | 33.3 | 9.4 F | 31.0 | 33.3 |
| Acushnet RAP 2017 | 27.4 | 7.2 F | 25.2 | 27.4 |
| Acushnet Millings 2017 | 29.9 | 8.1 F | 27.7 | 29.9 |

**F** = Failed to have a percentage of RAP greater than or equal to 15%.

## 5.2 RAP Binder Ratio

The RAP binder ratio (RAPR) is another method for specifying RAP in a mixture. As shown by Equation 1, the following must be known to calculate the RAPBR: binder content of the RAP, percent RAP by dry weight of the mixture, and total binder content in the mixture. Sometimes when specifying a mixture, these properties are not known, thus presenting a potential limitation of this approach. However, it is considered a more accurate approach compared to the percent by dry weight method. In this analysis, a total mixture binder content of 5.5% was used, which corresponds to the binder content for the mixtures outlined in Section 7.0.

As detailed in Table 5.1, at a RAPBR of <0.25, AASHTO M 323 recommends no PG change for the binder used in a mixture. Like the percent by dry weight method, this method is blind to the properties of the RAP and virgin binder at RAPBR <0.25.

The first step to evaluate the RAPBR method was to calculate the maximum RAPBR ($RAPBR_{max}$) to achieve a specific critical temperature. Using the same recovered RAP binder and virgin binder properties utilized in the previous dry weight method analysis, AASHTO M323 Equation X2.12 *(3)*, shown here as Equation 8, allowed for the calculation of the $RAPBR_{max}$ to achieve a specific critical temperature. The $T_{Need}$ were 64°C high temperature, 22°C intermediate temperature, and -28°C low temperature. The low-temperature analysis was the limiting case for all combinations.

$$RAPBR_{max} = \frac{T_{Need} - T_{Virgin}}{T_{RAP} - T_{Virgin}} \tag{8}$$

<u>Where:</u>
$RAPBR_{max}$ = Maximum RAP binder ratio.
$T_{Virgin}$ = Critical temperature of the virgin asphalt binder (high, intermediate, or low).
$T_{Need}$ = Critical temperature needed for the climate or pavement layer (high, intermediate, or low).
$T_{RAP}$ = Critical temperature of the recovered RAP binder (high, intermediate, or low).

With the $RAPBR_{max}$ values known, the maximum percentage of RAP corresponding to these values could also be calculated. This was done by substituting them back into Equation 1, which was rearranged to calculate the percent RAP by dry weight of the mixture, as shown in Equation 9.

$$\%\,RAP = \frac{100(RAPBR_{max})(Pb_{Total})}{(Pb_{RAP})} \tag{9}$$

<u>Where:</u>
$RAPBR_{max}$ = Maximum RAP binder ratio.
$Pb_{RAP}$ = Binder content of RAP.
% RAP = $P_{RAP}$ = Percent RAP by dry weight of mixture.
$Pb_{Total}$ = Total binder content of the mixture (5.5% for this study).

The $RAPBR_{max}$ and %RAP are shown in Table 5.3. As presented by this table, many combinations failed to have a $RAPBR_{max}$ of at least 0.25, and a lower criterion could not be established. The percent RAPs are all close to those in Table 5.2, because the binder contents of the RAPs were close to the design binder content of 5.5%. Thus, the two methods essentially provided the same conclusions. Based on this, the only accurate specification would be to require thorough testing of both the RAP and virgin binder to be used in combination with the actual mixture design and production. Simply specifying a cutoff threshold will not accurately ensure that the desired binder properties are obtained.

**Table 5.3: RAPBR$_{max}$ and predicted allowable percent RAP to maintain blended PG 64-28 binder in mixture**

| | Virgin Binder Source | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Deerfield | | Providence | | Newington | | Canada | |
| **District 1** | RAP BR$_{max}$ | % RAP | RAP BR$_{max}$ | % RAP | RAP BR$_{max}$ | % RAP | RAP BR$_{max}$ | % RAP |
| Lenoxdale RAP 2019 | 0.19 F | 17.2 | 0.05 F | 4.2 | 0.17 F | 15.7 | 0.19 F | 17.2 |
| **District 2** | | | | | | | | |
| Deerfield RAP 2017 | 0.23 F | 19.2 | 0.06 F | 4.9 | 0.21 F | 17.6 | 0.23 F | 19.2 |
| Deerfield RAP 2018 | 0.22 F | 19.5 | 0.06 F | 4.9 | 0.20 F | 17.9 | 0.22 F | 19.5 |
| Northfield RAP 2019 | 0.23 F | 20.9 | 0.06 F | 5.3 | 0.21 F | 19.2 | 0.23 F | 20.9 |
| **District 3** | | | | | | | | |
| Millbury RAP 2017 | 0.47 | 44.4 | 0.15 F | 14.6 | 0.44 | 41.8 | 0.47 | 44.4 |
| Cumberland RAP 2018 | 0.17 F | 16.6 | 0.04 F | 4.0 | 0.16 F | 15.1 | 0.17 F | 16.6 |
| **District 4** | | | | | | | | |
| Dracut RAP 2017 | 0.30 | 31.6 | 0.08 F | 8.6 | 0.28 | 29.3 | 0.30 | 31.6 |
| Dracut RAP 2018 | 0.27 | 27.3 | 0.07 F | 7.2 | 0.25 | 25.2 | 0.27 | 27.3 |
| Dracut Millings 2017 | 0.15 F | 13.4 | 0.03 F | 3.1 | 0.13 F | 12.2 | 0.15 F | 13.4 |
| Dracut Millings 2018 | 0.33 | 29.6 | 0.09 F | 8.3 | 0.31 | 27.5 | 0.33 | 29.6 |
| **District 5** | | | | | | | | |
| Wrentham RAP 2017 | 0.33 | 35.9 | 0.09 F | 10.1 | 0.31 | 33.4 | 0.33 | 35.9 |
| Acushnet RAP 2017 | 0.27 | 32.7 | 0.07 F | 8.6 | 0.25 | 30.2 | 0.27 | 32.7 |
| Acushnet Millings 2017 | 0.30 | 27.9 | 0.08 F | 7.6 | 0.28 | 25.8 | 0.30 | 27.9 |

**F** = Failed to have a RAPBR$_{max}$ of at least 0.25.

## 5.3 Blending Charts

An alternative way of presenting the data is to calculate the binder properties of the blended binders using AASHTO M 323 Equation X1.11 *(3)*, shown here as Equation 10. RAP percentages of 15%, 25%, and 35 % were used to determine how much RAP could be added while still having some combinations yielding a grade of at least PG 64-28. Part of this data was also needed for the mixture portion of this study. The advantage of this method is that it shows what continuous PG would be provided if a certain percentage of RAP were to be used.

$$T_{Virgin} = \frac{T_{Blend} - (\%RAP\ x\ T_{RAP})}{(1 - \%RAP)} \qquad (10)$$

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).
% RAP = Percentage of RAP Expressed as a decimal.

Table 5.4 shows that 15% RAP could not be used in 29% of the combinations, which matches what was found in Section 5.1, because the analysis in that section used a threshold of 15% RAP. At 25% RAP, shown in Table 5.5, 60% of the combinations could not be used. At 35% RAP, shown in Table 5.6, 94% of the combinations could not be used. (Note: the percent failure for any other chosen RAP percentage can be ascertained using Table 5.2. For example, at 10% RAP, Table 5.2 shows that 9 of 52 combinations would fail, or 17%, which all involve the Providence virgin binder.)

## Table 5.4: Calculated blended binder grade by AASHTO M 323 blending equation at 15% RAP

| | **Deerfield Virgin** | **Providence Virgin** | **Newington Virgin** | **Canada Virgin** |
|---|---|---|---|---|
| **Location - Type/Year** | Calculated Blended Binder Grade by Equation at 15% RAP | | | |
| **District 1** | | | | |
| Lenoxdale RAP 2019 | 69.7(18.1)-28.6<br>PG 64-28 | 70.1(22.1)-26.6<br>PG 70-22 F | 69.1(18.6)-28.3<br>PG 64-28 | 69.5(19.0)-28.6<br>PG 64-28 |
| **District 2** | | | | |
| Deerfield RAP 2017 | 68.9(18.0)-29.0<br>PG 64-28 | 69.3(21.9)-27.1<br>PG 64-22 F | 68.3(18.5)-28.8<br>PG 64-28 | 68.7(18.9)-29.0<br>PG 64-28 |
| Deerfield RAP 2018 | 68.7(18.1)-29.0<br>PG 64-28 | 69.1(22.0)-27.0<br>PG 64-22 F | 68.1(18.5)-28.7<br>PG 64-28 | 68.5(18.9)-29.0<br>PG 64-28 |
| Northfield RAP 2019 | 68.8(18.0)-29.0<br>PG 64-28 | 69.1(21.9)-27.0<br>PG 64-22 F | 68.1(18.4)-28.7<br>PG 64-28 | 68.5 (18.8)-29.0<br>PG 64-28 |
| **District 3** | | | | |
| Millbury RAP 2017 | 67.5(16.9)-30.0<br>PG 64-28 | 67.8(20.9)-28.0<br>PG 64-28 | 66.8(17.4)-29.7<br>PG 64-28 | 67.2(17.8)-30.0<br>PG 64-28 |
| Cumberland RAP 2018 | 69.6(18.3)-28.4<br>PG 64-28 | 70.0(22.2)-26.5<br>PG 70-22 F | 68.9(18.7)-28.2<br>PG 64-28 | 69.4(19.1)-28.4<br>PG 64-28 |
| **District 4** | | | | |
| Dracut RAP 2017 | 68.6(17.5)-29.4<br>PG 64-28 | 68.9(21.4)-27.5<br>PG 64-22 F | 67.9(17.9)-29.2<br>PG 64-28 | 68.3(18.3)-29.4<br>PG 64-28 |
| Dracut RAP 2018 | 68.8(17.8)-29.3<br>PG 64-28 | 69.1(21.7)-27.3<br>PG 64-22 F | 68.1(18.2)-29.0<br>PG 64-28 | 68.5(18.6)-29.3<br>PG 64-28 |
| Dracut Millings 2017 | 70.8(19.1)-27.9<br>PG 70-22 F | 71.2(23.0)-26.0<br>PG 70-22 F | 70.1(19.5)-27.7<br>PG 70-22 F | 70.6(19.9)-27.9<br>PG 70-22 F |
| Dracut Millings 2018 | 68.0(17.6)-29.6<br>PG 64-28 | 68.3(21.5)-27.6<br>PG 64-22 F | 67.3(18.0)-29.3<br>PG 64-28 | 67.7(18.4)-29.6<br>PG 64-28 |
| **District 5** | | | | |
| Wrentham RAP 2017 | 67.8(17.2)-29.6<br>PG 64-28 | 68.1(21.2)-27.6<br>PG 64-22 F | 67.1(17.7)-29.3<br>PG 64-28 | 67.5(18.1)-29.6<br>PG 64-28 |
| Acushnet RAP 2017 | 68.4(17.6)-29.3<br>PG 64-28 | 68.7(21.5)-27.4<br>PG 64-22 F | 67.7(18.0)-29.1<br>PG 64-28 | 68.1(18.5)-29.3<br>PG 64-28 |
| Acushnet Millings 2017 | 68.3(17.7)-29.4<br>PG 64-28 | 68.7(21.6)-27.5<br>PG 64-22 F | 67.7(18.1)-29.2<br>PG 64-28 | 68.1(18.5)-29.4<br>PG 64-28 |

Note: Calculated grade in format of High Temp. (Intermediate Temp.) Low Temp. all in °C.
**F** = Indicates blending chart equation estimated that at least a PG 64-28 binder was not maintained.

### Table 5.5: Calculated blended binder grade by AASHTO M 323 blending equation at 25% RAP

| | **Deerfield Virgin** | **Providence Virgin** | **Newington Virgin** | **Canada Virgin** |
|---|---|---|---|---|
| **Location - Type/Year** | Calculated Blended Binder Grade by Equation at 25% RAP | | | |
| **District 1** | | | | |
| Lenoxdale<br>RAP 2019 | 72.4(19.7)-27.0<br>PG 70-22 F | 72.7(23.2)-25.3<br>PG 70-22 F | 71.8(20.1)-26.8<br>PG 70-22 F | 72.2(20.5)-27.0<br>PG 70-22 F |
| **District 2** | | | | |
| Deerfield<br>RAP 2017 | 71.0(19.5)-27.8<br>PG 70-22 F | 71.3(23.0)-26.0<br>PG 70-22 F | 70.4(19.9)-27.5<br>PG 70-22 F | 70.8(20.3)-27.8<br>PG 70-22 F |
| Deerfield<br>RAP 2018 | 70.7(19.6)-27.7<br>PG 70-22 | 71.0(23.0)-25.9<br>PG 70-22 F | 70.1(20.0)-27.4<br>PG 70-22 F | 70.5(20.3)-27.7<br>PG 70-22 F |
| Northfield<br>RAP 2019 | 70.8(19.4)-27.7<br>PG 70-22 F | 71.1(22.9)-26.0<br>PG 70-22 F | 70.2(19.8)-27.5<br>PG 70-22 F | 70.6(20.2)-27.7<br>PG 70-22 F |
| **District 3** | | | | |
| Millbury<br>RAP 2017 | 68.6(17.7)-29.4<br>PG 64-28 | 68.9(21.2)-27.6<br>PG 64-22 F | 68.0(18.1)-29.1<br>PG 64-28 | 68.3(18.5)-29.4<br>PG 64-28 |
| Cumberland<br>RAP 2018 | 72.2(19.9)-26.8<br>PG 70-22 F | 72.5(23.4)-25.0<br>PG 70-22 F | 71.6(20.3)-26.5<br>PG 70-22 F | 71.9(20.7)-26.8<br>PG 70-22 F |
| **District 4** | | | | |
| Dracut<br>RAP 2017 | 70.4(18.6)-28.5<br>PG 70-28 | 70.7(22.1)-26.8<br>PG 70-22 F | 69.8(19.0)-28.3<br>PG 64-28 | 70.2(19.4)-28.5<br>PG 70-28 |
| Dracut<br>RAP 2018 | 70.8(19.1)-28.2<br>PG 70-28 | 71.1(22.6)-26.5<br>PG 70-22 F | 70.2(19.5)-28.0<br>PG 70-28 | 70.6(19.9)-28.2<br>PG 70-28 |
| Dracut<br>Millings 2017 | 74.2(21.3)-25.9<br>PG 70-22 F | 74.5(24.7)-24.2<br>PG 70-22 F | 73.6(21.7)-25.7<br>PG 70-22 F | 74.0(22.0)-25.9<br>PG 70-22 F |
| Dracut<br>Millings 2018 | 69.4(18.8)-28.7<br>PG 64-28 | 69.7(22.2)-27.0<br>PG 64-22 F | 68.8(19.1)-28.5<br>PG 64-28 | 69.2(19.5)-28.7<br>PG 64-28 |
| **District 5** | | | | |
| Wrentham<br>RAP 2017 | 69.1(18.2)-28.7<br>PG 64-28 | 69.4(21.7)-27.0<br>PG 64-22 F | 68.5(18.6)-28.5<br>PG 64-28 | 68.9(19.0)-28.7<br>PG 64-28 |
| Acushnet<br>RAP 2017 | 70.1(18.8)-28.3<br>PG 70-28 | 70.4(22.3)-26.5<br>PG 70-22 F | 69.5(19.2)-28.0<br>PG 64-28 | 69.9(19.6)-28.3<br>PG 64-28 |
| Acushnet<br>Millings 2017 | 70.0(18.9)-28.5<br>PG 70-28 | 70.3(22.4)-26.8<br>PG 70-22 F | 69.4(19.3)-28.3<br>PG 64-28 | 69.8(19.7)-28.5<br>PG 64-28 |

Note: Calculated grade in format of High Temp. (Intermediate Temp.) Low Temp., all in °C.

**F** = Indicates blending chart equation estimated that at least a PG 64-28 binder was not maintained.

**Table 5.6: Calculated blended binder grade by AASHTO M 323 blending equation at 35% RAP**

| | Deerfield Virgin | Providence Virgin | Newington Virgin | Canada Virgin |
|---|---|---|---|---|
| **Location - Type/Year** | Calculated Blended Binder Grade by Equation at 35% RAP | | | |
| **District 1** | | | | |
| Lenoxdale<br>RAP 2019 | 75.0(21.3)-25.5<br>PG 70-22 F | 75.3(24.3)-24.0<br>PG 70-22 F | 74.0(21.6)-25.3<br>PG 70-22 F | 74.8(21.9)-25.5<br>PG 70-22 F |
| **District 2** | | | | |
| Deerfield<br>RAP 2017 | 73.1(21.0)-26.5<br>PG 70-22 F | 73.4(24.0)-25.0<br>PG 70-22 F | 72.6(21.3)-26.3<br>PG 70-22 F | 72.9(21.7)-26.5<br>PG 70-22 F |
| Deerfield<br>RAP 2018 | 72.7(21.1)-26.4<br>PG 70-22 F | 72.9(24.1)-24.9<br>PG 70-22 F | 72.1(21.4)-26.2<br>PG 70-22 F | 72.5(21.7)-26.4<br>PG 70-22 F |
| Northfield<br>RAP 2019 | 72.8(20.8)-26.5<br>PG 70-22 F | 73.1(23.8)-25.0<br>PG 70-22 F | 72.3(21.2)-26.3<br>PG 70-22 F | 72.6(21.5)-26.5<br>PG 70-22 F |
| **District 3** | | | | |
| Millbury<br>RAP 2017 | 69.7(18.5)-28.7<br>PG 64-28 | 69.9(21.5)-27.2<br>PG 64-22 F | 69.1(18.8)-28.5<br>PG 64-28 | 69.5(19.1)-28.7<br>PG 64-28 |
| Cumberland<br>RAP 2018 | 74.7(21.6)-25.1<br>PG 70-22 F | 75.0(24.6)-23.6<br>PG 70-22 F | 74.2(21.9)-24.9<br>PG 70-22 F | 74.5(22.2)-25.1<br>PG 70-22 F |
| **District 4** | | | | |
| Dracut<br>RAP 2017 | 72.2(19.7)-27.5<br>PG 70-22 F | 72.5(22.7)-26.0<br>PG 70-22 F | 71.7(20.0)-27.3<br>PG 70-22 F | 72.0(20.4)-27.5<br>PG 70-22 F |
| Dracut<br>RAP 2018 | 72.8(20.5)-27.1<br>PG 70-22 F | 73.1(23.4)-25.6<br>PG 70-22 F | 72.3(20.8)-26.9<br>PG 70-22 F | 72.6(21.1)-27.1<br>PG 70-22 F |
| Dracut<br>Millings 2017 | 77.5(23.5)-23.9<br>PG 70-22 F | 77.8(26.5)-22.4<br>PG 76-22 F | 77.0(23.8)-23.7<br>PG 76-22 F | 77.3(24.1)-23.9<br>PG 70-22 F |
| Dracut<br>Millings 2018 | 70.8(19.9)-27.9<br>PG 70-22 F | 71.1(22.9)-26.4<br>PG 70-22 F | 70.3(20.3)-27.7<br>PG 70-22 F | 70.6(20.6)-27.9<br>PG 70-22 F |
| **District 5** | | | | |
| Wrentham<br>RAP 2017 | 70.5(19.2)-27.9<br>PG 70-22 F | 70.7(22.2)-26.4<br>PG 70-22 F | 69.9(19.5)-27.7<br>PG 64-22 F | 70.3(19.8)-27.9<br>PG 70-22 F |
| Acushnet<br>RAP 2017 | 71.8(20.0)-27.2<br>PG 70-22 F | 72.1(23.0)-25.7<br>PG 70-22 F | 71.3(20.4)-27.0<br>PG 70-22 F | 71.6(20.7)-27.2<br>PG 70-22 F |
| Acushnet<br>Millings 2017 | 71.7(20.1)-27.5<br>PG 70-22 F | 72.0(23.1)-26.0<br>PG 70-22 F | 71.2(20.5)-27.3<br>PG 70-22 F | 71.5(20.8)-27.5<br>PG 70-22 F |

Note: Calculated Grade in format of High Temp. (Intermediate Temp.) Low Temp., all in °C.
**F** = Indicates blending chart equation estimated that at least a PG 64-28 binder was not maintained.

## 5.4 Recommendation

The accuracies of the above methods need to be determined by looking at the performances of actual mixtures incorporating different RAP sources and virgin binder sources. One mixture evaluation is undertaken beginning in Section 7.0 of this report.

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# 6.0 Validate Allowable RAP Percentages

The AASHTO recommendations are based solely on mathematical calculations. Thus, it was of interest to verify that the equations accurately predicted that the blended mixture binder would remain at a grade of PG 64-28. One virgin binder was blended with recovered RAP binder from various sources using the maximum percentages of RAP noted in Table 5.2, in a typical 12.5-mm surface layer mixture with 5.5% total asphalt. The ratio of virgin and RAP binder were calculated as shown in Table 6.1, and the binders were blended together (assuming 100% blending). The blended binders were graded in accordance with AASHTO R 29 “Standard Practice for Grading or Verifying the Performance Grade of an Asphalt Binder” and M 320 “Standard Specification for Performance-Graded Asphalt Binder” *(3)* only at the low temperature (the limiting case for all RAPs noted in Section 5.0). Theoretically, if the AASHTO method was accurate, then the binders should grade to be near -28°C.

**Table 6.1: Verification of AASHTO equations prediction of PG 64-28 in blended binder of mixture**

| Virgin Binder Source | Recovered RAP Binder Source | Equation Predicted Maximum % RAP to Maintain PG 64-28 | % Virgin Binder to % Recovered RAP Binder to Make Blended Binder | Measured Low Temperature Continuous Grade |
|---|---|---|---|---|
| Canada | Millbury RAP 2017 | 46.8 | 53.0 / 47.0 | -26.0°C |
| Canada | Cumberland RAP 2018 | 17.5 | 82.1 / 17.9 | -28.0°C |
| Canada | Dracut Millings 2017 | 14.6 | 87.6 / 12.4 | -28.7°C |
| Canada | Dracut RAP 2017 | 29.9 | 73.9 / 29.9 | -26.7°C |

The data shown in Table 6.1 indicate that at smaller RAP percentages, this holds true, but as the RAP content increases, it appears the accuracy of the prediction is less, as two blended binders graded to be -26.0°C and -26.7°C instead of at least -28°C. This implies, in terms of specification, that the blended binder grade predicted by the AASHTO equations is not wholly accurate and may only be accurate at smaller RAP percentages. This requires further study with different virgin binders and RAP binders before a definitive conclusion can be made.

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# 7.0 Mixture Design with RAP Using Balanced Mix Design Approach

As described in the Introduction, the FHWA BMD Task Force *(2)* provides three approaches to balanced mixture design (BMD). For this study, the first approach (volumetric and performance) was utilized. MassDOT has been working to develop a protocol under this BMD approach. Currently, MassDOT requires mixtures to meet target volumetric properties in the design phase. MassDOT is looking to add performance components in its BMD protocol to ensure its mixtures are balanced in terms of rutting and cracking. The mixture testing in this study will help evaluate the proposed laboratory performance tests and associated criteria for use in the MassDOT BMD protocol.

For the mixture in this study, two RAP sources and two virgin binders were utilized to fabricate mixture specimens. The RAP sources selected were Dracut Millings 2017 and Millbury RAP 2017, also called the “stiff RAP” and “soft RAP,” respectively. The Deerfield and Providence virgin binders were selected for use in the mixture evaluation as they represented the two extremes in terms of the intermediate- and low-temperature continuous grade.

## 7.1 Mixture Aging Methods

A critical component for consideration in a BMD approach that has not been thoroughly addressed is mixture aging. Aging experienced in the field changes the behavior and performance of an asphalt mixture. It is well known that aging causes asphalt mixtures to stiffen and embrittle, which leads to higher potential for cracking. Hence, to accurately characterize the performance of an asphalt mixture, mixtures should be exposed to aging that represents in-service aging prior to testing. In the industry, aging is commonly considered either short-term or long-term.

### 7.1.1. Short-Term Aging

The industry standard for guidance to replicate field aging in the laboratory for asphalt mixtures has been AASHTO R 30 “Standard Practice for Mixture Conditioning of Hot-Mix Asphalt”*(3)*. In this study, the methods outlined in AASHTO R 30 were followed for the short-term aging for volumetric mixture design and for rutting performance testing.

For volumetric mixture design, AASHTO R 30 specifies that loose mixtures be conditioned in a forced-draft oven for two hours at the mixture’s specified compaction temperature prior to compaction.

Rutting is an early-onset distress, meaning it typically occurs early in the life of a pavement. Short-term aging more accurately simulates the aging experienced early in a pavement’s life. For rutting performance testing in this study, AASHTO R 30 guidance for short-term conditioning for mechanical property testing was followed. Loose mixtures were placed in a forced-draft oven for four hours at 135°C. After four hours of aging, the mixtures were brought to the compaction temperature and then compacted.

### 7.1.2. Long-Term Aging

Cracking is a distress that typically occurs later in the life of a pavement. An aging protocol was needed that accurately replicates the field aging experienced by a pavement long-term. AASHTO R 30 provides guidance for long-term aging. First, the loose mixture is short-term aged as noted above (four hours at 135°C and then compacted). The compacted specimens are cooled for 16 hours and then aged in a forced-draft oven for five days (120 hours) at a temperature of 85°C. Although AASHTO R 30 provides protocols for long-term aging of specimens, studies have indicated two specimen integrity problems arise when aging compacted specimens: distortion and oxidation gradient. Reed *(10)* states that distortion is the change in the specimen air voids due to softening. Houston et al. *(11)* demonstrated that the long-term oven aging of compacted specimens led to both radial and vertical oxidation. Given these specimen integrity problems, and since accurate aging is so critical for a BMD approach, other methods of laboratory long-term aging were explored.

The findings of NCHRP Project 09-54, "Long-Term Aging of Asphalt Mixtures for Performance Testing and Prediction," propose a laboratory aging procedure that represents the long-term-aged state of asphalt mixtures in a pavement as a function of climate and depth *(12)*. The procedure is capable of calculating laboratory aging durations that match field aging at any pavement depth and geographic location. Furthermore, a series of laboratory aging duration maps to match 4, 8, and 16 years of field aging at depths of 6 mm, 20 mm, and 50 mm below the pavement surfaces were provided. Based on this study, the maps provided by Kim et al. *(12)* were used to determine the laboratory protocols to simulate long-term pavement aging. Figures 7.1 and 7.2 show the maps used in this study to determine the long-term aging time duration in days. Under the proposed aging protocol, all mixtures are first short-term aged in a loose state, in accordance with AASHTO R 30 (4 hours at 135°C), and then long-term aged using the duration noted on the aging map at 95°C. After long-term aging, the mixture is returned to the compaction temperature and compacted.

Figure 7.1 shows the aging map corresponding to a depth of 20 mm below the pavement surface and 16 years of service life. This map was used to determine the aging duration for intermediate-temperature crack testing, which the map indicated was five days (at 95°C) for Massachusetts. The depth below pavement surface of 20 mm matches the input depth in LTPPBind, which is taken as 20 mm for determining the test temperature for intermediate cracking tests as outlined in AASHTO TP 107-18, "Standard Method of Test for Determining the Damage Characteristic Curve and Failure Criterion Using the Asphalt Mixture Performance Tester (AMPT) Cyclic Fatigue Test," Section 11.3 *(3)*.

Figure 7.2 shows the aging map corresponding to a depth of 6 mm below the pavement surface and 16 years of service life. This map was used to determine the aging duration for the low-temperature (thermal) cracking tests, which the map indicated was 11 days (at 95°C) for Massachusetts. A depth of 6 mm was considered more accurate for thermal cracking, as it is expected that this type of cracking will occur at or near the surface of a pavement.

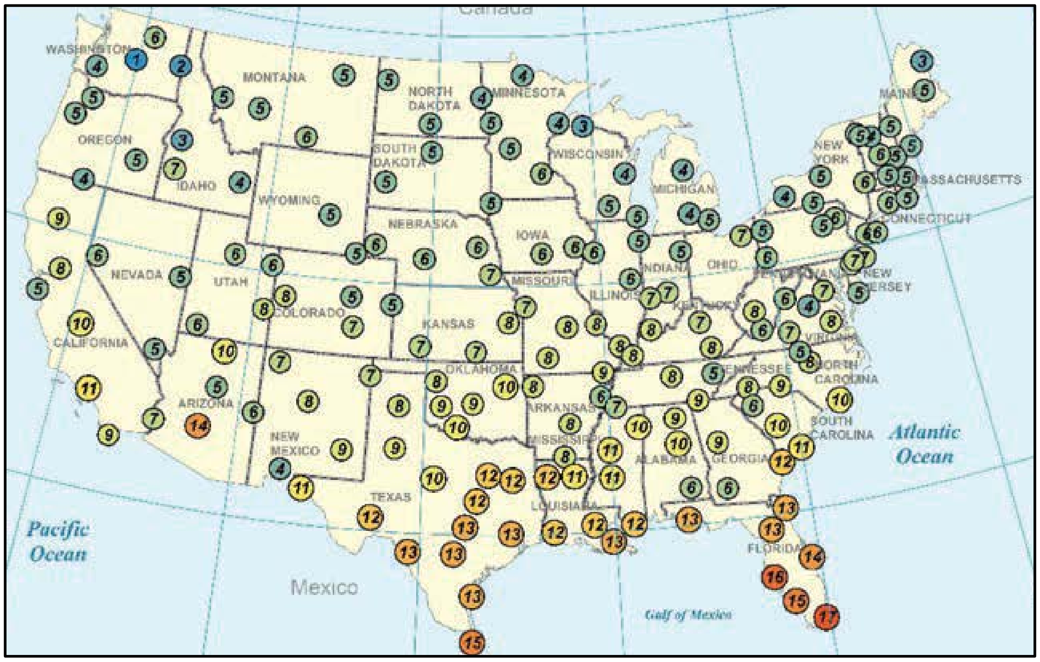

**Figure 7.1: NCHRP 09-54 recommended aging to match 16 years' field aging at 20 mm below pavement surface**

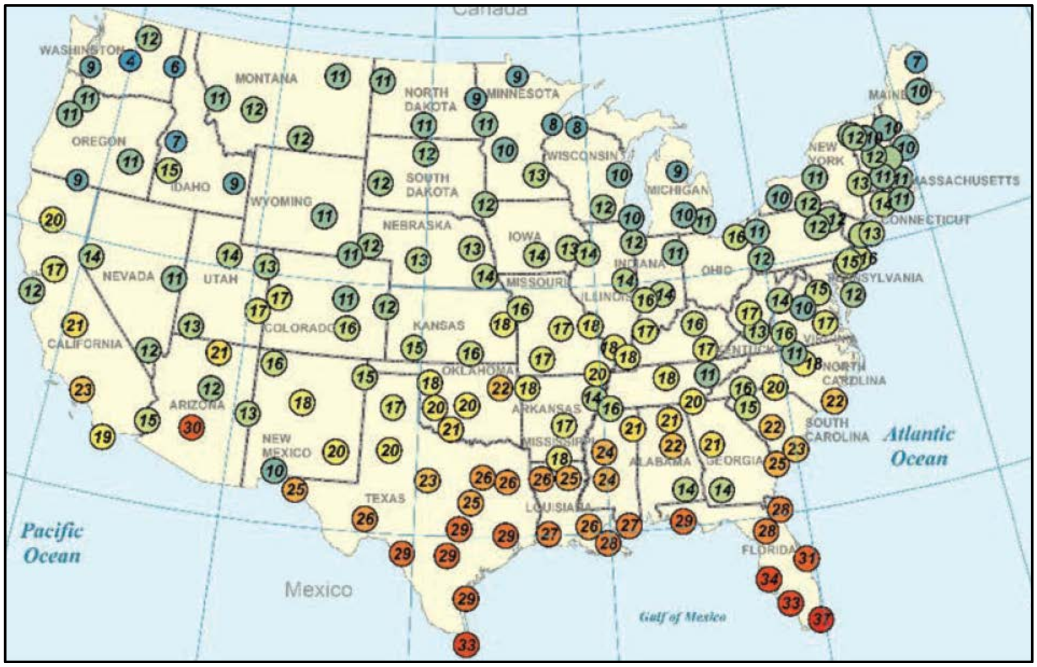

**Figure 7.2: NCHRP 09-54 recommended aging to match 16 years' field aging at 6 mm below pavement surface**

## 7.2 Mixture Design

As shown in Table 7.1, an existing state-approved 12.5 mm nominal maximum aggregate size (NMAS) surface course mixture design that incorporates 15% RAP was selected for the mixture evaluation portion of this study. This mixture has been produced and placed by a contractor in Massachusetts with a PG 64-28 binder and is considered a typical mixture containing 15% RAP. The mixture design met the Superpave requirements outlined in AASHTO M 323 "Standard Specification for Superpave Volumetric Mix Design" and AASHTO R 35 "Standard Practice for Superpave Volumetric Design for Asphalt Mixtures" *(3)*. The design ESALs for the mixture were 0.3 to <3 million, and the design Superpave gyratory compactive effort was $N_{design}$=75 gyrations. The optimum binder content was 5.5 based on volumetrics.

**Table 7.1: State-approved surface course mixture design used in study**

| Sieve Size (mm) | Percentage Passing by Weight | |
|---|---|---|
| | **12.5 mm Mixture** | **12.5 mm Superpave Specification** |
| 19.0 | 100 | 100 min |
| 12.5 | 94.0 | 90-100 |
| 9.5 | 86.0 | 90 max |
| 4.75 (No. 4) | 61.0 | - |
| 2.36 (No. 8) | 42.0 | 28-58 |
| 1.18 (No. 16) | 29.0 | - |
| 0.60 (No. 30) | 19.0 | - |
| 0.30 (No. 50) | 13.0 | - |
| 0.15 (No. 100) | 7.0 | - |
| 0.075 (No. 200) | 4.0 | 2-10 |

Mixture designs were completed using the two selected RAP sources, namely, Dracut Millings 2017 and Millbury RAP 2017, also called the "stiff RAP" and "soft RAP," respectively, and one PG 64-28 binder, which was the Deerfield continuous grade (CG) 65.8(15.8)-30.9. The gradation of the mixture was held constant while incorporating different amounts of RAP. It was assumed that there was 100% binder contribution from the RAP, which is what is generally assumed for mixture design. Blending analysis is further discussed in Section 10.0. Three amounts of each RAP stockpile were used: 15%, 25%, and 35% RAP.

The mixing and compaction temperatures for the mixtures were determined based on the viscosity of the virgin binder, as outlined in AASHTO T 312 "Standard Method of Test for Preparing and Determining the Density of Asphalt Mixture Specimens by Means of the Superpave Gyratory Compactor," Section 8.1.2.1 for mixing temperature and Section 8.1.7.1 for compaction temperature *(3)*. For the PG 64-28 virgin binders in this study, the average mid-range viscosity-based mixing temperature was determined to be 158°C, and the compaction temperature was 146°C. For all mixtures fabricated in this study, the virgin aggregates were heated overnight in an oven at the 158°C mixing temperature. Then, RAP was added on top of the heated aggregate for two hours prior to mixing with the virgin binder. This process was undertaken to more closely simulate actual mixing that occurs at the plant. After mixing, the mixture aging was conducted, as noted in Section 7.1. After aging, the mixture specimens were returned to the compaction temperature and compacted in the Superpave Gyratory Compactor (SGC).

As noted previously, the first FHWA-recommended BMD approach utilized in this study requires that mixtures must meet target volumetric properties and performance testing criteria. The volumetric requirements are listed in AASHTO M 323 "Standard Specification for Superpave Volumetric Mix Design" *(3)*, with the only difference being the requirement for the VMA, where MassDOT adds 1% to the AASHTO M 323 requirement. The primary performance test used by MassDOT during mixture design is the Hamburg Wheel Tracking Test (HWTT) for rutting. MassDOT specifies a maximum rut depth of 12.5 mm after 20,000 passes at 45ºC combined with no stripping inflection point (SIP) before 15,000 passes. MassDOT is currently researching which cracking test(s) to use for its BMD protocol, but Flexibility Index (FI) is currently being used to evaluate the cracking susceptibility of high-performance mixtures incorporating polymer at intermediate temperatures. This test was used for the cracking performance evaluations in this study with a test temperature of 25°C. The developers of the FI proposed that an FI of greater than 8.0 be used as a pass/fail criterion *(13)*. Both tests will be described in greater detail in Section 8.0. Although MassDOT guidelines for the FI only require the mixture design specimens be short-term aged as outlined in Section 7.1.1., additional mixture evaluations were completed using long-term aging as outlined in Section 7.1.2. The volumetric and performance results (after short-term aging) are shown in Table 7.2.

For mixtures with 15% RAP, regardless of the RAP source used, the mixtures met the required volumetric and performance requirements. As RAP was increased to 25%, the use of the softer RAP source yielded a mixture passing the volumetric and performance requirements. The use of the stiffer RAP source yielded a mixture with higher-than-targeted air voids (4.8%), while all other requirements were met. Moving up to 35% RAP, neither mixture passed all requirements.

At 35% RAP, using the softer RAP yielded a mixture with 14.5% VMA, which failed to meet the minimum 15% VMA required by MassDOT specification but passed the VMA required by Superpave for a 12.5 mm mixture, which is 14%. Using the stiffer RAP source yielded a mixture with higher-than-targeted air voids (5.2%), while all other requirements were met. In total, three of the six combinations met all BMD requirements. The remaining mixtures failed for volumetric reasons (air voids or VMA specified by MassDOT). These failing mixtures were included in further mixture analyses for a variety of reasons. First, the mixture failing the MassDOT VMA requirement easily passed the Superpave VMA requirement, so it was still a passing Superpave mixture design. Second, for the third BMD approach suggested by FHWA, mixtures would only have to meet target performance criteria regardless of the volumetric properties of the mixture. All mixtures passed the required performance testing, meaning under this third approach, all would be approved as BMDs. Finally, the air voids of two mixtures with the stiffer RAP were not 4.0% but were within the acceptable production target for acceptance testing for MassDOT, which is 4±1.3%, or from

2.7% to 5.3%. In a production scenario, these mixtures would be considered to have acceptable air voids and thus worthy of further analysis in this study.

Overall, it is noteworthy that RAP source had a pronounced effect on mixture air voids. The stiffer RAP showed a trend of increased air voids as the amount of RAP increased, while the air voids remained nearly constant for the softer RAP. This is relevant to one of the objectives of this study, which was to determine what changes are needed to the current MassDOT specification for RAP use in surface mixtures. If the complete set of test data shows that an increase in RAP is justified, the MassDOT specification must be revised to address the fact that higher amounts of RAP from different sources may not always yield acceptable volumetric properties.

**Table 7.2: Mixture design using BMD approach – volumetric properties and performance**

| **RAP Source = Stiff RAP PG94-10 [99.3(37.7)-11.0]** | | | | |
|---|---|---|---|---|
| | 15% RAP | 25% RAP | 35% RAP | Criteria |
| **Volumetric Properties** | | | | |
| Air Voids, % | 4.2 | 4.8 | 5.2 | 4% |
| Voids in Mineral Aggregate (VMA), % | 15.5 | 15.9 | 15.9 | 15% min.* |
| Voids Filled with Asphalt (VFA), % | 73.1 | 69.9 | 67.2 | 65-78% |
| Dust to Binder Ratio | 0.95 | 0.96 | 1.00 | 0.6-1.2 |
| **Performance - Rutting** | | | | |
| HWTT rutting at 20,000 passes, mm | 3.3 | 3.0 | 2.4 | < 12.5 mm** |
| HWTT Stripping Inflection Point | NONE | NONE | NONE | - |
| **Performance - Cracking** | | | | |
| Average FIT Flexibility Index (FI) @ 25°C | 14.5 | 11.8 | 9.4 | ≥8.0** |
| **RAP Source = Soft RAP PG76-22 [76.8(23.4)-24.7]** | | | | |
| | 15% RAP | 25% RAP | 35% RAP | Criteria |
| **Volumetric Properties** | | | | |
| Air Voids, % | 3.9 | 3.9 | 3.9 | 4% |
| Voids in Mineral Aggregate (VMA), % | 15.3 | 15.0 | 14.5 | 15% min.* |
| Voids Filled with Asphalt (VFA), % | 74.6 | 74.0 | 73.2 | 65-78% |
| Dust to Binder Ratio | 0.94 | 0.98 | 1.02 | 0.6-1.2 |
| **Performance - Rutting** | | | | |
| HWTT rutting at 20,000 passes, mm | 1.8 | 2.0 | 2.2 | < 12.5 mm** |
| HWTT Stripping Inflection Point | NONE | NONE | NONE | - |
| **Performance - Cracking** | | | | |
| Average FIT Flexibility Index (FI) @ 25°C | 8.8 | 10.6 | 10.7 | ≥8.0** |

* MassDOT specifications require a 1% increase in VMA as presented here.

****** Specimens were short-term aged.

# 8.0 Dynamic Modulus and Mixture Performance Testing

To evaluate the effect of RAP characteristics and virgin binder source on the performance of asphalt mixtures, mixture stiffness and performance testing were conducted using the Superpave 12.5 mm design outlined in Section 7.0. As stated previously, two RAP sources were selected and used, which were Dracut Millings 2017 and Millbury RAP 2017, also called the “stiff RAP” and “soft RAP,” respectively. These RAPs represent the extremes in terms of RAP binder properties in the state. The Deerfield [CG 65.8 (15.8) -30.9] and Providence [CG 66.2 (20.4) -28.6] binders were selected for use in the mixture evaluation, as they represented the two extremes in terms of the intermediate- and low-temperature binder continuous grade.

## 8.1 Dynamic Modulus |E*|

The dynamic modulus, which gives an indication of the overall mixture stiffness at a specific temperature and loading frequency, was determined for each mixture in accordance with AASHTO TP 132 “Standard Method of Test for Determining the Dynamic Modulus for Asphalt Mixtures Using Small Specimens in the Asphalt Mixture Performance Tester (AMPT)” *(3)*. The data was used to develop the dynamic modulus master curve for each mixture in accordance with AASHTO R 84 “Standard Practice for Developing Dynamic Modulus Master Curves for Asphalt Mixtures Using the Asphalt Mixture Performance Tester (AMPT)” *(3)*. One 180-mm-tall specimen was compacted using the Superpave Gyratory Compactor (SGC). Four testing specimens were then cored and cut to the final test specimen dimensions of 38 mm in diameter and 110 mm in height. The target air voids of these specimens were 7±1%. Specimens were conditioned overnight at 4ºC and then tested for dynamic modulus at loading frequencies of 10, 1, and 0.1 Hz. The specimens were next conditioned at 20ºC for a minimum of one hour and tested again at the same loading frequencies of 10, 1, and 0.1 Hz. Finally, the specimens were conditioned at 40ºC for between one and two hours and tested at loading frequencies of 10, 1, and 0.1 Hz.

The master curves for the mixture fabricated with stiff RAP are shown in Figure 8.1 and for the soft RAP are shown in Figure 8.2. The Deerfield virgin binder [CG 65.8 (15.8) -30.9] and Providence virgin binder [CG 66.2 (20.4) -28.6] were used to fabricate the specimens. The data indicates in both cases that the stiffness of the mixture is both a function of the amount of RAP and the virgin binder utilized. Larger amounts of RAP yield mixture with higher stiffness. This increased stiffness may indicate that these mixtures may be more susceptible to distresses like cracking.

Figure 8.3 shows a comparison of the same mixture fabricated with the same virgin binder (Providence binder), but with the two different RAP sources. The master curves indicate that the use of stiff RAP yielded a mixture that was stiffer than the same mixture fabricated with the soft RAP at each RAP percentage tested. This suggests that mixture stiffness is also a function of the individual property of the RAP utilized. Utilizing the stiffer RAP may yield mixture with higher stiffness and thus may be more susceptible to distresses like cracking.

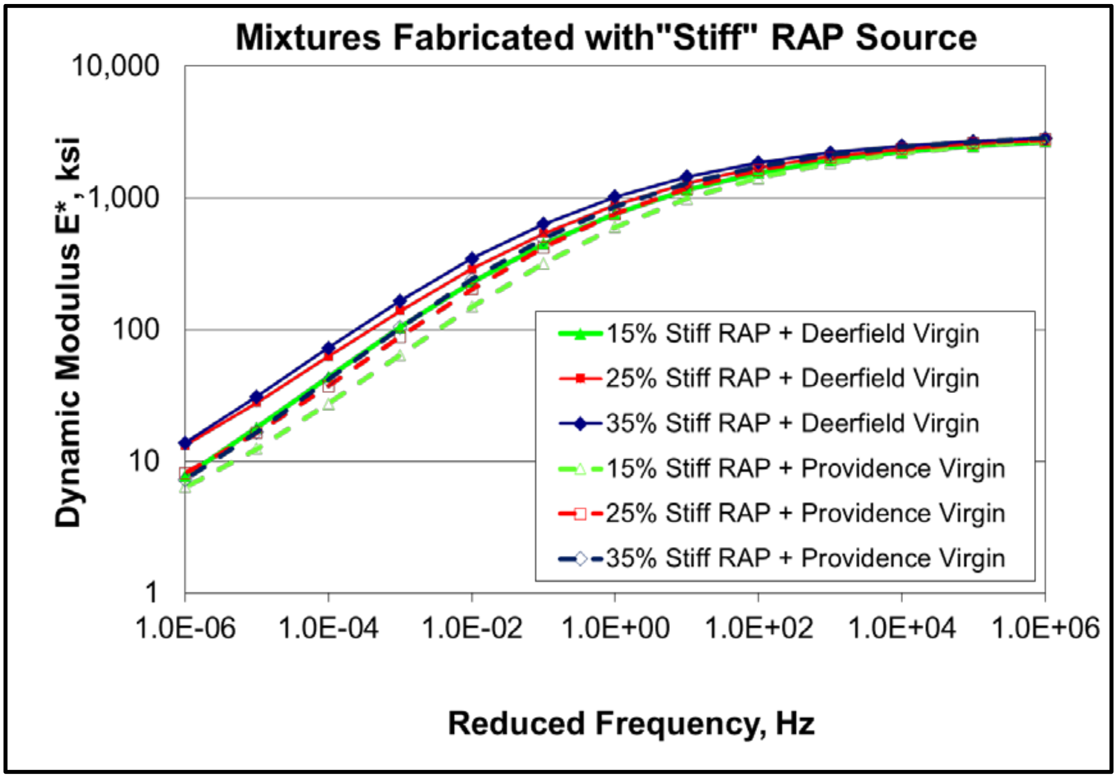

**Figure 8.1: Master curves for mixtures fabricated with “stiff” RAP source**

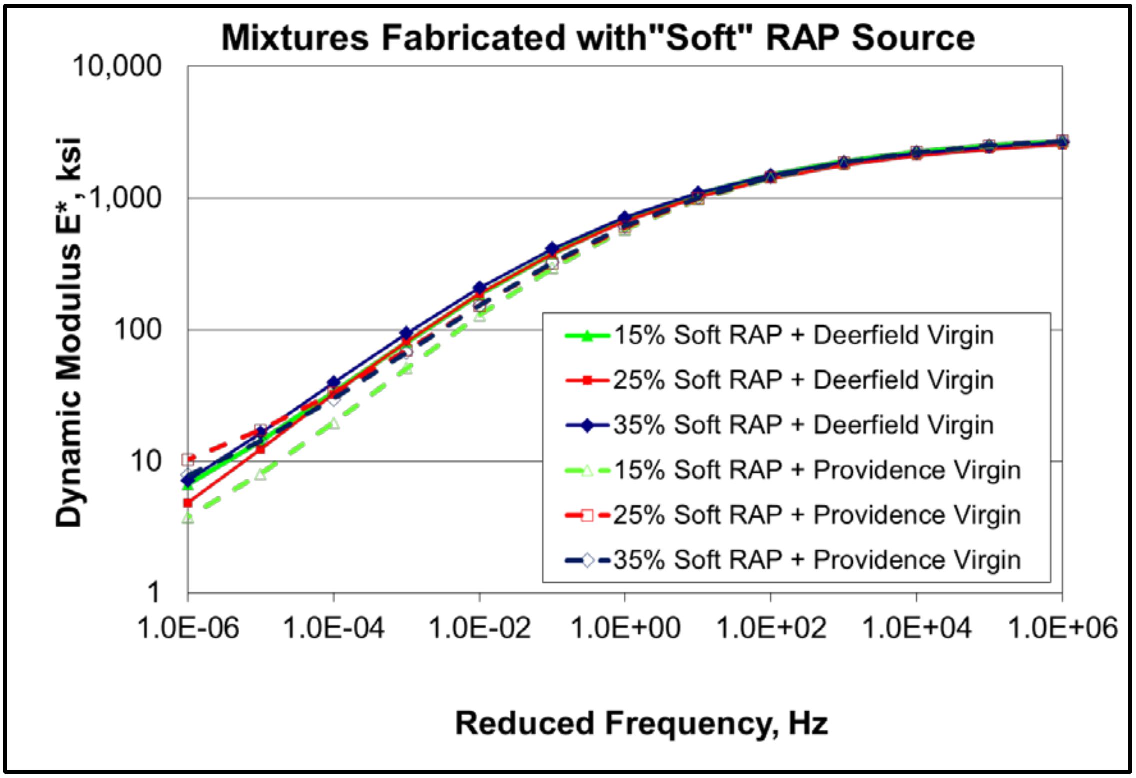

**Figure 8.2: Master curves for mixtures fabricated with “soft” RAP source**

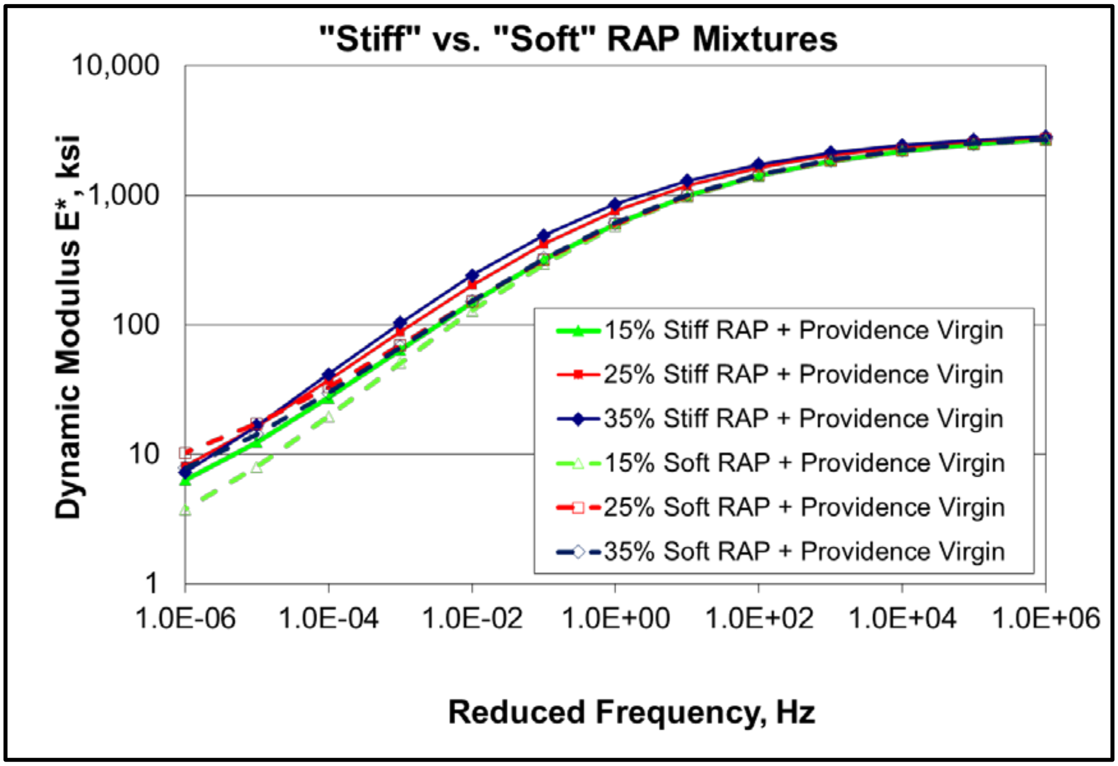

**Figure 8.3: Master curves comparison, “stiff “ vs. “soft” RAP source**

Overall, the mixture master curve data derived from the dynamic modulus tests suggests that the amount of RAP, the properties of the binder in the RAP, and the virgin binder utilized all have an effect on the overall mixture stiffness. Thus, these variables can have a profound effect on the overall performance of the mixture. Mixture performance will be evaluated in subsequent sections of this report.

## 8.2 Hamburg Wheel Tracking Test for Rutting and Moisture Susceptibility

The Hamburg Wheel Tracking Test (HWTT) is the test used by MassDOT to evaluate a mixture's resistance to rutting and moisture susceptibility. This test was conducted in accordance with AASHTO T 324 "Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Asphalt Mixtures" *(3)*. Test specimens were prepared by compacting loose mixtures, after short-term aging, in the SGC to a 150 mm diameter by a 60 mm height while achieving 7.0±1.0% air voids.

Four compacted specimens are placed in two HWTT molds, placed side by side under water, and tested at 45ºC according to MassDOT requirements. The specimens are subjected to repeated loading provided by a 158 lb. steel wheel. Specimens were tested at a rate of 52 passes/min. after a soak time of 30 min. at 45ºC. As the steel wheel loads the specimen, the corresponding rut depth of the specimen is recorded. From this rut depth data, the stripping inflection point (SIP) can be determined. The SIP gives an indication of the onset of moisture damage in the mixture. Prior to the SIP, or in the absence of a SIP, the rut depth can give an indication of the rutting performance of the mixture.

All new mixture designs must meet the MassDOT HWTT specification criteria after acceptable volumetric criteria properties are obtained. The MassDOT criteria are a maximum rut depth of 12.5 mm after 20,000 passes combined with no SIP before 15,000 passes at 45ºC.

Table 8.1 illustrates the results from the HWTT test. This is a pass/fail test. All mixtures met the passing criteria, indicating that RAP source, virgin binder source, and RAP content had no effect on the rutting and moisture susceptibilities (no stripping inflection point) of these mixtures. Hence, for the BMD, all mixtures stayed balanced in terms of rutting.

**Table 8.1: HWTT test results at 45°C (short-term aged)**

| RAP Source | PG 64-28 Virgin Binder Source | % RAP Specified by Weight | RAPBR | Stripping Inflection Point (SIP) | Maximum Rut Depth at 20,000 Passes (mm) |
|---|---|---|---|---|---|
| Dracut Millings<br>Stiff RAP<br>PG 94-10<br>(99.3-11.0) | Deerfield<br>CG (65.8 -30.9) | 15% | 0.16 | None | 3.3 |
| | Providence<br>CG (66.2-28.6) | 15% | 0.16 | None | 2.4 |
| | Deerfield<br>CG (65.8 -30.9) | 25% | 0.27 | None | 3.0 |
| | Providence<br>CG (66.2-28.6) | 25% | 0.27 | None | 2.5 |
| | Deerfield<br>CG (65.8 -30.9) | 35% | 0.38 | None | 2.4 |
| | Providence<br>CG (66.2-28.6) | 35% | 0.38 | None | 2.0 |
| Millbury Soft<br>RAP<br>PG 76-22<br>(76.8-24.7) | Deerfield<br>CG (65.8 -30.9) | 15% | 0.16 | None | 1.8 |
| | Providence<br>CG (66.2-28.6) | 15% | 0.16 | None | 1.4 |
| | Deerfield<br>CG (65.8 -30.9) | 25% | 0.26 | None | 2.0 |
| | Providence<br>CG (66.2-28.6) | 25% | 0.26 | None | 1.3 |
| | Deerfield<br>CG (65.8 -30.9) | 35% | 0.37 | None | 2.2 |
| | Providence<br>CG (66.2-28.6) | 35% | 0.37 | None | 1.3 |

CG = Continuous Grade

## 8.3 Asphalt Pavement Analyzer for Rutting

In the HWTT test, the mixture specimens are tested under load in heated water for both rutting and moisture susceptibility, which makes it a very rigorous test to evaluate mixtures. Even though no moisture damage was noted in any specimen tested and corresponding rut depths were low, the rutting results were confirmed in a separate test that evaluates rutting alone. The Asphalt Pavement Analyzer (APA) was selected for rutting evaluation because MassDOT is exploring it as a rutting test for its bridge mixtures. Furthermore, the APA evaluates the rutting susceptibility of mixtures differently than the HWTT. The HWTT test is a loaded wheel test conducted in heated water, whereas the APA is a loaded pressurized hose test conducted in heated air. Both tests provide a means to evaluate rutting potential.

APA testing was conducted in accordance with AASHTO T 340 “Standard Method of Test for Determining Rutting Susceptibility of Hot-Mix Asphalt (HMA) Using the Asphalt Pavement Analyzer (APA)” *(3)*. Four specimens, 75 mm tall, were fabricated in the SGC to a desired air void level of 7±0.5%. Prior to testing, these mixture specimens were conditioned for a minimum of six hours at the 64°C test temperature, which corresponds to the typical high temperature PG for Massachusetts. The APA hose pressure for testing was 100 psi, and the constant load on the hose was 100 lbs. per the specification. Testing was conducted for 8,000 cycles, and the average rut depth was calculated.

Specimens were fabricated using the soft RAP with the Providence virgin binder. This combination yielded the lowest stiffness mixture as shown in the mixture master curve in Figure 8.2. Lower stiffness generally indicates a mixture more susceptible to rutting. If this mixture passed the rutting test, there would be no justification to test the other combinations as they had higher stiffness and also already passed the more rigorous HWTT test.

The average APA rut depth for the specimens fabricated using the soft RAP with the Providence virgin binder was 5.3 mm, which was below the 8.0 mm threshold suggested for mixtures with the design gyration level of $N_{design}$=75 gyrations (the design gyration level of the 12.5 mm mixture for this study). This confirms that the mixtures exhibited acceptable rutting performance and remained balanced in terms of rutting.

## 8.4 Flexibility Index for Intermediate Temperature Cracking

The Flexibility Index (FI) is used to evaluate an asphalt mixture’s susceptibility to cracking at intermediate temperatures. This test was conducted at 25°C and in accordance with AASHTO TP 124 “Standard Method of Test for Determining the Fracture Potential of Asphalt Mixtures Using Semicircular Bend Geometry (SCB) at Intermediate Temperature” *(3)*.

It should be noted that the research team attempted to test the mixtures at 15°C, as that is the typical intermediate-testing temperature in Massachusetts. However, the data obtained were unrealistic, as the loading curve was nearly a straight line downwards after the peak load was reached, and the corresponding FI value was close to zero. Further investigation showed that testing the mixtures at 15°C would require the loading rate to be changed. Hence, for this test, it was decided to test at the temperature that is typically being used, which is 25°C, instead of exploring changing the test parameters that are listed in the AASHTO TP 124.

The specimens needed for this test were compacted in the SGC to a height of 180 mm. Two 50 mm slices were cut from the middle of each specimen. Each slice was cut in half across the diameter to yield four specimens. Subsequently, each specimen had a 15 mm vertical notch cut up from the midpoint of the base of each specimen. The target air-void level was 7.0±1.0%. A minimum of eight specimens were tested for each mixture.

In this test, the specimen is placed on two rollers on its flat side. A monotonic load is applied along the vertical diameter of a notched semicircular mixture specimen at a displacement rate of 50 mm/min. *(14)*, and a load vs. displacement curve is obtained. From this curve, two cracking properties are obtained, fracture energy (FE) and flexibility index (FI). FE is calculated using the work of fracture method by finding the area under the load-displacement curve and dividing it by the crack propagation area. The FI accounts for both fracture energy and the post-peak behavior of a mixture. Methods for determining FE and FI are detailed in other studies *(14)*. Both FE and FI give an indication of a mixture's intermediate-temperatures cracking performance, with a higher value being more desirable. A preliminary criterion for the FI was set at a minimum of 8.0 by the developer of the test for mixtures fabricated after short-term aging.

Tables 8.2 and 8.3 show the results of the FI and FE after short-term and long-term aging, respectively. These results from short-term aging were used to make sure, using the preliminary criterion of 8.0 for FI, that the mixtures were balanced in terms of cracking at intermediate temperatures. To investigate the effects of RAP source, virgin binder source, and RAP content, it was decided to test mixtures after long-term aging, as it is expected that intermediate-temperature cracking would not occur during the early part of a pavement service life. Since there is no set pass/fail criterion for this test after long-term aging, statistical analysis was implemented in Section 9.0 to investigate the effects of the mentioned parameters on the FI and FE results.

**Table 8.2: SCB FIT test results at 25°C (short-term aged)**

| RAP Source | PG 64-28 Virgin Binder Source | % RAP Specified by Weight | RAPBR | Average Flexibility Index (FI) | Average Fracture Energy (J/m$^2$) |
|---|---|---|---|---|---|
| Dracut Millings Stiff RAP<br>PG 94-10<br>(99.3-11.0) | Deerfield<br>CG (65.8 -30.9) | 15% | 0.16 | 14.5 | 2,039 |
| | | 25% | 0.27 | 11.8 | 2,148 |
| | | 35% | 0.38 | 9.4 | 2,219 |
| Millbury Soft RAP<br>PG 76-22<br>(76.8-24.7) | Deerfield<br>CG (65.8 -30.9) | 15% | 0.16 | 8.8 | 1,734 |
| | | 25% | 0.26 | 10.6 | 1,803 |
| | | 35% | 0.37 | 10.7 | 1,905 |

CG = Continuous Grade

**Table 8.3: SCB FIT test results at 25°C (long-term aged)**

| RAP Source | PG 64-28 Virgin Binder Source | % RAP by Wgt | RAPBR | Blended Intermediate CG | FI | FE (J/m$^2$) |
|---|---|---|---|---|---|---|
| Dracut Millings Stiff RAP<br>PG 94-10<br>(99.3-11.0) | Deerfield<br>CG (65.8 -30.9) | 15% | 0.16 | 23.0 | 3.3 | 1,907 |
| | Providence<br>CG (66.2-28.6) | 15% | 0.16 | 23.0 | 1.9 | 1,782 |
| | Deerfield<br>CG (65.8 -30.9) | 25% | 0.27 | 21.3 | 3.3 | 1,830 |
| | Providence<br>CG (66.2-28.6) | 25% | 0.27 | 24.7 | 2.0 | 1,773 |
| | Deerfield<br>CG (65.8 -30.9) | 35% | 0.38 | 23.5 | 2.7 | 1,933 |
| | Providence<br>CG (66.2-28.6) | 35% | 0.38 | 26.5 | 1.0 | 1,332 |
| Millbury Soft RAP<br>PG 76-22<br>(76.8-24.7) | Deerfield<br>CG (65.8 -30.9) | 15% | 0.16 | 16.9 | 3.4 | 1,816 |
| | Providence<br>CG (66.2-28.6) | 15% | 0.16 | 20.9 | 3.7 | 1,801 |
| | Deerfield<br>CG (65.8 -30.9) | 25% | 0.26 | 17.7 | 3.8 | 1,882 |
| | Providence<br>CG (66.2-28.6) | 25% | 0.26 | 21.2 | 2.6 | 1,685 |
| | Deerfield<br>CG (65.8 -30.9) | 35% | 0.37 | 18.5 | 3.7 | 1,829 |
| | Providence<br>CG (66.2-28.6) | 35% | 0.37 | 21.5 | 2.6 | 1,700 |

CG = Continuous Grade

## 8.5 Indirect Tension Asphalt Cracking Test for Intermediate Temperature Cracking

The Indirect Tension Asphalt Cracking Test (IDEAL-CT) is a fracture test developed by Zhou et al. *(15)* under NCHRP IDEA Project 195: “Development of an IDEAL Cracking Test for Asphalt Mix Design, Quality Control (QC), and Quality Assurance (QA).” This test has been outlined in ASTM standard D8225-19 “Standard Test Method for Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature” *(7)*.

Similar to the traditional Indirect Tension (IDT) strength test, the IDEAL-CT is performed at an intermediate temperature with cylindrical specimens and at a loading rate of 50±2 mm/min. The specimen size is 150 mm in diameter and 62 mm in height with 7±0.5 percent air voids. Three specimens were compacted and tested for each mixture in this study. All specimens were tested at a temperature of 15ºC, which is the calculated typical intermediate temperature for Massachusetts as outlined in AASHTO TP 107-18 “Standard Method of Test for Determining the Damage Characteristic Curve and Failure Criterion Using the Asphalt Mixture Performance Tester (AMPT) Cyclic Fatigue Test,” Section 11.3 *(3)*. A major feature of the IDEAL-CT is the simplicity of preparing lab specimens: no cutting, coring, gluing, notching, or instrumentation.

A fracture mechanics-based cracking index, $\text{CT}_{\text{Index}}$, was recommended to characterize the cracking resistances of asphalt mixtures using this test. $\text{CT}_{\text{Index}}$ is calculated from parameters obtained using the load-displacement curve. The higher the $\text{CT}_{\text{Index}}$, the better the cracking resistance. Table 8.4 shows the results from the IDEAL-CT test.

To investigate the effect of RAP source, virgin binder source, and RAP content on the resistance of the mixtures to cracking at intermediate temperatures, the mixtures were long-term aged, as it was expected that this type of cracking will not occur at the early part of a pavement service life. Since there are no set pass/fail criteria for this test after long-term aging, statistical analysis was implemented in Section 9.0 to investigate the effects of the RAP source, virgin binder source, and percent RAP on the $\text{CT}_{\text{Index}}$ and FE results.

**Table 8.4: IDEAL-CT test results at 15°C (long-term aged)**

| **RAP Source** | **PG 64-28 Virgin Binder Source** | **% RAP by Wgt.** | **RAPBR** | **Blended Intermediate CG** | **$\text{CT}_{\text{Index}}$** | **FE (J/m$^2$)** |
|---|---|---|---|---|---|---|
| Dracut Millings<br>Stiff RAP<br>PG 94-10<br>(99.3-11.0) | Deerfield<br>CG (65.8 -30.9) | 15% | 0.16 | 23.0 | 15.2 | 10,378 |
| | Providence<br>CG (66.2-28.6) | 15% | 0.16 | 23.0 | 9.7 | 8,543 |
| | Deerfield<br>CG (65.8 -30.9) | 25% | 0.27 | 21.3 | 15.5 | 11,241 |
| | Providence<br>CG (66.2-28.6) | 25% | 0.27 | 24.7 | 6.4 | 8,398 |
| | Deerfield<br>CG (65.8 -30.9) | 35% | 0.38 | 23.5 | 9.9 | 10,416 |
| | Providence<br>CG (66.2-28.6) | 35% | 0.38 | 26.5 | 2.8 | 7,468 |
| Millbury Soft<br>RAP<br>PG 76-22<br>(76.8-24.7) | Deerfield<br>CG (65.8 -30.9) | 15% | 0.16 | 16.9 | 15.4 | 10,032 |
| | Providence<br>CG (66.2-28.6) | 15% | 0.16 | 20.9 | 11.9 | 9,141 |
| | Deerfield<br>CG (65.8 -30.9) | 25% | 0.26 | 17.7 | 22.1 | 10,267 |
| | Providence<br>CG (66.2-28.6) | 25% | 0.26 | 21.2 | 16.9 | 9,857 |
| | Deerfield<br>CG (65.8 -30.9) | 35% | 0.37 | 18.5 | 13.6 | 9,693 |
| | Providence<br>CG (66.2-28.6) | 35% | 0.37 | 21.5 | 17.3 | 10,131 |

CG = Continuous Grade

## 8.6 Disc-Shaped Compact Tension for Low-Temperature Cracking

The Disc-Shaped Compact Tension (DC(T)) test was utilized to evaluate the effect of RAP source, virgin binder source, and RAP content on the BMD in terms of thermal cracking. SGC specimens were compacted to a height of 180 mm for each mixture.

Two 50 mm slices were cut from the middle of each specimen. Each slice was further prepared by coring and notching it in accordance with ASTM D7313 "Standard Test Method for Determining Fracture Energy of Asphalt-Aggregate Mixtures Using the Disk-Shaped Compact Tension Geometry" *(7).* The target air-void level of the specimens was 7.0±1.0%. Minimum threshold DC(T) fracture energies have been developed based on pavement investigations of thermally induced cracks under a FHWA Pooled Fund Study on low-temperature cracking *(16).* The thresholds for low, medium, and high traffic levels were set at 400, 460, and 690 J/m$^2$, respectively, at a test temperature that is 10°C warmer than the low-temperature PG, which was -28°C in this study.

The average test results using four test replicates of each mixture after long-term aging are shown in Table 8.5. These results are after long-term aging. Similar to the FI and the IDEAL-CT tests, statistical analysis was used in Section 9.0 to evaluate the effect of RAP source, virgin binder source, and RAP content on the thermal cracking of the mixtures.

Table 8.5: DC(T) test results at -18°C (long-term aged)

| RAP Source | PG 64-28 Virgin Binder Source | % RAP by Wgt | RAPBR | Blended Low Temperature CG | FE (J/m²) |
|---|---|---|---|---|---|
| Dracut<br>Millings Stiff RAP<br>PG 94-10<br>(99.3-11.0) | Deerfield<br>CG (65.8 -30.9) | 15% | 0.16 | -27.9 | 443 |
| | Providence<br>CG (66.2-28.6) | 15% | 0.16 | -26.0 | 333 |
| | Deerfield<br>CG (65.8 -30.9) | 25% | 0.27 | -25.9 | 537 |
| | Providence<br>CG (66.2-28.6) | 25% | 0.27 | -24.2 | 418 |
| | Deerfield<br>CG (65.8 -30.9) | 35% | 0.38 | -23.9 | 397 |
| | Providence<br>CG (66.2-28.6) | 35% | 0.38 | -22.4 | 360 |
| Millbury Soft RAP<br>PG 76-22<br>(76.8-24.7) | Deerfield<br>CG (65.8 -30.9) | 15% | 0.16 | -30.0 | 479 |
| | Providence<br>CG (66.2-28.6) | 15% | 0.16 | -28.0 | 371 |
| | Deerfield<br>CG (65.8 -30.9) | 25% | 0.26 | -29.4 | 474 |
| | Providence<br>CG (66.2-28.6) | 25% | 0.26 | -27.6 | 382 |
| | Deerfield<br>CG (65.8 -30.9) | 35% | 0.37 | -28.7 | 478 |
| | Providence<br>CG (66.2-28.6) | 35% | 0.37 | -27.2 | 403 |

CG = Continuous Grade.

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# 9.0 Analysis of Performance Test Results

A three-way analysis of variance (ANOVA) is a statistical method used to determine the effects of three independent variables on a dependent variable. In this study, the analysis was performed using the Statistical Package for the Social Sciences (SPSS) software to determine the effects of RAP source, virgin binder source, and percent RAP on the performance of the mixtures tested. As presented in Table 9.1, virgin binder source had a significant effect on all five measures of performance. RAP source and percent RAP had a significant effect on the FI and the $CT_{Index}$, which are the two intermediate cracking performance measures being explored by MassDOT to incorporate in a BMD protocol. The analyses also showed that there is an inconsistency among the four intermediate-temperature cracking performance measures, except that virgin binder source has a significant effect. Thus, for example, if an agency decided to use the FE instead of the FI from the FI test, then RAP source would have no significant effect based on these data.

**Table 9.1: ANOVA statistical analysis summary – three cracking tests**

| Variable | FI Test FI | FI Test FE | IDEAL $CT_{Index}$ | IDEAL FE | DC(T) FE |
|---|---|---|---|---|---|
| RAP Source | SIG | - | SIG | - | - |
| Virgin Binder Source | SIG | SIG | SIG | SIG | SIG |
| Percent RAP | SIG | SIG | SIG | - | - |

SIG = Statistically significant at a 95% level.

The mixture test data were also used to validate the findings of the analyses involving the blended binders in Section 5.0. Based on Table 5.2, for the mixture designed with RAP from Dracut millings 2017 (stiff RAP) combined with the virgin binder from Providence, CG [66.2(20.4)-28.6], the maximum percent RAP by weight of dry mixture was 3.4% to maintain PG 64-28. Using the virgin binder from Deerfield, CG [65.8(15.8)-30.9], it was 14.6%. Hence, using more than 15% RAP in this mixture would cause the blended binder to fail the low-temperature PG for PG 64-28. For the mixtures designed with RAP from Millbury 2017 (Soft RAP) and the virgin binder from Providence, CG [66.2(20.4)-28.6], the maximum percent RAP by weight of dry mixture was 15.4% to maintain PG 64-28. Using the virgin binder from Deerfield, CG [65.8(15.8)-30.9], it was 46.8%. Hence, the overall range in allowable percent RAP was 3.4% to 46.8%, while the range in the low-temperature CGs for the blended binders in these mixtures as presented in Table 8.5 was -22.4°C to -30.0°C. Based on this wide range, it was expected that the DC(T) would provide some significant differences in low-temperature cracking properties. However, as presented by Tables 8.5 and 9.1, many of the average fracture energies were close to each other, although virgin binder source did have a significant effect. The virgin binder from Providence, CG [66.2(20.4)-28.6], provided lower average fracture energies, which would mean poorer performance including at 15% RAP, which agrees with the findings presenting in Section 5.0 on the properties of the blended binders. Even so, the overall r squared ($r^2$) was 0.18, indicating a poor relationship between the blended low-temperature CG and the fracture energies measured by the DC(T).

The range in the intermediate-temperature CGs for the blended binders as presented by Tables 8.3 and 8.4 was 16.9°C to 26.5°C. Based on this wide range, it was expected that the FI and IDEAL $CT_{Index}$ would provide some significant differences in intermediate-temperature cracking properties. However, as presented by Tables 8.3 and 9.1, the average FIs were close to each other, although RAP source, virgin binder source, and percent RAP did have a significant effect on the FI. Similar to this, Tables 8.4 and 9.1 show that RAP source, virgin binder source, and percent RAP had a significant effect on the IDEAL $CT_{Index}$. The softer RAP generally provided better performance, according to both the FI and $CT_{Index}$. The virgin binder from Providence, CG [66.2(20.4)-28.6], tended to provide poorer performance than the virgin binder from Deerfield, CG [65.8(15.8)-30.9], according to both the FI and $CT_{Index}$. Increased percent RAP tended to provide poorer performance using the FI, while there was no trend using the $CT_{Index}$. The $r^2$ values between the blended intermediate-temperature CG and the FI and IDEAL $CT_{Index}$ were poor at 0.61 and 0.67, respectively. While part of this could be due to variability in the degree of blending in the mixtures, a good correlation would not be expected based on the closeness of the mixture test results.

Because of the closeness of the mixture test data within each test, no additional mixture tests were warranted. Furthermore, the findings indicated if additional mixtures using the other RAP and virgin asphalt binder sources were to be tested to evaluate the 15% RAP specification, all of them would probably perform similarly.

# 10.0 Degree of Blending Between RAP and Virgin Binder in Mixtures

For mixtures incorporating RAP, the term “blending” refers to how much of the aged RAP binder actually is activated and comingles with the virgin binder to make up the total binder content in a mixture. This is sometimes referred to as the amount of RAP binder activation, diffusion, mobilization, or contribution. Throughout this study, up to this analysis section, it was assumed that 100% blending occurred between the aged RAP binder and the virgin binder in the mixture. This is a common industry assumption currently made for mixtures with smaller RAP contents (i.e., <15% RAP by dry weight of mixture).

## 10.1 Background

Blending within a mixture is believed to occur to three varying cases. In the first case, the RAP binder is so highly aged and hardened that it contributes no binder to the total binder content of a mixture. This is a zero-blending condition, also known as the “black rock” condition. The second case, on the other end of the extreme, is the fully blended condition. In this condition, the RAP binder is able to fully activate and mix with the virgin binder, therefore contributing 100% of the RAP binder to the total binder content of the mixture. The third case lies somewhere between these two extremes of zero and 100% blending. This is referred to as partial blending. This is a scenario in which some, but not all, of the RAP binder is activated and mixes with the virgin binder.

Determining this degree of partial blending is of significant importance for mixture design and performance evaluation. This importance increases as more RAP is incorporated in a mixture. Mixtures incorporating RAP that have less than the 100% blending assumption will in actuality have less total binder than needed in the mixture. This will result in a mixture more susceptible to distresses related to low binder content, including cracking and moisture susceptibility. In order to remedy these deficiencies, more virgin binder will need to be added to the mixtures to meet volumetric and performance thresholds. This should be addressed during the mixture design phase.

The major hurdle for the asphalt industry has been how to accurately quantify the amount of partial blending that occurs within a mixture. Many methodologies have been attempted to evaluate partial blending, but for the majority they only provide a qualitative evaluation (i.e., good vs. poor blending), with no definitive value determined. While this information is somewhat useful in a general sense, it does not provide mix designers the quantitative value needed to ensure the binder content needed in a mixture to prevent distresses is achieved. Furthermore, designers and specifiers need to know how the individual properties of different RAPs (performance grade, binder content, etc.) impact the degree of partial blending. The blending analysis in this study attempted to address these critical issues of blending quantification and determining the impacts of RAP properties on partial blending in a mixture.

## 10.2 Selection of Blending Analysis Method

There have been many chemical and mechanical approaches undertaken to investigate RAP binder blending in a mixture. These approaches include the binder-marked methods, difference-identified methods, staged extraction methods and indirect pavement performance measured methods *(17)*. Perhaps the most commonly utilized method, a mechanical approach, has been to determine the quality of blending indirectly by comparing the measured mixture dynamic modulus to a dynamic modulus predicted from the Hirsch model. This predicted dynamic modulus is based on the rheological properties (complex modulus) of the recovered binder from the mixture incorporating RAP *(18)*. The largest limitation of a majority of any of these methods is that blending is evaluated mostly indirectly and qualitatively, which leads to questions about their accuracy.

Recently, more direct blending evaluation methods using microscopic techniques have been presented for evaluating the micromorphology of blending zone between the aged RAP binder and virgin binder in a mixture. These include blending zone morphology *(19)* and scanning electron microscopy (SEM) combined with computer tomography *(20)*. The studies using these methods have focused on the diffusion characteristics between the RAP and virgin binders or used specially engineered mixtures that did not represent the actual blending experienced in real mixtures *(19,20).* Thus, these approaches have limited value in quantifying blending. Recently, in 2016, researchers began using the microscopic techniques on actual RAP mixtures simulating real-world blending conditions, not mixtures that were artificially created to simulate a specific blending condition *(21).* The researchers evaluated blending in high RAP mixtures using energy dispersive X-ray spectroscopy (EDS) scanning electron microscopy.

EDS allows for the detection of elements within a specimen, in this case an asphalt mixture specimen. The EDS mapping feature also allows for the determination of the distribution and proportion of the elements at specific locations within the specimen. Since an asphalt binder is elementally comprised of carbon and sulfur, a tracer element must be added to one of the binder types (RAP or virgin) so that they can be distinguished from one another in a sample. In the aforementioned study *(21)*, the researchers used a titanium dioxide ($TiO_2$) powder tracer element at a dose of 20% to distinguish between RAP and virgin binders. The tracer element was blended with the virgin binder prior to specimen fabrication. Therefore, in the mixture sample, virgin binder was identified as areas with both carbon and titanium. RAP binder alone, that did not blend with the virgin binder, was identified by carbon only, without titanium. Partially blended RAP and virgin binders consisted of both carbon and titanium, but at lower concentrations than the purely virgin binder areas. It is also worth noting that the aggregate areas of the specimens were composed primarily of silica, so they were dissimilar from the binder areas in terms of elemental composition.

In the Castorena et al. study *(21)*, two different HMA mixtures incorporating 50% RAP were fabricated using different fabrication procedures (varying aggregate heating temperature, aging time, etc.). EDS samples were prepared, and mapping was conducted on small portions of the mixture specimens in the vicinity of known RAP aggregates. Blending analysis was conducted by comparing the carbon element maps (representing asphalt areas) and titanium element maps (indicating the presence of virgin binder) in these areas. Qualitatively speaking, the presence of titanium in the carbon area in near vicinity to the known RAP aggregate provided evidence of blending. The absence of titanium in this area suggested there was no blending or very poor blending. This research provided a framework to be able to quantify the degree of blending in a mixture. This could be accomplished by comparing the element mass ratio of titanium to carbon (Ti:C) in different regions near known RAP aggregates within the mixture. Due to its potential to be able to quantitatively measure the blending between RAP and virgin binders, this EDS SEM approach was utilized for this study.

A separate experimental plan was developed for the blending analysis attempted for this study, as shown in Figure 10.1. Like the aforementioned study, a tracer element was added to the virgin binder and the appropriate dose was determined. This traced virgin binder was then used to fabricate two sets of mixtures for EDS SEM analysis, both with identical gradations and total binder contents. One set of mixtures was fabricated to represent a true 100% blended condition. This was accomplished by extracting and recovering the RAP binder and aggregates. The recovered RAP binder was added to the traced virgin binder and then fully blended. This blended binder was then used in conjunction with recovered RAP aggregates and virgin aggregates to fabricate specimens. Thus, these specimens were known to have binders that were 100% fully blended. The second set of mixtures were fabricated using typical lab fabrication procedures which are outlined in Section 7.2. They represented the actual partial blending condition that occurs between the RAP and virgin binder. EDS mapping of areas near known RAP aggregates was performed for each set of mixtures in multiple locations. By comparing the EDS-determined average titanium to sulfur element mass ratio (Ti:S) of the actual blended specimens to 100% blended specimens, a quantitative value of blending could be determined. This ratio was originally proposed by Jiang et al. *(22)*.

As noted previously, it was important to not only try to quantify the amount of blending but also understand the impacts of RAP properties on blending. Thus, three separate RAP stockpiles were selected to be used for this analysis that represented the extremes in differing RAP binder properties (i.e., “stiff” versus “soft” and higher binder content RAP). Each set of mixtures was developed at RAP percentages of 15%, 25%, and 40%. The 15% and 25% levels correspond to the RAP levels used throughout this study for the other analysis and performance testing. The higher RAP percentage was increased to 40% from 35% to get the maximum extreme amount of RAP that could be used in the mixture while maintaining the same mixture gradation as all the other mixtures tested. Mixtures incorporating more than 40% RAP would be different in terms of gradation and therefore could not be compared to the other mixtures tested.

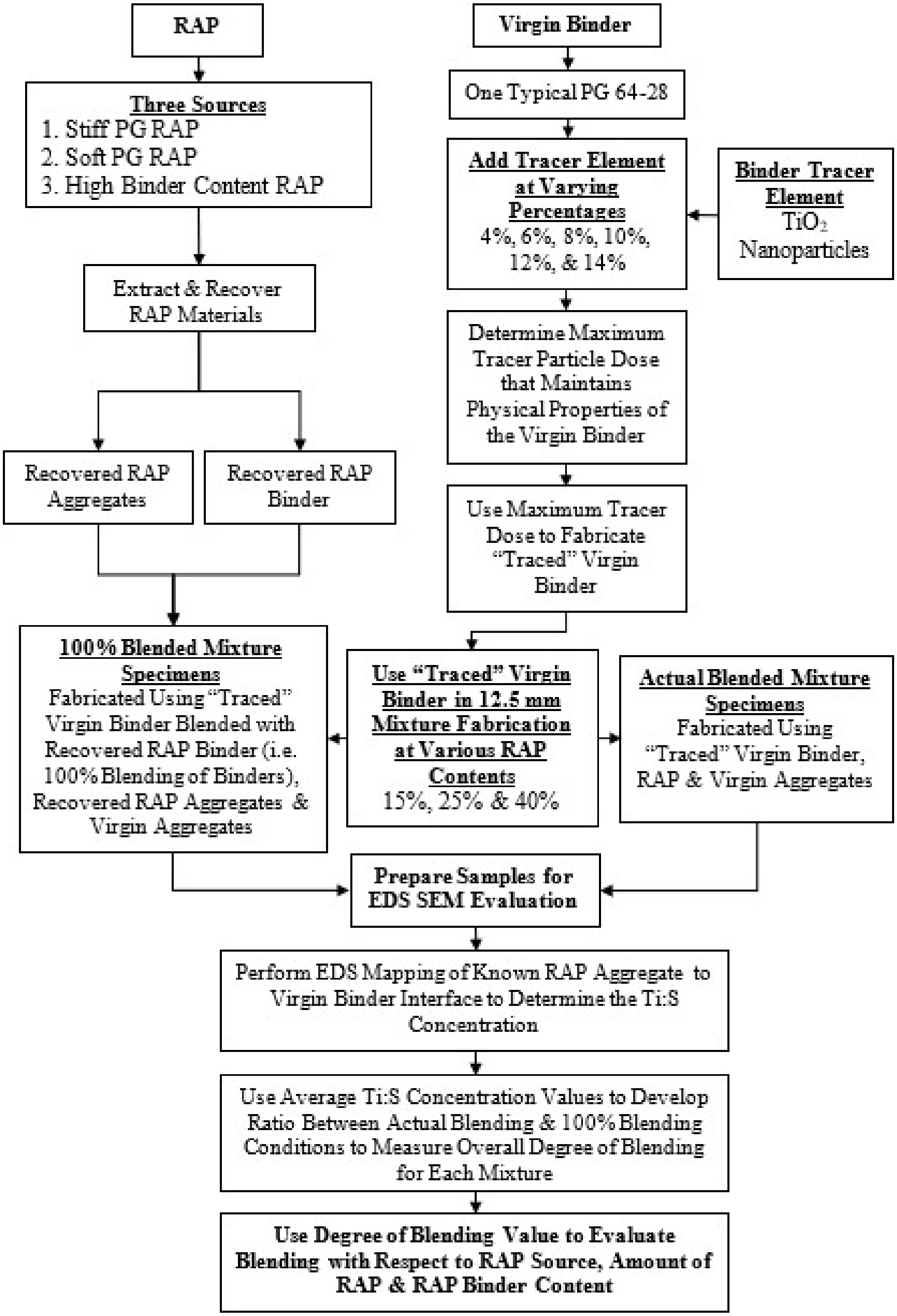


**Figure 10.1: Blending analysis methodology**

## 10.3 Materials Used for Blending Analysis

This section outlines the material used for the blending analysis, including the tracer element, virgin binder, RAPs, and virgin aggregates.

### 10.3.1. Tracer Element

Previous research studies *(23, 24)* have indicated that titanium dioxide nanoparticles could be a tracer element for virgin asphalt used in chemical microanalysis, due to their high surface area and small size. These properties allow the titanium dioxide nanoparticles to distribute and separate more uniformly inside the asphalt matrix, as compared to the titanium dioxide powder that was used in the previously mentioned study by Castorena et al. (*21*). Therefore, the tracer element selected for use in this study was a commercial titanium dioxide ($TiO_2$) nanoparticle with 99.5% purity, 40 nm average particle size, and surface area of 35 $m^2/g$.

### 10.3.2. Virgin Binder

One virgin binder was selected for the blending analysis, Providence PG 64-28 [66.2 (20.4) -28.6]. This binder was used in the specification analysis and mixture performance evaluation discussed previously. The binder represents the warmest extreme in terms of the intermediate- and low-temperature continuous grade of all the virgin binders tested. The other properties of this binder are outlined in Section 4.0.

### 10.3.3. RAP Selection

Three RAP sources were selected for the blending analysis. Two RAP sources were selected and used, Dracut Millings 2017 and Millbury RAP 2017, also called the “stiff RAP” and “soft RAP,” respectively. These RAPs represent the extremes in terms of RAP binder properties in the state. These RAPs were used for the specification analysis and mixture performance evaluation discussed previously. These RAPs were used to evaluate the effects of RAP binder properties (i.e., stiffness) on the blending in the mixture. The third RAP stockpile selected was Deerfield RAP 2017. This RAP stockpile had the largest binder content of any source tested, based on the ignition oven results (6.6%). This RAP was used to determine any effects on blending in the mixture due to more available binder from the RAP. All other RAP property information is available in Section 3.0. Finally, it is noteworthy that all recovered RAP aggregates were gray in color. This was important so that the RAP aggregates could be easily identified in the cut specimen and was an integral part in selecting the areas to analyze with the EDS mapping. The RAP aggregates’ gray color easily contrasted to the pink color of the virgin aggregate source.

### 10.3.4. Virgin Aggregates

The same virgin aggregate stockpile sources (12.5 mm crushed stone, 9.5 mm crushed stone, stone sand, and washed sand) that were used to design and develop the 12.5 mm mixtures previously evaluated in this study were used for this blending analysis. Details on the mixture design are located in Section 7.2. The aggregates from this source were pink in color and were easily distinguishable from the RAP aggregates in the mixture, which were a gray color.

## 10.4 Specimen Fabrication and Preparation

### 10.4.1. Tracer Element Dose Determination

The first step in the mixture fabrication process was to determine the appropriate dose of the tracer element ($TiO_2$ nanoparticles). It was important to maximize the dose of the tracer element introduced into the specimen while simultaneously ensuring the rheological properties of the virgin binder were not changed significantly. Maximizing the tracer dose ensured that there would be an adequate concentration of the tracer element in the specimen so that it was easily detectable with EDS.

The tracer element was added to the Providence PG 64-28 binder at dosage rates of 4%, 6%, 8%, 10%, 12%, and 14% by total weight of the binder. These dosage rates were developed based on simple trial and error, as the previous study used a much larger dose (20%) of the powdered $TiO_2$ tracer element *(21)*. For each dosage trial, the tracer element was blended into the virgin binder using a high shear mixer. The mixing process was divided into two phases. First, the tracer element was gradually added to the heated virgin asphalt (160°C) at a speed of 2,000 rpm. This addition process was completed within 15 minutes and the temperature was maintained at 160°C. Second, the mixing speed was then increased in the high shear mixer to 5,000 rpm. Mixing continued at this speed for 30 minutes to obtain a homogenous blended asphalt binder with tracer element particles thoroughly dispersed. This is referred to as the “traced” virgin binder in this study. The original Providence PG 64-28 virgin binder and the traced virgin binders were then evaluated in a suite of binder tests to characterize their fundamental rheological properties in accordance with AASHTO M320 *(3)*. The results are shown in Table 10.1. The properties of each traced virgin binder were compared to the original Providence PG 64-28 binder in order to determine the maximum tracer element dose that could be used without significantly changing the original binder properties.

The results shown in Table 10.1 suggest that incorporating the tracer element, at any percentage, resulted in a marginal increase in the viscosity and high temperature stiffness ($G^*/\sin(\delta)$) of the traced virgin binders as compared to the original binder. This variation led to some small increases in the high temperature continuous grades, but the differences in values were generally low (< 1.5°C except at 14% tracer element, which was 2.1°C). The continuous grades at intermediate and low temperatures, and performance grades, were similar between all binders at a tracer element dose less than 14%. The 14% tracer element dose yielded a binder with low temperature creep stiffness (299 MPa) very close to the 300 MPa threshold outlined in AASHTO M320; thus, this binder was borderline graded to -28°C. Therefore, because of the overall relatively small changes in binder properties, the tracer element dose selected to be used for this study was 12%, as it was the maximum dose that most closely maintained the properties of the original virgin binder as shown in Table 10.1.

**Table 10.1: Average original and traced virgin binder properties**

| | Spec. | Test Temp. (°C) | Original Virgin Binder | Virgin Binder Traced with $TiO_2$ | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | 4% | 6% | 8% | 10% | 12% | 14% |
| **Binder Tests Results in Original Condition** | | | | | | | | | |
| *G**/sin(δ) (kPa) | > 1.0 | 64 | 1.34 | 1.52 | 1.50 | 1.54 | 1.56 | 1.55 | 1.72 |
| | | 70 | 0.65 | 0.73 | 0.73 | 0.74 | 0.76 | 0.75 | 0.83 |
| Viscosity (Pa-s) | < 3.0 | 135 | 0.44 | 0.49 | 0.49 | 0.52 | 0.55 | 0.55 | 0.58 |
| | | 165 | 0.12 | 0.14 | 0.14 | 0.15 | 0.15 | 0.16 | 0.16 |
| **Binder Tests after RTFO Aging** | | | | | | | | | |
| *G**/sin(δ) (kPa) | > 2.2 | 64 | 3.50 | 3.62 | 3.64 | 3.75 | 3.84 | 3.63 | 4.05 |
| | | 70 | 1.65 | 1.71 | 1.71 | 1.75 | 1.8 | 1.72 | 1.91 |
| **Binder Tests after RTFO and PAV Aging** | | | | | | | | | |
| *G** x sin(δ) (kPa) | <5,000 | 22 | 4,070 | 3,670 | 3,860 | 4,400 | 4,097 | 4,475 | 4,320 |
| | | 19 | 5,940 | 5,260 | 5,640 | 6,400 | 5,933 | 6,555 | 6,545 |
| BBR Creep Stiffness (MPa) | < 300 | -18 | 250 | 256 | 268 | 275 | 289 | 291 | 299 |
| | | -24 | 476 | 515 | 515 | 600 | 590 | 587 | 588 |
| BBR *m*-value | > 0.3 | -18 | 0.306 | 0.300 | 0.301 | 0.303 | 0.307 | 0.310 | 0.306 |
| | | -24 | 0.232 | 0.252 | 0.244 | 0.240 | 0.245 | 0.247 | 0.249 |
| **Binder Grading** | | | | | | | | | |
| High Temp. Continuous Grade (°C) | | | 66.4 | 67.4 | 67.4 | 67.5 | 67.7 | 67.6 | 68.5 |
| Intermediate Temp. Continuous Grade (°C) | | | 20.5 | 19.5 | 20.1 | 21.1 | 20.5 | 21.2 | 21.1 |
| Low Temp. Continuous Grade (°C) | | | -28.5 | -28.0 | -28.1 | -28.3 | -28.3 | -28.3 | -28.0 |
| Performance Grade | | | 64-28 | 64-28 | 64-28 | 64-28 | 64-28 | 64-28 | 64-28 |

RTFO = Rolling Thin Film Oven; PAV = Pressure Aging Vessel; BBR = Bending Beam Rheometer

### 10.4.2. Mixture Design and Fabrication Details

As noted previously, two separate sets of mixture types were fabricated for blending analysis using the traced PG 64-28 virgin binder with a 12% tracer element dose. The traced virgin binder for mixture fabrication was prepared as outlined for the trial tracer element doses in Section 10.4.1. Each mixture set was developed with 15%, 25%, and 40% RAP using the three different RAP sources. One set of mixtures was fabricated to represent a true 100% blended condition. This was accomplished by extracting and recovering the RAP binder and aggregates. The recovered RAP binder was added to the traced virgin binder and then fully blended. This blended binder was then used in conjunction with recovered RAP aggregates and virgin aggregates to fabricate specimens. Thus, these specimens were known to have binders that were 100% fully blended. The second set of mixtures were fabricated using typical lab fabrication procedures. They represented the actual partial blending condition that occurs between the RAP and virgin binder. In total, 18 mixtures were fabricated (2 mixture types {100% blended & actual blended} x 3 RAP sources x 3 RAP contents).

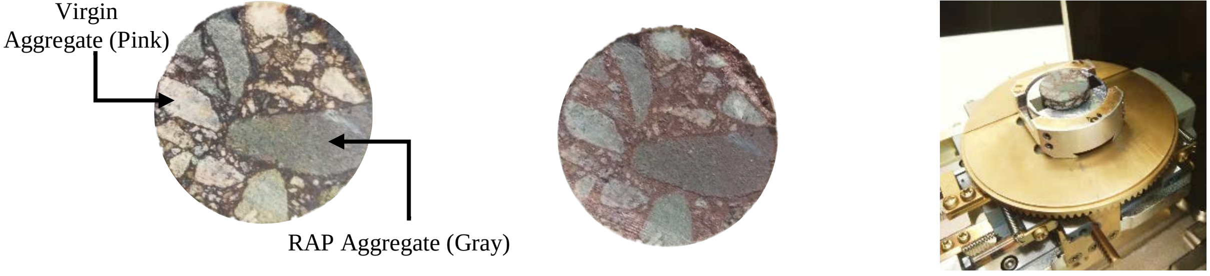
Mixture gradation and the optimum binder content were held constant for all mixtures. Mixture gradation was maintained by sieving the virgin materials to individual sieve sizes. As more RAP was introduced into the mixture, the amount of virgin material at each sieve size could be adjusted up or down to exactly maintain the gradation. The details of the mixture designs can be found in Section 7.2, with the details of typical mixture fabrication procedures (mixing temperature, RAP heating procedures, compaction details, etc.). Each mixture was short-term aged in accordance with AASHTO R 30 *(3)* as outlined in Section 7.1.1., which specifies the loose asphalt mixture is conditioned at 135°C for four hours, then brought to the compaction temperature and compacted.

Mixture specimens were compacted using the SGC to final dimensions of 80 mm in height and 150 mm in diameter. The target air voids were 4.0% ± 0.5%. From these SGC specimens, EDS SEM specimens were obtained as shown in Figure 10.2.

a) 80mm Tall SGC Specimen.

b) SGC Specimen with Ends Trimmed Off to a Height of 55 mm. Cores (20 mm in Diameter) Drilled Out of Specimen.

c) Cores Sliced into 3–4mm Slices.



d) Typical 20 mm Diameter by 3 mm Thick Slice.

e) Slice Coated with a Thin Layer of Gold.

f) Specimen Slice Attached to the Holder and Ready for EDS Analysis.

**Figure 10.2: Sample preparation for EDS SEM analysis**

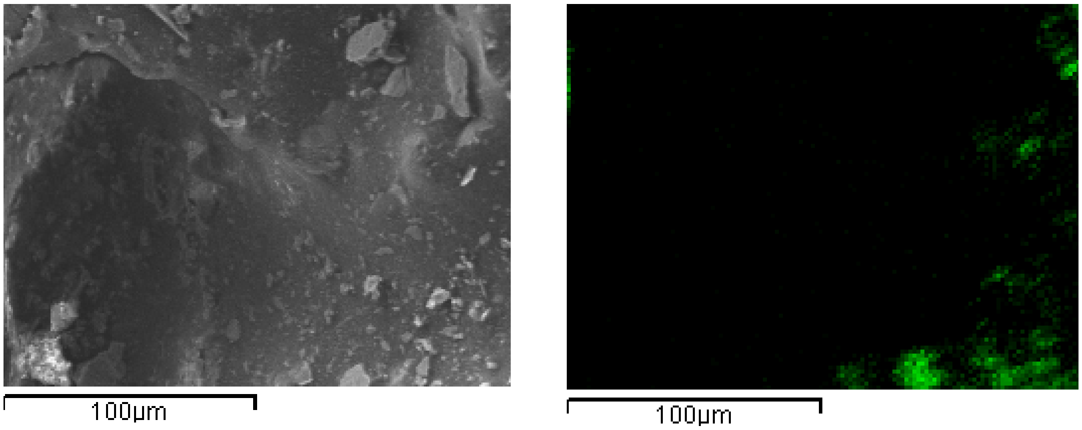
First, the ends of the SGC specimens were trimmed to yield a specimen with a cylindrical height of 55 mm. Next, using a 20 mm core drill bit, small cores were drilled from around the inner perimeter of the specimen. Then, small slices (3 to 4 mm in thickness) were taken from each of these cores. These slice specimens were then allowed to completely dry. Four different specimen slices were then selected for EDS analysis of each mixture type. A Denton vacuum coater was then used to sputter the top surface of each of the selected specimens with 20 nm of gold to make them conductive and avoid charging the sample surface. This step was critical for EDS testing. These sputtered samples were then attached to the cylindrical holder using double-stick carbon tape and were then ready for testing and analysis.

## 10.5 Blending Analysis Using EDS SEM Microanalysis

To conduct the blending analysis, a Jeol USA JSM-5610LV scanning electron microscope with an Oxford Instruments 6587 energy dispersive X-ray spectrometer was used. A magnification of 500× was used with an accelerating voltage of 20 kV.

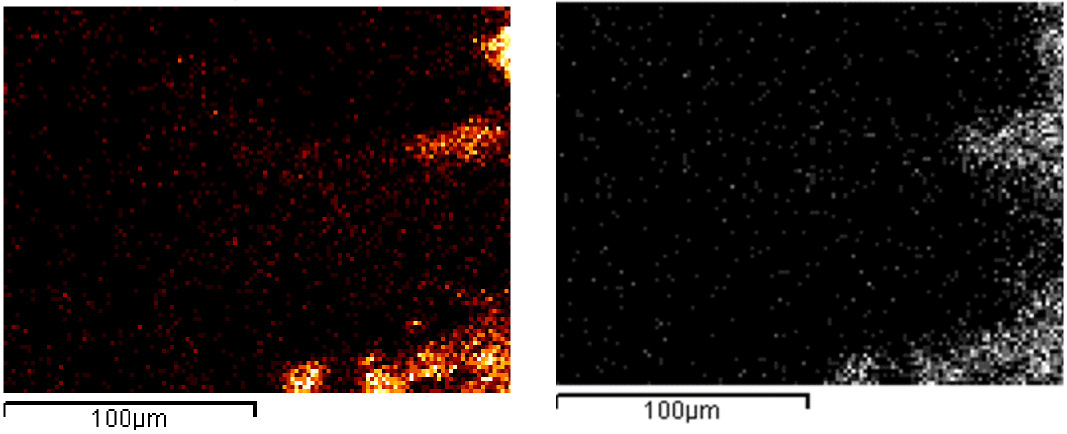
First, an element mapping analysis was performed to evaluate the dispersion quality of tracer element in the binder region inside each mixture specimen slice. Element mapping compresses both the topographic and compositional information into a single view by utilizing the X-ray spectrums, detected by the EDS, over the selected region of the sample. A color response map can then be constructed showing the elemental distribution *(25)*. Figure 10.3 shows an example of the SEM image and corresponding silica, carbon, sulfur and titanium elemental maps in an area around a known aggregate. Note that the aggregate particles can be identified by the silica element ,while asphalt binder is identified by both carbon and sulfur elements. Figures 10.3c and Figure 10.3d show the strong correlation between carbon and sulfur which are inherently present in the asphalt binder as the maps appear visually similar. Now, by comparing the titanium element map shown in Figure 10.3e with carbon or sulfur element maps, it was concluded that the tracer element ($TiO_2$ nanoparticles) was distributed fairly evenly within the asphalt binder, as the map took a similar shape to the carbon and sulfur maps. Thus, it was confirmed that tracer element was dispersed in the mixture sample.

Next, EDS testing was conducted to determine the partial degree of blending in the specimen. This was accomplished through EDS testing at different locations on the surface of the specimen slices corresponding to each companion mixture set. Each set had mixture specimen slices representing the 100% blended condition and the actual blended condition for each RAP source and at each RAP content. If only a qualitative evaluation of blending was required, then only mixtures in the actual blended condition would need to be tested. In order to quantify blending, testing of known 100% blended specimens was also required.



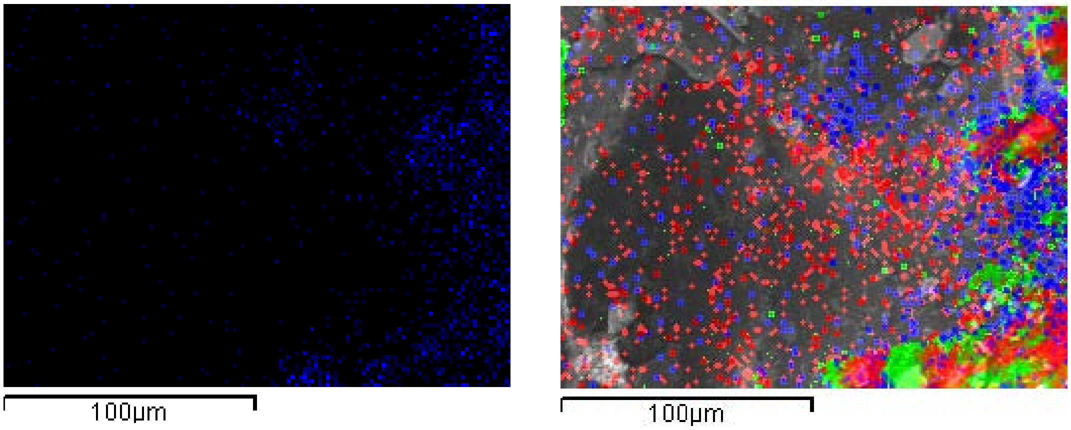
a) SEM Image of Mapped Area

b) Silica EDS Map



c) Carbon EDS Map

d) Sulfur EDS Map



e) Titanium EDS Map

f) Overlay Map Showing Silica, Carbon, and Titanium

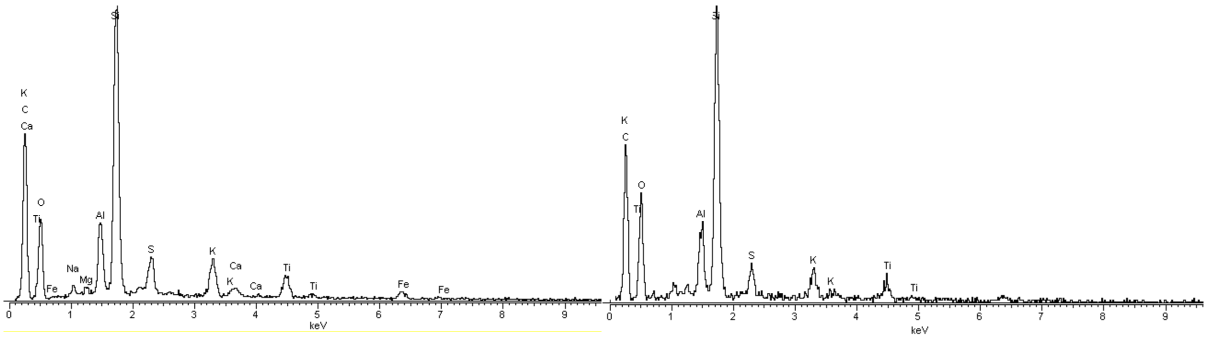
**Figure 10.3: Example of EDS maps showing elements**

The two different mixture sets were identical in terms of their components, with the exception of binder blending state inside between the RAP and virgin binder. For the 100% blended condition specimens, the two binders were manually forced to form a homogeneous 100% blend. The actual blended-condition specimens were produced using the normal mixing methods which represent the actual degree of blending state between the RAP and virgin binder. Since the virgin binder traced with the trace element ($TiO_2$ nanoparticles) was used in fabrication of both mixture sets, the state of blending was evaluated by detecting the titanium concentration inside the asphalt (carbon and sulfur areas) near to the known RAP aggregates (gray aggregates). In the actual blended specimens, if the RAP and virgin binders did not blend during the production process of the mixture, titanium would not be detected (i.e., the Ti:S mass ratio equals zero). Detecting higher titanium to sulfur (Ti:S) value in the vicinity of the RAP aggregate in these specimens provided qualitative evidence of better blending between the two binders. In order to make a quantitative blending evaluation (i.e., degree of partial blending), the Ti:S mass ratios determined for the actual blended condition and the 100% blended condition specimen were utilized as shown in Equation 11.

$$\text{Degree of Partial Blending (\%)} = \frac{(Ti{:}S)_{Actual\ Blended}}{(Ti{:}S)_{100\%\ Blended}} * 100 \qquad (11)$$

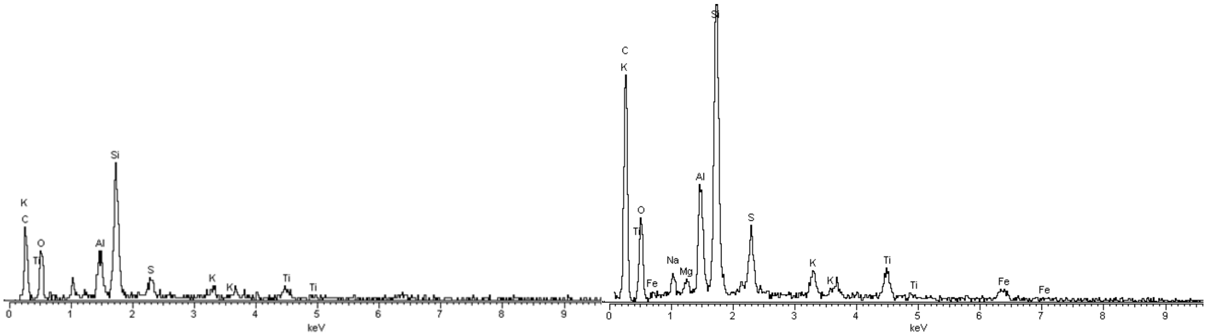
Where:
$(Ti{:}S)_{\text{Actual Blended}}$ = Titanium to sulfur mass ratio in actual blended mixture specimens adjacent to the RAP aggregate.
$(Ti{:}S)_{\text{100\% Blended}}$ = Titanium to sulfur mass ratio in 100% blended mixture specimens adjacent to the RAP aggregate.

EDS elemental spectrum data was collected for both the actual and 100% blended condition specimens, an example of which is shown in Figure 10.4. From this spectrum data, the titanium to sulfur ratio (Ti:S) mass ratio was calculated. This data was used to calculate the partial degree of blending in each mixture set due to RAP source and RAP content, as shown in Equation 11. The average degree of blending was calculated based on 12 observations (three different locations per specimen for four specimens slices per mixture). It should be noted that some RAP surfaces within a test specimen could be without aged binder, as the milling process can fracture the aggregate, leaving an uncoated surface. In this scenario, only virgin binder would coat these surfaces, and there would be no blending due to the absence of the aged binder. Thus, the measured titanium to sulfur (Ti:S) mass ratio corresponding to this situation was eliminated to accurately measure the degree of blending. In this study, this case was identified if $(Ti{:}S)_{\text{Actual Blended}}$ was greater than $(Ti{:}S)_{\text{100\% Bended}}$.



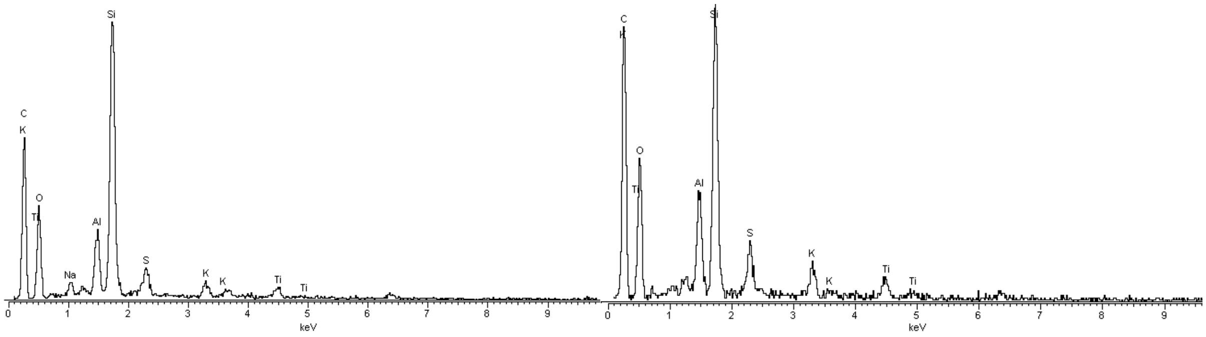
a) EDS Spectrum – Actual Blended Specimen using 15% Stiff RAP

b) EDS Spectrum – 100% Blended Specimen using 15% Stiff RAP



c) EDS Spectrum – Actual Blended Specimen using 25% High Binder Content RAP

d) EDS Spectrum – 100% Blended Specimen using 25% High Binder Content RAP



e) EDS Spectrum – Actual Blended Specimen using 40% Soft RAP

f) EDS Spectrum – 100% Blended Specimen using 40% Soft RAP

**Figure 10.4: Example of EDS element spectrum plots for actual blended and 100% blended specimens**

## 10.6 Blending Results

The average blending results are shown in Figure 10.5. The average degree of partial blending ranged from 77% to 95% for all mixtures tested. This indicates that the assumption of 100% blending that is a common industry assumption is not accurate. At the current specification limit of 15% RAP by dry weight limit, the average degree of blending ranged from 90% to 95% in the mixtures tested, suggesting that the 100% blending assumption at this RAP content is close to the actual partial blending that occurs. However, as the RAP content was increased in the mixtures, the 100% blending assumption became more inaccurate. Much lower degrees of blending were observed for the 40% RAP content mixtures (77% to 84%). This clearly demonstrated that the 100% blending assumption is inaccurate and the degree of blending was reduced as the RAP content was increased, regardless of the RAP source used.

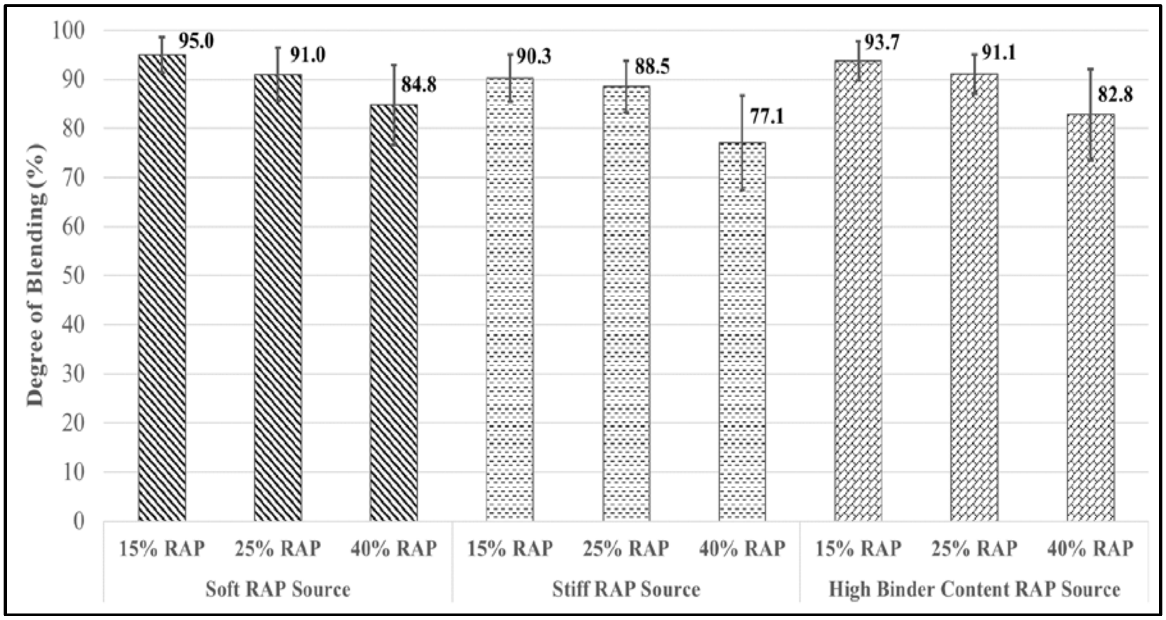


**Figure 10.5: Average degree of partial blending results**

In terms of the RAP source impact on blending, it was observed that the degree of blending was generally higher when the softer RAP was used at each RAP content. As the amount of RAP was increased, this trend was more pronounced with the stiffer RAP exhibiting less blending. This demonstrates that all RAP sources will not behave the same in the mixture and cannot be treated equally. Testing of each individual RAP stockpile’s properties is needed to account for these binder property differences during the design phase.

No definitive conclusions could be made regarding the use of a higher binder content RAP source. It was anticipated that this RAP source may have less blending due to more aged RAP binder being available in the mixture. However, the blending observed was on a level similar to that of the softer RAP source with a lower binder content (5.8% compared to

6.6%). Further investigations with other RAP sources with higher binder contents are needed to understand this occurrence.

Overall, based on the mixtures tested, the blending analysis suggests that the assumption of 100% blending between RAP and virgin binders is inaccurate. Furthermore, the degree of blending in a mixture appears to be a function of both the amount of RAP used in a mixture and the properties of the RAP source. This demonstrates there is a need to test the properties of the RAP that is used at any percentage in any mixture.

# 11.0 Conclusions

Based on the testing and analysis presented in this study, the following conclusions were determined.

## 11.1 RAP Properties

- The ignition oven-determined binder content was generally greater than the centrifuge extraction binder content. For the majority, the ignition oven- and centrifuge-determined binder contents were within ±0.5%.
- Testing of extracted and recovered RAP binder indicated that the PGs of the RAPs in Massachusetts varied from PG 76-22 to PG 94-10. MSCR data indicated that the majority of the RAP binders were suitable for E (extremely high) traffic level, while one was a V (very high) traffic level. LAS tests indicated that the fracture resistance of the RAP binders varied based on source.
- RAP maximum theoretical specific gravity ($G_{mm}$) varied between and within the districts. When the RAP aggregate specific gravity is estimated from the $G_{mm}$, sample volumetric calculations indicated that the RAP $G_{mm}$ has significance on the final calculated mixture volumetric properties. At the currently specified 15% RAP, some mixtures fail to meet the required VFA.
- The values of the measured aggregate specific gravity for the RAP stockpiles were consistently lower than those that were calculated from the RAP $G_{mm}$. Sample volumetric calculations indicated that two of the RAP stockpiles would yield mixtures failing the VMA requirement of >15%, but all mixtures passed the VFA requirement. In terms of RAP specifications, MassDOT should decide which method is preferred for determining the specific gravity of the RAP aggregate, as each method will yield mixtures with different volumetric properties, and not all may conform to current volumetric thresholds.
- Generally speaking, the recovered RAP aggregate gradations obtained post-ignition oven were finer than the those obtained after chemical extraction. This is likely due to the fact that aggregates will break down during the ignition oven process.
- Some RAP stockpiles exhibited high variability in gradation on certain sieve sizes, with some sieve sizes having standard deviations of 10 measurements greater than 10%. If the limits proposed in NCHRP Report 752 were to be incorporated into the future specification, these stockpiles would not be uniform enough for suitable use. The current MassDOT specification does not address RAP stockpile variability, thus allowing for potentially highly variable stockpiles to be used. This would result in nonconforming mixtures being produced, with potentially reduced volumetric and performance characteristics.
- The properties of the RAPs did not vary greatly from year to year, except for the Dracut millings. The recovered RAP binder grade went from very stiff at PG 94-10 to much less stiff at PG 76-22. This demonstrates that RAP properties must be tested thoroughly every season or when new RAP is processed. Another complication is that

sections of a particular stockpile may have RAPs with different properties. Moreover, RAP stockpile properties cannot be accurately determined without knowing the properties of the RAP binder. The current MassDOT specification does not account for these properties at low RAP contents (≤15%).

## 11.2 Virgin Binder Properties

- Massachusetts has four regional suppliers of PG 64-28 asphalt binder that currently serve the state. Testing confirmed the grade of each of the binders to be PG 64-28. One binder source had intermediate- and low-temperature continuous grades close to the specification criterion. This will have an impact on the capacity of this virgin binder to accommodate RAP in any mixture, because the aged RAP binder might not make the blended binder PG 64-28.
- MSCR rutting performance data indicated that all virgin binders are suitable for S (standard) traffic levels. LAS results indicate that the fracture resistance of the virgin binders varied based on source, with one source exhibiting a reduced fatigue performance as compared to the remaining binders tested.

## 11.3 Allowable RAP Percentage and Blending Equations

- The current MassDOT specification, which allows up to 15% RAP in surface mixtures by dry weight of the mixture without using a softer-grade virgin binder or blending equations, was not valid based on blended binder properties. Analyses using AASHTO blending equations and laboratory-determined RAP and virgin binder properties indicated that 28.9% of the time, the required PG 64-28 would not be maintained. The disparity between the estimated amounts of allowable RAP that would maintain PG 64-28, ranging from 3.1% to 46.8%, shows the high influence of RAP source and virgin binder sources on the amount of RAP that can be added to a mixture. Therefore, a specification change for MassDOT is warranted.
- Utilizing the RAPBR for specifying RAP in lieu of the percent by dry weight of the mixture produced similar results. The reason is that the binder contents of the RAPs were all close to the design binder content of 5.5%.
- Blended binder grading to validate the allowable RAP percentage determined by the AASHTO blending equations indicated that at smaller RAP percentages, the low temperature -28°C grade (limiting case) is maintained, but as the RAP content increases, it appears the accuracy of the prediction is less accurate, with actual temperature being warmer than -28°C. In terms of specification, this implies that the blended binder grade predicted by the AASHTO blending equations is not wholly accurate and may only be accurate at smaller RAP percentages.

## 11.4 Mixture Design

- RAP source had a pronounced effect on mixture air voids. The stiffer RAP showed a trend of increased air voids as the amount of RAP increased, while the air voids remained nearly constant for the softer RAP. MassDOT specification must be revised to address the fact that higher amounts of RAP from different sources may not always yield acceptable volumetric properties.

## 11.5 Mixture Stiffness and Performance Tests

- Mixture master curve data derived from the dynamic modulus tests suggest that the amount of RAP, the properties of the binder in the RAP, and the virgin binder utilized all have an effect on the overall mixture stiffness. Mixtures with higher stiffness may be more prone to distresses like cracking. Softer mixes may be more prone to distresses like rutting.
- A statistical analysis of the mixture test data indicated universally that virgin binder source significantly impacted all cracking performance measures. RAP source and percent RAP also had a significant effect on the FI and the CT Index, which are the two intermediate cracking measures being explored by MassDOT to incorporate in a BMD protocol. However, there was inconsistency among all of the cracking performance tests, except that virgin binder source has a significant effect.
- Although the low- and intermediate-temperature mixture test results often showed that RAP source, virgin binder source, and percent RAP had a significant effect, the lack of pass/fail criteria for these tests precluded stating exactly which mixtures were balanced or unbalanced. Furthermore, the closeness of the mixture test data for each test prevented suggesting any pass/fail criteria even though the percent RAP ranged from 15% to 35% with no soft asphalts or rejuvenators being used. Although it was assumed that the degree of blending in the mixture study was 100%, if it was not always this, it would be expected that this additional variable would have increased the range in the mixture test results. Based on these findings, the mixture tests appear to be deficient for use in a BMD using the current protocols. Still, the significant effects of certain variables indicate that both low- and intermediate-temperature properties must be considered when incorporating RAP in a mixture.

## 11.6 Blending

- Blending analysis using the EDS indicated that the assumption of 100% blending between RAP and virgin binders is inaccurate. Furthermore, the analysis illustrated that the degree of blending in a mixture is a function of RAP content, source, and properties.

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# 12.0 Recommendations

The following recommendations are made based on the testing and analysis in this study:

- MassDOT should choose which method is preferred for determining the specific gravity of the RAP aggregate (estimated from maximum theoretical specific gravity or directly measured). The utilization of either method will yield mixtures with different volumetric properties, and not all may conform to current volumetric thresholds. This should be added into the specification for using RAP at any percentage.
- Testing showed some RAP stockpiles with high aggregate gradation variability. The current MassDOT specification does not address RAP stockpile variability, thus allowing for potentially nonconforming mixtures being produced. The limits proposed in NCHRP Report 752 for aggregate gradation could be used as a starting point in the specification to address this variability.
- Certain properties of the RAPs, specifically PG of the recovered RAP binder, did vary from year to year for the same RAP stockpile. The current MassDOT specification does not account for these properties at low RAP contents (≤15%). It is suggested to incorporate into the specification mandatory testing and documentation of the recovered RAP binder properties (continuous and performance grade) at a specific frequency of time interval or tonnage.
- As important as RAP property variability, virgin binder properties based on source were just as influential on the performance of the resultant mixtures. The capacity of a mixture to accommodate RAP is a function of these properties. It is suggested to revise the specification to determine the continuous and performance grade of the virgin binder being used for a specific project in lieu of verifying the grade, which is the common practice currently. Determining the grade is more accurate than verification and will give an indication of the capacity to add RAP to a mixture.
- Overall, a three-tiered approach is needed to properly specify RAP in a mixture even at RAP contents ≤15%:
    1. The properties of the RAP including binder content, recovered binder grade, etc., and virgin binder properties need to be determined. Appropriate RAP and virgin binder tests and their frequency need to be established.
    2. AASHTO blending charts equations need to be utilized to estimate if the desired blended binder properties are obtained and to assist in properly limiting the amount of RAP.
    3. After the appropriate RAP content is determined, the actual mixture to be produced must be tested to ensure adequate performance after appropriate aging that is related to the in-service aging experienced.

    As shown in this study, the mixture performance test results were not always significantly impacted by the same variables, except for virgin binder source. Thus, it is important for MassDOT to have confidence in the mixture performance tests used and their pass/fail criteria. MassDOT has been utilizing a rutting/moisture susceptibility test successfully for years but needs to select and appropriate cracking test(s) and associated thresholds. Using this type of three-tiered approach should help ensure that quality mixtures are produced and the amount of RAP utilized is appropriate to maintain performance.

- It is recommended to implement the three-tiered approach in a multiphase methodology. It is imperative to make sure that the resources are available to implement the suggested recommendation.

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