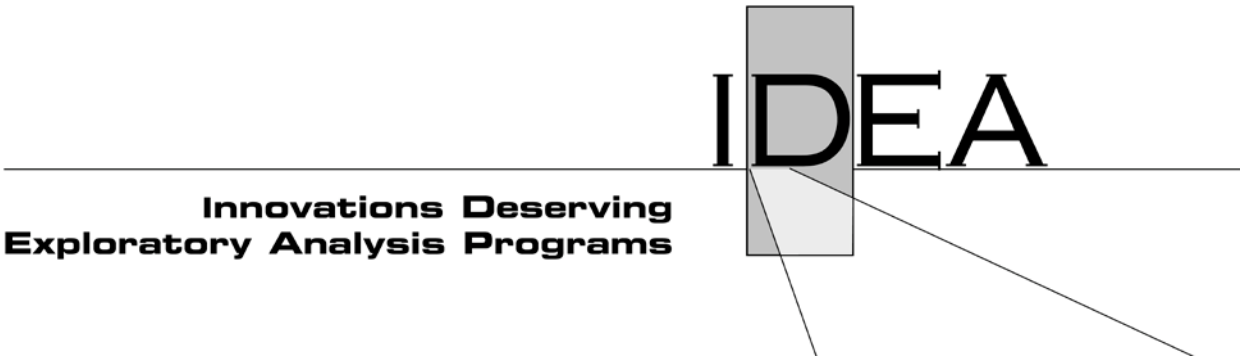

NCHRP IDEA Program

A Practical Method to Determine Reclaimed Asphalt Pavement (RAP) Binder Availability

Final Report for
NCHRP IDEA Project 236

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Trimat Materials Testing

January 2024

NATIONAL ACADEMIES Sciences Engineering Medicine

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A Practical Method to Determine Reclaimed Asphalt Pavement (RAP) Binder Availability

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IDEA Project NCHRP 236

Prepared for

The NCHRP IDEA Program
Transportation Research Board
National Academies of Sciences, Engineering, and Medicine

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EXECUTIVE SUMMARY

Recycled binder availability (RBA) is the proportion of total recycled binder in a reclaimed asphalt pavement (RAP) source that is available to blend with virgin asphalt. Partial RBA is a consequence of agglomerations of adhered RAP particles. RAP binder locked inside of an agglomeration is 'unavailable' whereas the binder within the peripheral mastic coating of an agglomeration is 'available'. The innovation developed through this project is a practical method to quantify the extent of agglomeration in a given RAP source, and in turn, the RBA using comparative sieve analysis of RAP and recovered RAP aggregate. The vast majority of asphalt mixtures produced today contain RAP due to associated cost and economic benefits. However, RBA is not accounted for in the majority of state highway agency design procedures. Consequently, the innovation developed through this project serves an urgent need to address uncertainty in the performance of RAP asphalt mixtures designed under current procedures.

The sieve analysis approach developed in this project is predicated on two primary hypotheses: (1) RAP agglomerations are preexisting and do not fully break during production, and (2) RBA measurements can be used to estimate the recycled binder contribution (RBC) in asphalt mixtures. Correspondingly, the investigation undertaken sought to: (1) validate the aforementioned sieve analysis method by examining its applicability to a diverse range of nine RAP sources from four states, encompassing varying characteristics such as aggregate type, gradation, binder grade, and binder content; (2) test hypotheses 1 and 2; and (3) evaluate the effects of adjustments to mixture design procedures to address RBA on asphalt mixture performance. The latter is important to identify the practical implications of incorporating RBA measurements into mixture design procedures.

Several sieve analysis procedural variables were evaluated, including RAP drying and preheating procedures, use of washed versus dry sieve analysis of the RAP, and washing time. The RBA derived from a washed sieve analysis of RAP conditioned at 100°C (100°C BC) demonstrated favorable agreement with RBC measurements, making it the recommended procedure for implementation. The omission of washing and subsequent preheating fails to break weak agglomerations that may break during asphalt mixture production whereas the use of higher conditioning temperatures can cause new agglomerations to form that are unlikely to form during mixture production. The close agreement between RBA and RBC results suggests that all available RAP binder is activated in asphalt mixtures produced at typical production conditions. Tracer-based microscopy analysis of asphalt mixtures fabricated using alternative preheating and conditioning procedures further indicates that RBC in asphalt mixtures does not vary significantly with laboratory production conditions. Consequently, the results suggest promise that the RBA results reflect RBC in asphalt mixtures produced under variable conditions.

Statistical analyses indicate that RBA cannot be predicted from the commonly measured constituent RAP properties, thereby suggesting that the established sieve analysis procedure is necessary to precisely quantify source-specific RBA. While exhibiting statistical distinctions, the majority of sources exhibited RBA values near 60 percent, implying that a constant value of 60 percent could serve as a pragmatic alternative when sieve analysis measurements are not possible.

The effects of RBA on asphalt mixture design were evaluated by comparing the composition and performance of control asphalt mixtures designed under the assumption of 100 percent RBA with those redesigned according to the availability adjusted mixture design (AAMD) method. The AAMD method explicitly considers the role of RAP agglomerations and RBA on the design and evaluation of asphalt mixtures. The AAMD method generally produced mixtures with enhanced cracking performance and similar rutting resistance compared to the control mixtures. Also, virgin mixtures and AAMD RAP mixtures prepared with similar available volumetric and effective properties yielded similar cracking performance, suggesting potential for applying the AAMD method to counteracts RAP's detrimental effects on cracking resistance.

IDEA PRODUCT

Recycled binder availability (RBA) is the proportion of total recycled binder in a RAP source that is available to blend with virgin asphalt. Partial RBA is a consequence of agglomerations of adhered RAP particles. The innovation developed through this project is a practical method to quantify the extent of agglomeration in a given RAP source, and in turn, the RBA using comparative sieve analysis of RAP and recovered RAP aggregate.

The vast majority of asphalt mixtures produced today contain RAP due to associated cost and economic benefits. It is generally accepted that 100 percent RBA is not achieved in practice, which is not accounted for in the majority of state highway agency design procedures. Consequently, the innovation developed through this project serves an urgent need to address uncertainty in the performance of RAP asphalt mixtures designed under current procedures.

CONCEPT AND INNOVATION

RBA represents an intrinsic property of a given RAP source that reflects the percentage of total recycled binder that is available to blend with virgin asphalt binder (*1*). Previous studies as well as the results herein show that agglomerations are an inevitable result of milling (*2-3*), and that approximately 30 percent to 50 percent of RAP particles are agglomerated (*1*). Tracer-based microscopy investigations reveal that these agglomerations are the main cause of partial recycled binder contribution (RBC) in asphalt mixtures (*5-8*). In tracer-based microscopy, titanium dioxide is added to the virgin asphalt binder prior to mixture fabrication to distinguish it from unavailable recycled binder using energy dispersive x-ray spectroscopy scanning electron microscopy (EDS-SEM). Bressi et al. (*5*) first observed the existence of RAP agglomerations within asphalt mixtures through EDS-SEM analysis. Pape and Castorena (*8*) subsequently applied EDS-SEM method and also observed the presence of adhered RAP particle agglomerations and found that fatigue cracks in asphalt mixture propagate around the agglomerations, suggesting they function as 'black rocks'.

RAP locked inside of an agglomeration is 'unavailable' whereas the binder within the peripheral mastic coating of an agglomeration is 'available' based on tracer-based microscopy experiments. Figure 1(a) presents a visual representation of an actual RAP particle while Figures 1(b), 1(c), and 1(d) present possible configurations of the internal structure of a RAP particle. Figure 1(b) depicts a scenario in which the RAP particle includes a single core aggregate coated by asphalt mastic. Figure 1(c) illustrates a scenario in which a core coarse aggregate RAP particle is surrounded by agglomerated fine particles. Figure 1(d) illustrates a scenario in which the RAP particle is composed of an agglomeration of fine particles only. Figure 2 shows evidence of these hypothesized agglomeration internal structures by depicting authentic agglomerations that were intentionally fractured.

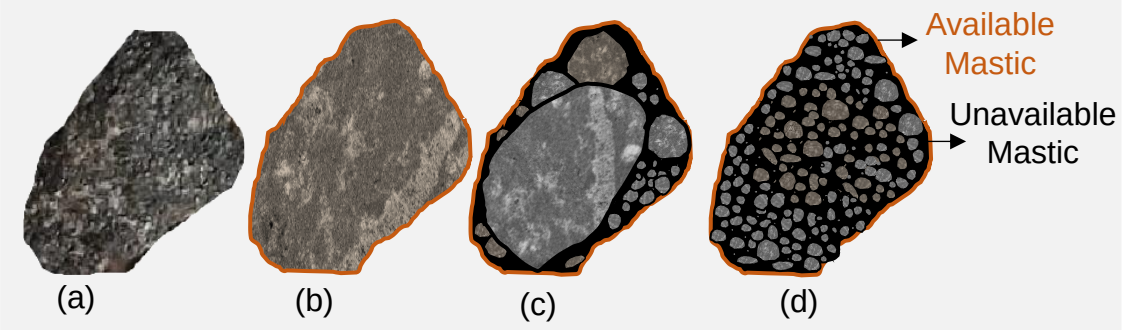

FIGURE 1 Depiction of RAP particles (a) photo of a RAP particle, (b) RAP particle with one core aggregate, (c) RAP particle containing a coarse aggregate particle surrounded by fine aggregates, and (d) RAP particle containing agglomerated fine aggregates

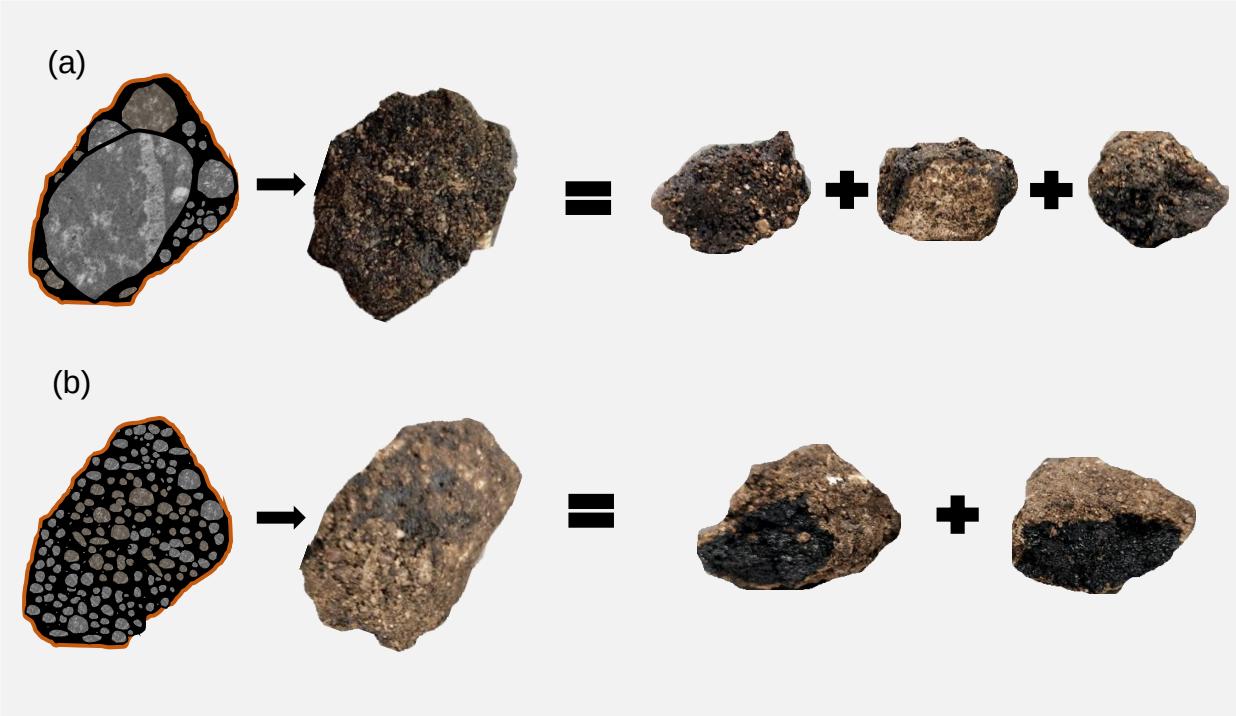

FIGURE 2 Picture of fractured agglomerations showing (a) coarse RAP aggregate surrounded by agglomerations of finer RAP particles, and (b) agglomeration of fine RAP particles

The present project builds on the initial work by Pape and Castorena (*6*) to develop a practical method to quantify RBA by comparing the particle size distribution of the recycled materials (referred to as the 'black curve') and the recovered recycled aggregates (referred to as the 'white curve'). This method involves adding a washed sieve analysis of the recycled material to existing practices for measuring the asphalt content, specific gravity, and recovered aggregate gradation of the RAP. Pape and Castorena (*6*) found that the proportion passing the No. 200 (0.075 mm) sieve in the RAP was limited, suggesting that all RAP particles retain a peripheral mastic coating. Accordingly, the method is based on the premise that the mastic coating surrounding the RAP particles can mix with the virgin asphalt while the mastic bound within agglomerations is inaccessible.

INVESTIGATION

Overview

Within the investigation, several distinct properties are used to quantify and evaluate the mobilization of recycled asphalt binder in RAP. RBA and the degree of activity (DoA) are considered RAP properties. FIGURE 3 illustrates the concepts of RBA and DoA using an agglomeration of RAP aggregates adhered by RAP binder. As previously defined, RBA is the proportion of recycled binder in a RAP material that is available for blending with virgin asphalt. As illustrated in FIGURE 3(a), binder that is inside of the agglomerated RAP particle that does not separate during the mixing process is 'unavailable' whereas the binder within the peripheral mastic coating of the RAP particle is 'available' to blend with virgin asphalt. On the other hand, DoA represents the percentage of the available recycled binder that becomes activated during production without the use of recycling agents (*9-10*). The available recycled binder can be either fully or partially activated as depicted in FIGURE 3(b). Furthermore, recycled binder contribution (RBC) is an asphalt mixture property that denotes the portion of recycled asphalt binder incorporated into the virgin binder within an asphalt mixture (*1*) and is a consequence of both the RBA and DoA of the RAP as well as any interactions between the virgin and RAP materials in the mixture.

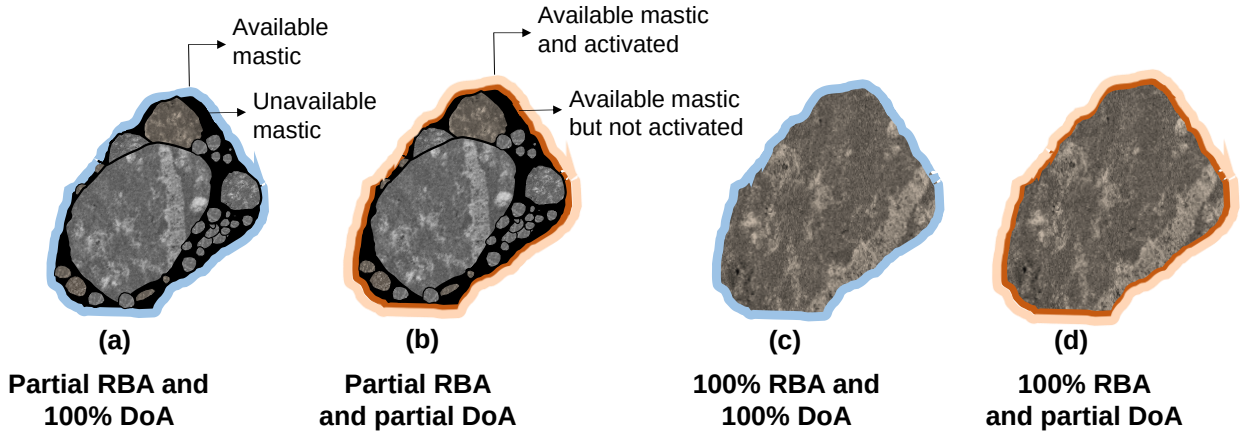

FIGURE 3 Illustration of RAP particle with (a) partial RBA and 100% DoA, (b) partial RBA and partial DoA, (c) 100% RBA and 100% DoA, and (d) 100% RBA and partial DoA

The aforementioned sieve analysis approach developed to quantify RBA in this project is predicated on two primary hypotheses:

1. RAP agglomerations are preexisting and do not fully break during production.
2. RBA measurements can be used to estimate the RBC in asphalt mixtures. In other words, the DoA is approximately 100 percent under typical production conditions.

Correspondingly, the investigation undertaken sought to: (1) validate the aforementioned sieve analysis method by examining its applicability to a diverse range of nine RAP sources from four states, encompassing varying characteristics such as aggregate type, gradation, binder grade, and binder content; (2) test hypotheses 1 and 2; and (3) evaluate the effects of adjustments to mixture design procedures to address RBA on asphalt mixture performance. The latter is important to identify the practical implications of incorporating RBA measurements into mixture design procedures.

Methodology

Materials

TABLE 1 details the study mixtures, encompassing nine state agency-approved mixture designs sourced from four states. All mixtures evaluated are surface mixtures with a nominal maximum aggregate size

(NMAS) of 9.5 mm or 12.5 mm. The selected mixtures encompass a range of climatic characteristics (and therefore, virgin binder grades and RAP binder properties), reclaimed binder replacement ratios (RBRs), and aggregate absorption (P_{ba}) characteristics. Sources 8-NC and 9-NC contain fractionated (i.e., fine and coarse) RAP. The component materials for each mixture design were acquired. Asphalt mixtures were verified to meet the specified air void content (4%) and adjusted, where necessary.

TABLE 1 Summary of the Study Materials as Reported in JMF

ID No.	Source	NMAS	RBR	Virgin PG	N_{des}	Mixing & Compaction Temps. (°C)	Min VMA @ N_{des} (%)	VMA @ N_{des} (%)	P_{ba} (%)
1	NC	9.5	0.25	58-28	65	152 & 142	15.5	17.1	0.3
2	NC	9.5	0.18	64-22	65	152 & 142	15.5	15.9	0.4
3	NC	9.5	0.39	58-28	65	152 & 142	15.5	17.1	0.1
4	WI	12.5	0.39	52-34	60	146 & 141	14.0	14.8	0.9
5	TX	12.5	0.18	64-22	50	152 & 146	14.0	15.8	1.7
6	NC	9.5	0.23	64-22	50	152 & 142	16.0	17.6	0.5
7	ME	9.5	0.16	58-28	65	154 & 148	16.0	17.1	0.9
8	NC	9.5	0.30	58-28	50	152 & 142	15.0	18.0	0.2
9	NC	9.5	0.25	64-22	65	152 & 142	15.5	16.7	0.6

Experiments

Conventional Material Characterization

TABLE 2 details the properties of the acquired RAP sources. Note that Sources 8-NC and 9-NC include fractionated coarse (C) and fine (F) RAP stockpiles. Extraction and recovery of the RAP binders was performed following ASTM D2172 and ASTM D5404 to measure the asphalt content and enable binder characterization. The asphalt content (AC) of the RAP sources was also measured using the ignition furnace in accordance with AASHTO T 308. The continuous high-temperature grades (HPG) of the recovered RAP binders and virgin binders were determined per AASHTO T 315 and AASHTO M 320. The theoretical maximum specific gravity of the RAP sources was measured following ASTM D6857 (CoreLok® method). The effective specific gravity of the aggregate (G_{se}) was calculated from the theoretical maximum specific gravity (G_{mm}) of the RAP and measured binder content from extraction and an assumed binder specific gravity of 1.02. The calculated G_{se} values were used along with the percent absorption reported in the JMF to calculate the bulk specific gravity of the aggregate (G_{sb}) of each RAP source.

TABLE 2 Summary of Material Characterization

ID	NMAS	HPG(°C)	AC (%) Extraction	AC (%) Ignition	G_{mm}	G_{se}	G_{sb}
1-NC	9.5	98.6	4.7	4.8	2.535	2.761	2.738
2-NC	9.5	95.4	4.8	5.1	2.472	2.676	2.647
3-NC	9.5	105.4	5.7	5.7	2.534	2.784	2.776
4-WI	12.5	89.0	4.2	5.5	2.527	2.700	2.629
5-TX	12.5	100.0	4.3	4.6	2.477	2.642	2.475
6-NC	9.5	85.4	4.8	5.0	2.493	2.689	2.653
7-ME	9.5	85.7	4.9	5.8	2.507	2.730	2.663
8F-NC	9.5	99.1	5.6	5.3	2.311	2.487	2.474
8C-NC	12.5	97.9	4.9	4.0	2.351	2.525	2.512
9F-NC	9.5	96.8	5.2	5.0	2.381	2.574	2.534
9C-NC	12.5	98.7	4.0	3.9	2.432	2.577	2.537

RAP Sieve Analysis Procedure

Sieve analysis of RAP and recovered RAP aggregate were used to obtain the black curve (BC) and white curve (WC), respectively. A comparative analysis of BC and WC combined with the asphalt content and specific gravity of the RAP aggregate was used to calculate RBA. The control method utilized in this study is based on the sieve analysis approach developed by Pape and Castorena (*6*), and it was implemented for all sources under evaluation. Henceforth, this method will be referred to as '100°C BC.' Additionally, this procedure was modified to evaluate the effect of temperature on the extent of agglomeration and the resulting BC for three sources. The procedure entailed subjecting RAP samples to four sieve analyses, which were conducted at ambient temperature following preheating at varying temperatures. The steps of the experimental procedure are described in FIGURE 4. Initially, the RAP was dried at 60°C in an oven. After cooling down, the RAP samples underwent a dry RAP sieve analysis as per AASHTO T 27. This gradation is referred to as '60°C BC'. Subsequently, the samples underwent mechanical washing in accordance with AASHTO T 11, and then were dried at 100°C. While the samples were still hot, any weak agglomerations that may have formed during the drying process, as well as pre-existing weak agglomerations, were broken apart by hand similarly to the preparation of G_{mm} samples. After cooling to room temperature, the samples were subjected to a second sieve analysis according to AASHTO T 27 and the resulting curve is called the '100°C BC', which aligns with the method proposed by Pape and Castorena (*6*) for measuring RBA. Following this step, the samples were collected from each sieve and conditioned at mixing temperature for two hours. While still hot, the material was spread in a large pan to prevent new and potentially weak agglomerations from forming that could break during production. The weak agglomerations were then broken apart and the sample was cooled to room temperature and underwent a third sieve analysis to obtain the 'T_{mix} BC'. The RAP was collected from each sieve and ignited following AASHTO T 308. Finally, the recovered aggregate was subjected to a second washed sieve analysis, including the dust lost during the initial washing process. The gradation of the recovered RAP aggregate, referred to as WC hereafter, was utilized along with the 60°C, 100°C, and T_{mix} BCs to measure the corresponding 60°C, 100°C, and T_{mix} RBAs, respectively. While the 100°C was measured for all RAP sources, the 60°C and T_{mix} BCs were only measured for select RAP sources.

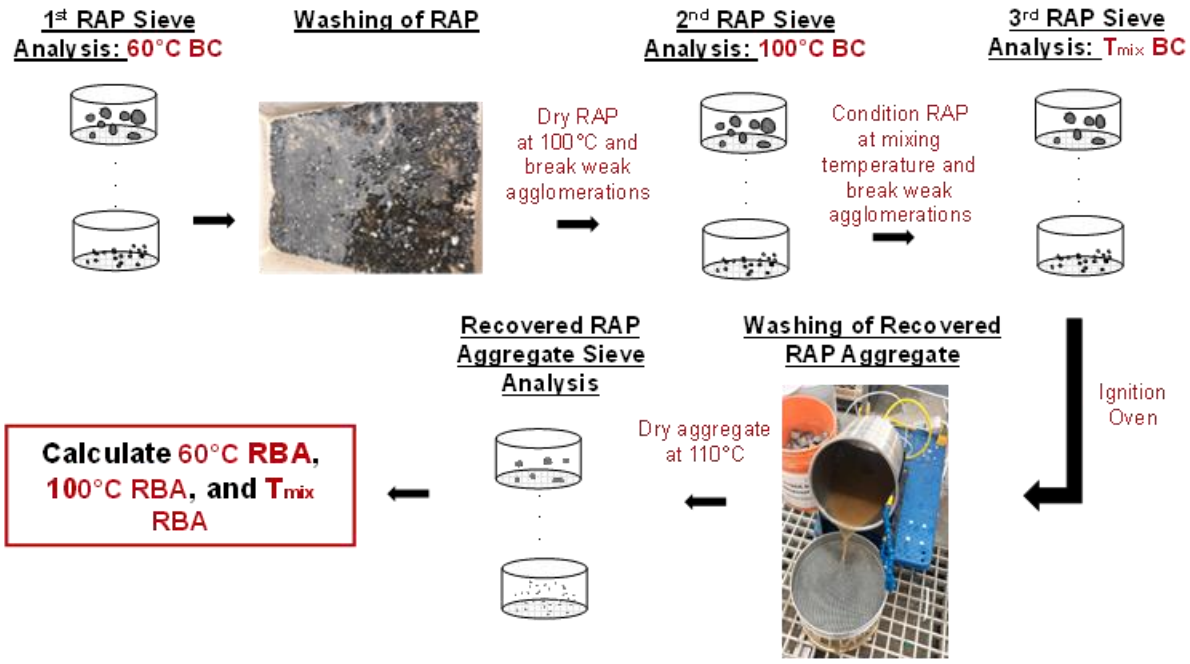

FIGURE 4 Sieve analysis experimental procedure

In addition to the experimental procedure above, an additional experiment was conducted for a single RAP source wherein the RAP was heated to the compaction temperature and sieved while hot. This alternative procedure is called Hot Sieving herein.

It is also important to mention that the samples were initially manually washed but this process took in excess of two hours for some dusty RAP sources, and therefore, manual washing was deemed impractical. Subsequently, an automatic washer was adopted to wash the RAP samples which were then dried. An automatic washer was used to wash a single RAP source for durations of 8, 10, and 15 minutes to evaluate the sensitivity of the RBA results to washing time. For all other experiments, a washing duration of approximately 8 to 10 minutes was used. The 100°C preheating temperature, ambient sieving temperature, and washed RAP preparation coincide with the procedure used by Pape and Castorena (*6*) and is thus, considered the 'control' procedure herein.

TABLE 3 summarizes the different sieve analysis experiments applied to the different RAP sources. The sensitivity of the RBA results to the procedural variables and their impacts on the agreement with tracer-based microscopy RBC measurements in asphalt mixtures were used to optimize the sieve analysis procedure. The 100°C preheating temperature, ambient sieving temperature, and washed RAP preparation coincide with the procedure used by Pape and Castorena (*6*) and is thus, considered the 'control' procedure herein.

TABLE 3 Summary of Sieve Analysis Experiment

Procedure			Source								
PreheatTemp.	**Sieving Temperature**	**RAP Sieving**	**1-NC**	**2-NC**	**3-NC**	**4-WI**	**5-TX**	**6-NC**	**7-ME**	**8-NC**	**9-NC**
60°C	Ambient	Dry	✓			✓	✓				
100°C	Ambient	Washed	✓	✓	✓	✓[1]	✓	✓	✓	✓	✓
	Compaction Temperature	Washed		✓							
T_{mix}	Ambient	Washed	✓			✓	✓				

[1] Sieve analysis conducted using washing times of 8, 10, and 15 minutes

RBA Calculations

The RAP gradation measurements, asphalt content, and effective specific gravity results were used to calculate the RBA using several steps. First, the total volume of mastic in a sample of RAP containing 100 g of aggregate was calculated using Equation (1).

$$V_{mastic} = V_{be} + V_{filler} = \frac{P_{be}\left(1 + \frac{P_{be}}{(100 - P_{be})}\right)}{G_b} + \frac{P_{200}}{G_{sb}} \quad (1)$$

where: V_{mastic} = volume of mastic in a mix with 100 g of aggregate (cm^3); V_b = binder volume (cm^3); V_{filler} = volume of filler (cm^3); P_{be} = effective binder content; G_b = binder specific gravity; G_{sb} = bulk specific gravity of the aggregate; and P200 = percent passing the No. 200 (0.075 mm) sieve for the recovered aggregate.

Next, the average mastic film thickness in the RAP, *t*, was calculated via a least squared error optimization to minimize the absolute difference between the volume of mastic calculated using Equation (2) and the total known volume of mastic calculated using Equation (1). Equation (2) was used to compute the volume of mastic in the RAP by assuming spherical aggregate particles are coated in a concentric shell of mastic with a uniform thickness equal to *t*. Underwood and Kim (*11*) showed that Equation (2) reasonably reflects the distribution of mastic within asphalt mixtures based on microscopic measurements of the mastic film thickness within asphalt mixture samples.

$$V_{mastic} = \sum N_i \times V_i = \sum \frac{P_{i+1} - P_i}{G_{sb} \times \rho_{water} \times \pi/6 \times \left((d_{i+1} + d_i)/2\right)^3} \times \frac{\pi}{6}\left[\left(\frac{d_{i+1} + d_i}{2} + 2t\right)^3 - \left(\frac{d_{i+1} + d_i}{2}\right)^3\right] \quad (2)$$

where: V_{mastic} = volume of mastic in a mix with 100 g of aggregate (cm^3); N_i = number of particles of size *i*; V_i = volume of mastic coating aggregate of size *i* (cm^3); P_i = recovered aggregate percent passing sieve size *i*; and d_i = sieve size (mm).

Subsequently, the RAP gradation and calculated *t* were used to calculate the volume of peripheral (i.e., available) mastic coating the RAP particles using Equation (3). Equation (3) resembles Equation (2) but utilizes the RAP gradation instead of the recovered aggregate gradation. Equation (3) includes an adjustment to the particle diameter corresponding to each sieve size to account for the peripheral mastic film present on the RAP particles (i.e., particle size = $d_i - 2t$).

$$V_{available\ mastic} = \sum N_i \times V_i = \sum \frac{RP_{i+1} - RP_i}{G_{sb} \times \rho_{water} \times \pi/6 \times \left(\left(d_{i+1} + d_i \right)/2 - 2t \right)^3} \times \frac{\pi}{6} \left[\left(\frac{d_{i+1} + d_i}{2} \right)^3 - \left(\frac{d_{i+1} + d_i}{2} - 2t \right)^3 \right] \quad (3)$$

where: $V_{available\ mastic}$ = volume of available mastic in a mix with 100 g of aggregate (cm^3); and RP_i = RAP percent passing sieve size *i*.

Lastly, the RBA was calculated using Equation (4). The filler content of the mastic was assumed to be consistent within the available and unavailable mastic. Thus, the ratio of available to total mastic volume provided the RBA.

$$RBA = \frac{V_{available\ mastic}}{V_{mastic}} \times 100\% = \frac{V_{available\ binder}}{V_{binder}} \times 100\% \quad (4)$$

where: $V_{available\ binder}$ = volume of available binder in the mastic; and V_{binder} = volume of binder in the mastic.

A sensitivity analysis was conducted to evaluate the sensitivity of the calculated RBA to the inputs of binder content, absorbed binder content of the aggregate, and aggregate bulk specific gravity. The sensitivity analysis was conducted analytically by systematically modifying the asphalt content, absorption, and specific gravity inputs to the RBA calculation without modifying the sieve analysis results.

Quantification of DoA from ITS

As a measure of DoA, the Indirect Tensile Strength (ITS) of 100 percent RAP specimens was obtained by following the test procedure but not sample fabrication procedure specified in ASTM D8225 for IDEAL CT tests. The approach taken was inspired by research carried out by Menegusso et al. (*10*) that performed ITS tests on 100 percent RAP specimens conditioned at various temperature. Menegusso et al. conditioned RAP samples conditioned for four hours at different temperatures (70°C, 100°C, 140°C, 170°C) prior to mixing. At least five different replicate specimens were tested for each RAP source at each conditioning temperature. The method was adopted as a part of the ongoing RILEM TC264 RAP TG5 effort. The hypothesis behind the method is that the ITS of a RAP where the binder is 100 percent active should be higher than those where the RAP is surrounded by inactive binder (*10*). Accordingly, the DoA was determined by dividing the ITS of each RAP source by the corresponding maximum ITS observed at various conditioning temperatures as shown in Equation (5).

$$DoA(\%) = 100 \times \frac{ITS_{RAP}(X^{\circ}C)}{MaxITS_{RAP}} \quad (5)$$

where: $ITS_{RAP}(X°C)$ is the ITS result at a specific temperature "X" and $MaxITS_{RAP}$ is the maximum average ITS observed among the temperatures evaluated.

In this study, the RAP samples from Sources 1-NC, 4-WI and 5-TX were conditioned at 100°C, 140°C, 155°C, and 170°C. Despite the TC264 RAP TG5 effort not encompassing 155°C, the range from 140°C to 155°C is crucial to grasp the sensitivity of DoA to variations in realistic production conditions. The samples were manually mixed and compacted into cylindrical specimens 150 mm in diameter and 63.5 ± 1.27 mm in height in the Superpave gyratory using 30 gyrations (*10*). The air void content of the specimens was determined by utilizing the bulk specific gravity (G_{mb}) of the compacted RAP samples in conjunction with their corresponding G_{mm}. Subsequently, the ITS of the specimens was used to quantify the DoA.

Fabrication of Tracer-based Microscopy Samples

Tracer-based microscopy measurements of RBC in laboratory-mixed, laboratory-compacted asphalt mixtures served as a reference to evaluate the sieve analysis procedure. Furthermore, tracer-based microscopy measurements were used to evaluate the sensitivity of RBC to laboratory production variables. Assessing the sensitivity of the RBC to laboratory production variables was important to (1) test the hypothesis that RAP agglomerations are pre-existing and generally do not form or breakdown

during production and (2) evaluate the potential for differences in RBC due to potential plant and laboratory variables that cannot be accounted for using sieve analysis alone. The latter was important to assess the generalizability of sieve analysis RBA results to reflect asphalt mixtures produced under variable conditions.

Asphalt binder and mixture sample fabrication and the tracer-based microscopy analysis followed the general recommendations of Pape and Castorena (*12*). The experimental procedure for the fabrication of asphalt mixtures for EDS analysis is shown in FIGURE 5. Titanium dioxide (TiO_2) nanoparticles were used as a tracer due to the necessity of differentiating the recycled binder from the virgin binder. The tracer content was 10 percent by mass of virgin binder. The blend was prepared using a high-shear mixer. Initially, the TiO_2 nanoparticles were added to the virgin binder and stirred for 1 min at a speed of 1,000 rpm. Then, the speed was increased to 5,000 rpm for an additional 9 minutes of mixing to obtain a homogenous binder. The virgin binder was heated to 155°C when mixing with the tracer. Small samples of the blended binder were poured into 25-mm diameter silicon molds which were stored in a freezer before being analyzed in the microscope. Recovered RAP binders were also imaged in the microscope. The sulfur content of RAP binders and both titanium and sulfur contents of the tracer-modified virgin binders were measured using energy dispersive x-ray spectroscopy (EDS) in a variable pressure scanning electron microscope (SEM).

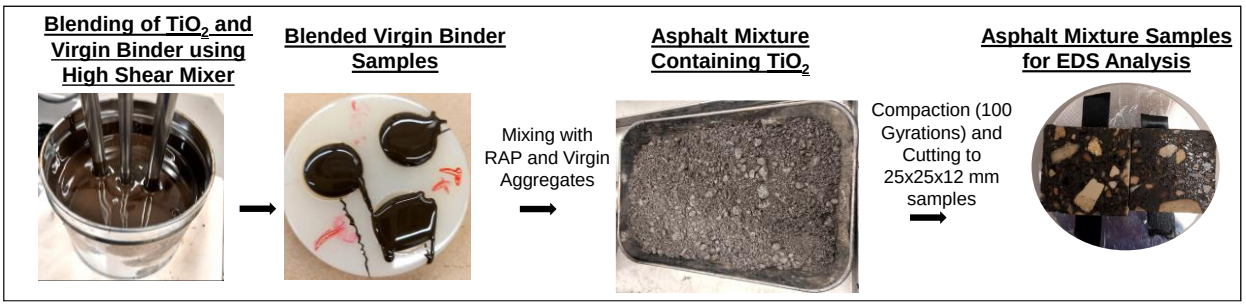

FIGURE 5 EDS analysis experimental procedure

There is no standardized procedure for preheating virgin materials and RAP when preparing laboratory-mixed, laboratory-compacted asphalt mixture samples. Therefore, a preheating procedure that is commonly employed in North Carolina was used to fabricate the laboratory-mixed samples of all study mixtures, termed the control procedure herein. Sources 1-NC, 4-WI, and 5-TX were also fabricated using additional preheating procedures and laboratory simulated silo storage. The control preheating procedure involves preheating the virgin aggregate to the target mixing temperature plus 10°C and preheating the virgin binder to the mixing temperature. The preheated aggregate was taken out of the oven and mixed with the dried, ambient-temperature RAP. The combined aggregates and RAP were returned to the virgin aggregate oven for 45 minutes before mixing.

After mixing, short-term aging was conducted for 2 hours, which aligns with AASHTO R 30. Gyratory-compacted samples approximately 4,500 g in mass were prepared with tracer-modified virgin binder according to AASHTO T 312. Then, the gyratory samples were cut using a saw to obtain prism specimens with dimensions of 25x25x12 mm and later polished following the procedure described by Pape and Castorena (*12*).

The three alternative preheating procedures evaluated include: (a) the same general process as the control procedure but with a 10°C increase in the mixing temperature, (b) the same general process as the control procedure but with the mixing temperature equal to 170°C, and (c) superheating virgin aggregate combined with room temperature pre-dried RAP to achieve the specified mixing temperature when combined. The virgin binder in the superheating procedure was heated to the specified mixing temperature.

Richmann's law of mixtures, detailed in Equation (6), was used to calculate the virgin aggregate superheating temperature that, when combined with ambient temperature RAP, would yield a mixture

temperature equal to the mixing temperature. Equation (6) was verified to yield reasonably accurate temperature estimates (within a few degrees) using an infrared thermometer to check the temperature of the RAP and virgin aggregate once combined.

$$T_m = \frac{\sum m_i \times c_i \times T_i}{\sum m_i \times c_i} \quad (6)$$

where: T_m = final temperature of the mixture, m_i = mass fraction of material i, c_i = specific heat capacity of material i, T_i = initial temperature of material i. For this analysis, the following specific heat capacities were assumed: aggregate (granite) = 0.79 kJ/kg·C, and RAP = 0.90 kJ/kg·C (consistent with (*13*)).

To simulate silo storage in the laboratory, loose mixture samples were prepared using the control procedure and then poured into a bucket, and then sealed. The sealed bucket was conditioned in the oven for 8 hours at compaction temperature. Despite the considerable variation in silo storage time, a conditioning period of eight hours was selected based on the recommendation provided by an asphalt plant. The samples were immediately compacted after 8 hours and thus the simulated silo storage samples were not subjected to conventional short-term aging in accordance with AASHTO R 30.

Quantitative Assessment of RBC

EDS analysis of the binders and mixtures was performed in a Hitachi S3200N VPSEM outfitted with an Oxford X-Max silicon drift detector. Optical observations and EDS maps were used in this study to detect the presence of RAP agglomerations and identify locations for the quantification of RBC.

FIGURE 6 shows three different views of the same region identified as a potential location for measuring the RBC. The first is the layered image with all of the selected elements shown, including Ca, K, S, Si, Al, and C in this example. The second image is a map of the distribution of Sulfur (S) only. In this image, areas with S appear bright orange and correspond to locations containing asphalt binder. The third image, representing the Titanium (Ti) map, appears bright yellow in areas containing Ti. Note that the less bright yellow areas indicate background noise and not the presence of Ti. While S is present wherever there is an asphalt binder, either recycled or virgin, titanium is only present in locations containing the virgin binder. Thus, regions such as the one shown in FIGURE 6 that contain S but no Ti coincide with agglomerations. Images containing agglomerations were omitted from the quantitative analysis since RBC reflects the proportion of total recycled binder contained within the virgin binder matrix.

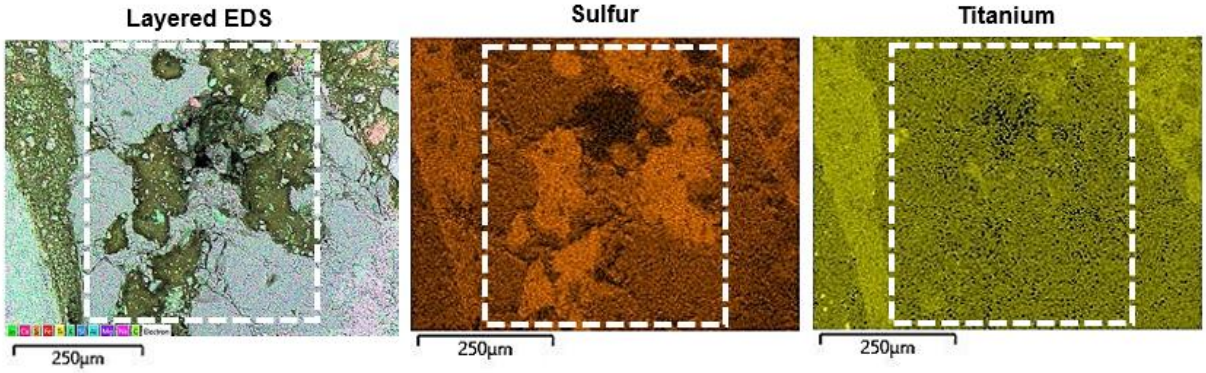

FIGURE 6 Example of visual observations of RAP agglomerations in asphalt mixture

To obtain the RBC of a given mixture, at least 10 microscopy measurements of the elemental composition were acquired at different locations within the mix (where agglomerations were absent) (*8*). The local RBC was determined at each site using Equation (7). Calculation of the RBC using Equation (7) considers the amount of recycled binder present in the image using the Ti:S ratios. These are compared to the theoretical level of the perfect contribution scenario to calculate the RBC. The average local RBC in the mixture is reported as the result.

$$\text{Local Recycled Binder Contribution (\%)} = \left(\frac{Virgin_{Ti:S}}{Mix_{Ti:S}} - 1\right) \times \frac{AC - RAP_{AC} - RAS_{AC}}{RAP_{AC} + RAS_{AC}} \times \frac{S_V}{S_R} \times 100\% \quad (7)$$

Where: Local Recycled Binder Contribution (%) = ratio of measured recycled binder concentration divided by the recycled binder concentration expected under the condition of complete contribution; $Virgin_{Ti:S}$ = titanium to sulfur concentration ratio in the virgin binder; $Mix_{Ti:S}$= Ti:S concentration ratio of mix sample in area of interest; AC = total asphalt content; RAP_{AC} = RAP binder content; RAS_{AC} =RAS binder content; S_v = sulfur content of the virgin binder; and S_R = sulfur content of the recycled binder.

The $Virgin_{Ti:S}$ values required to calculate the RBC using Equation (7) should reflect the Ti:S ratio in the mixture if it contained no recycled binder. Two methods of obtaining the $Virgin_{Ti:S}$ values were investigated (1) measuring S and Ti concentrations within tracer-modified virgin binder samples and (2) measuring the S and Ti concentrations in binder rich areas of virgin mixtures prepared with the tracer-modified binder and no RAP. Using the binder samples instead of virgin mixtures reduces the amount of time and material required. The $Virgin_{Ti:S}$ values of virgin binder and virgin asphalt mixture samples were equivalent for the North Carolina mixtures with low absorption. However, it was observed a substantial difference between the $Virgin_{Ti:S}$ values obtained from binder and mixture samples can occur in mixtures with more absorptive aggregate (i.e., Sources 4-WI, 5-TX and 7-ME). It was inferred that the tracer is not absorbed by aggregates, which affects the $Virgin_{Ti:S}$ measurements made in the effective binder matrix of the mixture. Therefore, virgin mixtures were prepared for Sources 4-WI, 5-TX, and 7-ME to obtain the $Virgin_{Ti:S}$ values while measurements from virgin binder samples were used for the remaining mixes.

Mixture Designs

Mocelin and Castorena proposed several changes to mixture design procedures to account for RAP agglomerations and RBA, termed Availability Adjusted Mix Design (AAMD) (*1*). AAMD differs from conventional mixture designs in two ways: (1) the RAP black curve rather than the white curve is used to design the aggregate structure because tracer-based microscopy suggests that RAP agglomerates function as black rocks, (2) the unavailable recycled binder bound within agglomerations is considered as part of the bulk aggregate volume when inferring the volumetric composition of the mixture. Including the unavailable binder in the bulk aggregate volume lowers the calculated Voids in Mineral Aggregate (VMA) and Voids Filled with Asphalt (VFA) compared to the current practice for the case of partial RBA. The changes to both the interpretation of the RAP gradation and volumetric composition also impact the calculated dust-to-effective binder ratio of a mixture. Collectively, the changes suggest that mixtures designed assuming 100 percent availability may yield an actual VMA that is smaller than the calculated VMA when assuming 100 percent RBA so that the actual, available VMA may fall below the acceptable limits. The amendment of Superpave mixture design for RBA according to the AAMD method is detailed in Mocelin et al. (*14*). Herein, volumetric properties calculated according to AASHTO R 35 are reported as the ‘specified’ properties whereas those calculated on the basis of RBA according to the AAMD method are termed the ‘available’ properties.

Five of the ‘control’ mixtures detailed in TABLE 1 were redesigned according to the AAMD method using the same RAP and virgin stockpiles but adjusting their proportions in the mixture. The performance of the control and AAMD mixtures were compared to evaluate the implications of incorporating RBA into mixture design procedures. TABLE 4 summarizes the control and redesigned mixtures in terms of the source and RAP content. Four of the control mixture designs were redesigned using the AAMD method while maintaining the same RAP content as the respective control mixture. In addition, three AAMD mixtures were prepared using higher RAP contents than the respective control mixture and two ‘comparative’ virgin mixture designs were prepared. Some of the NC mixture results are also reported in the final report for NCDOT RP 2021-06 (*15*), which were leveraged as cost share herein.

TABLE 4 Summary of the Control and AAMD Mixtures

ID	Control Mixture RAP Content	AAMD Mixture RAP Content(s)
1-NC	30	0, 30, 50
4-WI	40	40
7-ME	20	40
8-NC	40	0, 40
9-NC	35	35, 50

The AAMD method can be used as a stand-alone mix design method for new mixtures without the need for a prior control mixture design. To redesign the RAP mixtures herein, the virgin stockpile proportions were adjusted to yield a blend gradation when using the RAP black curve that is close to the existing mixture gradation prepared using the RAP white curve. These adjustments were achieved by decreasing coarse aggregate stockpile proportions and increasing fine stockpile proportions. This approach generally yielded a satisfactory available VMA based on the majority of cases evaluated, often similar to the specified VMA for the control mixture. In cases it did not, additional trial aggregate blends were prepared and evaluated. In all cases, samples were prepared using the trial aggregate blend at four asphalt contents and used to select the optimum asphalt content that yielded four percent air voids at the design compaction level. Note that RBA does not affect the interpreted air void content of the asphalt mixture.

The virgin binder used for the AAMD mixtures prepared at the control RAP content was the same as the respective control mixtures. For the AAMD mixtures prepared at higher RAP content than the respective control, the virgin binder selected was one grade lower than the respective control mixture to achieve a similar available blended binder performance grade (e.g., PG 58-28 was used if the control mix with lower RAP content used a PG 64-22 and PG 52-34 if the control mixture with lower RAP content used a PG 58-28).

The comparative virgin mixture designs were prepared to achieve equivalent available volumetric properties to the respective AAMD mixtures with the control RAP content. These virgin mixture designs were prepared to enable a direct assessment of the performance of virgin and RAP containing mixtures that are volumetrically equivalent according to the AAMD method. This was achieved by adjusting the virgin aggregate stockpile proportions to yield gradations that provided similar available binder content and VMA to the respective AAMD mixture from the same source. In addition, the virgin binder for the comparative virgin mixtures were selected with AASHTO M 320 HPGs that were very similar to the estimated HPGs of the effective binder matrix in the respective AAMD mixture. The HPGs of the effective binder matrix in the AAMD mixtures were estimated using blending charts under the assumption of complete blending between the available recycled binder and the virgin binder, according to AASHTO M 323. Equation (8) shows the calculation of the critical temperature of the total binder blend according to AASHTO M 323 and Equation (9) shows how the equation was amended to align with the AAMD method.

$$T_{blend} = T_{virgin} \times (1 - RBR) + T_{RAP} \times RBR \tag{8}$$

$$Available\ T_{blend} = T_{virgin} \times (1 - Available\ RBR) + T_{RAP} \times Available\ RBR \tag{9}$$

where: T_{blend} = critical temperature of the total binder blend, T_{virgin} = critical temperature of the virgin asphalt binder, RBR = recycled binder replacement ratio, T_{RAP} = critical temperature of the RAP binder, $Available\ T_{blend}$ = critical temperature of the available binder blend, and $Available\ RBR$ = effective recycled binder replacement ratio, equal to the available recycled binder content by weight of total mixture divided by the total available binder content by weight of total mixture.

A naming convention was adopted to represent each of study mixture, with three sections:

- Section 1: a letter representing the material's ID number.
- Section 2: state abbreviation for the material source (ME, NC, or WI)

- Section 2: the percentage of RAP in the mix (%RAP).
- Section 3: the experimental classification of the mix (C for the control mixtures; AAMD for mixtures redesigned following the AAMD method; or E for the comparative virgin mixtures designed with equivalent properties to the AAMD mixtures with RAP).

As an example, the control mixture from Source 1-NC with 30% RAP is named 1-NC-30-C.

Laboratory Performance Tests

IDEAL CT tests were used to measure the cracking tolerance index (CT_{index}) of all study mixture designs according to ASTM D8225. A minimum of three test specimens with 150-mm diameter and 62-mm height were fabricated and tested with 7 ± 0.5 percent air voids.

APA tests were used to assess the rutting resistance of all study mixture designs from North Carolina, according to AASHTO T 340 and NCDOT specifications. The tests were conducted at 64°C on two sets of two specimens for each mixture. The test results are reported as the average rut depth after 8,000 load repetitions. The APA specimens were fabricated with 4 ± 0.5 percent air voids and with 150-mm diameter and 75-mm height.

Hamburg Wheel Track Tests (HWTTs) were utilized to assess the rutting resistance of mixtures 4-WI and 7-ME because the HWTT is specified in those states. The test was carried out in accordance with AASHTO T 324. HWTT specimens were compacted to a height of 62 mm, and then cut at the edges. The specimens were fabricated with an air void content of 7 ± 0.5 percent and submerged in water at 46°C and 45°C for sources 4-WI and 7-ME, respectively, in accordance with the respective state specifications. Given the potential influence of stripping on HWTT results, and considering that this study does not encompass an assessment of the mixture's resistance to this specific distress, the Corrected Rutting Depth (CRD) proposed by Yin et al. (*16*) was employed as an alternative to the total rutting depth for evaluating rutting resistance. CRD has proven effective in isolating the rut depth attributable to permanent deformation of the mixture from that induced by the stripping of asphalt binder from the aggregates, and a good correlation with field data has been observed (*16*). To calculate CRD, the entire rut depth curve is initially fitted with a three-parameter deformation model given in Equation (10). This fitted curve comprises two distinct segments: one characterized by negative curvature followed by another exhibiting positive curvature. The point at which the curvature transitions from negative to positive curvature is defined as the Stripping Number (SN), marking the onset of stripping in the mixture. Subsequently, the rut depth data up to the Stripping Number (SN) is fitted with the modified Tseng-Lytton model given in Equation (11) and utilized to extrapolate rut depth values beyond SN.

$$RD = \rho\left[\ln\left(\frac{N_{ult}}{N}\right)\right]^{-\frac{1}{\beta}} \tag{10}$$

where: RD = rut depth, N = number of wheel passes, and N_{ult}, ρ, and β = model coefficients.

$$RD = RD_{ult}e^{\left(\left(-\frac{\alpha}{N}\right)^{\gamma}\right)} \tag{11}$$

where: RD_{ult}, α and γ = model coefficients.

It is worth noting that this property is presently being considered by WisDOT for potential inclusion in Balanced Mix Design (BMD) specifications (*17*). No HWTT criteria or recommendations pertaining to the removal of moisture-induced damage from rutting depth results were identified for MaineDOT. The CRD was calculated and reported for all Source 4 and 7 mixtures.

In all cases, samples were short-term aged as per AASHTO R 30 for 4 hours at 135°C prior to compaction. One-way analysis of variance (ANOVA) tests were used to support the observations and conclusions of the index test results for all the relevant pairwise comparisons of each mixture source. It is noted that Asphalt Mixture Performance Tester (AMPT) testing was also carried out for the Source 1 and 9 mixtures as part of NCDOT RP 2021-06. The results are presented elsewhere (*15*).

Results

RBA Results from Sieve Analysis

Summary of the Collective RBA Results

FIGURE 7 shows the RBA results of all procedures investigated. The 100°C BC was measured for all RAP sources, which is the considered the control procedure. The control procedure yielded RBA results spanning from 44 to 62 percent for the 11 stockpiles evaluated with an average of 55 percent. A slightly higher average RBA result of 63 percent was observed by Pape and Castorena (*6*) wherein the RBA was assessed for four RAP sources. The span of RBA results observed by Pape and Castorena (*6*) spanned from 50 and 85 percent. In both studies, the results suggest that the assumption of 100 percent RBA that forms the basis of the majority of mixture design procedures is erroneous. Furthermore, the average RBA obtained through the proposed methodology is close to the fixed value of 60 percent availability utilized in the corrected optimum asphalt content (COAC) method implemented by the Georgia department of transportation (*18*).

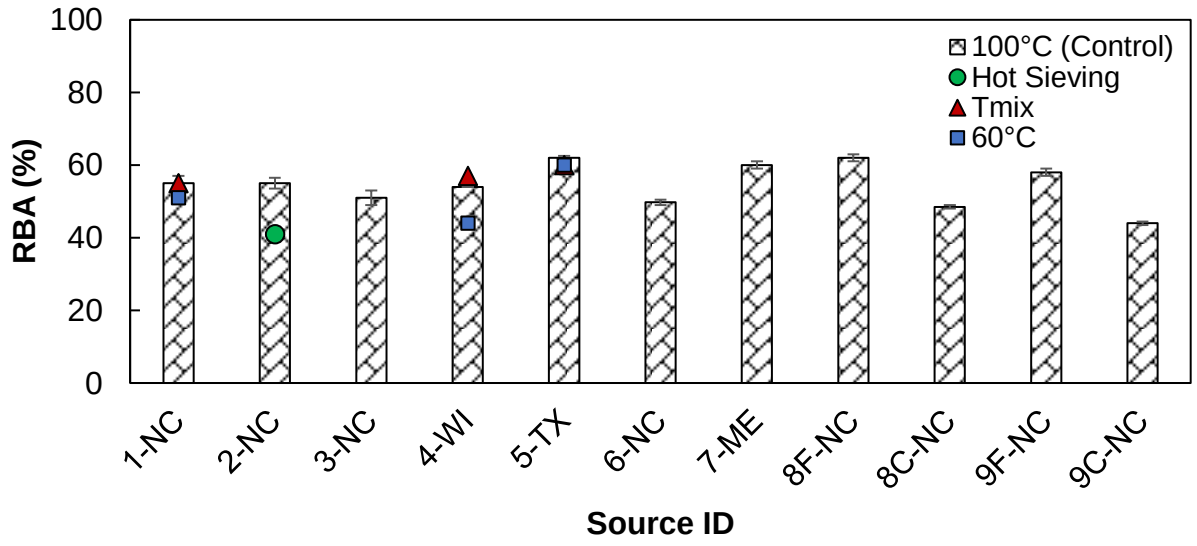

FIGURE 7 RBA results from sieve analysis (error bars reflect the standard error)

FIGURE 7 shows that the hot sieving condition where the RAP was sieved at the compaction temperature led to a lower RBA than the control procedure. This decline in RBA can be attributed to the agglomeration of additional RAP particles, which occurs due to the annealing of the RAP binder. It is noteworthy to mention that these agglomerations might not accurately replicate the events that occur in an asphalt plant, as the RAP is typically blended with virgin aggregates. This blending prevents RAP particles from coming into contact and agglomerating to the extent that occurs when the RAP is heated and mixed alone.

FIGURE 7 shows that the 60°C, 100°C, and T_{mix} scenarios, wherein the preheating temperature of the RAP differed but the RAP was always sieved at ambient temperature, resulted in similar RBA results with one exception. The RBA results of the Source 4-WI RAP obtained from the 60°C preheating temperature resulted in a lower RBA than the other conditions evaluated. Please note the 60°C BC was obtained without washing unlike the 100°C and T_{mix} scenarios. Additionally, a single RAP source was washed for 8, 10, and 15 minutes using an automatic washer which resulted in RBA values of 53, 53, and 55 percent, respectively. It is noted that the RBA for replicate samples analyzed with the same washing time also commonly differ by two percent. Therefore, it is concluded that a time of 8 to 10 minutes is reasonable when using an automatic washer. AASHTO T 30 recommends washing recovered RAP aggregates for no longer than 10 minutes and thus, it appears that similar guidance can be adopted for

washing RAP. The effects of RAP source and preheating temperature are further evaluated in the subsequent sections through the evaluation of the BC and WC gradations and visual observations of the samples.

Control Procedure Gradations

The 100°C BC along with its respective WC were measured for all sources. The BCs and WCs obtained following the 100°C BC procedure are shown in FIGURE 8, FIGURE 9, and FIGURE 10. The coarser curve corresponds to the BC and the finer curve corresponds to the WC. FIGURE 8 shows the BCs and WCs of RAP stockpiles with RBA lower than 50 percent (Sources 6-NC, 8C-NC, and 9C-NC). FIGURE 9 shows the gradations for the RAP stockpiles with RBA between 50 percent and 60 percent (Sources 1-NC, 2-NC, 3-NC, and 9F-NC). FIGURE 10 shows the gradations for the RAP stockpiles with RBA equal or above 60 percent (Sources 4-WI, 5-TX, 7-ME and 8F-NC). In all cases, the RAP is much coarser than the recovered aggregate, especially at the finest sieves. Furthermore, the black curves exhibit minimal material passing the No. 200 sieve for all cases, supporting the hypothesis that all RAP particles contain a mastic coating.

The Source 8F-NC (i.e., fine fraction of the Source 8-NC RAP) had the highest RBA while the Source 9C-NC (i.e., coarse fraction of the Source 9-NC RAP) had the lowest RBA of all sources evaluated. By comparing Source 8F-NC versus Source 8C-NC and Source 9F-NC versus Source 9C-NC, it is evident that fine RAP has higher RBA than the coarse RAP crushed from the same source millings.

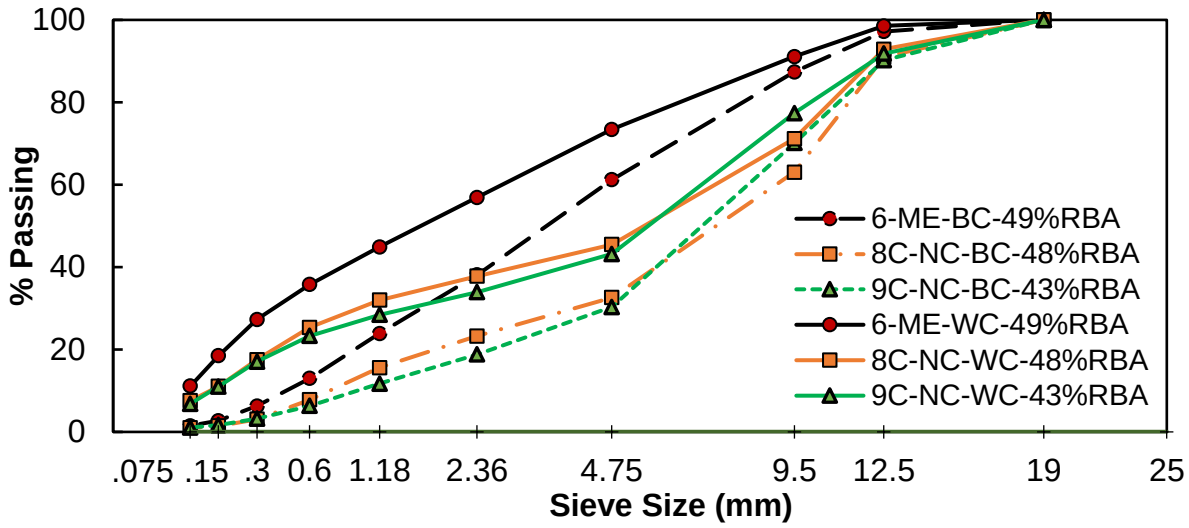

FIGURE 8 BC and WC for sources below 50 percent RBA (6, 8C, and 9C)

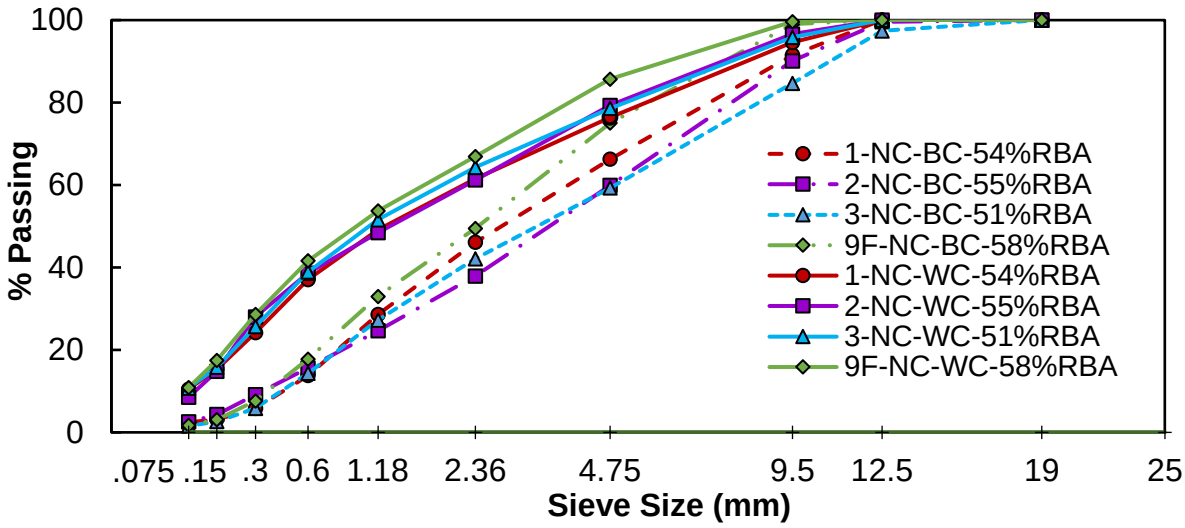

FIGURE 9 BC and WC for sources with RBA between 50 and 60 percent (1, 2, 3, and 9F)

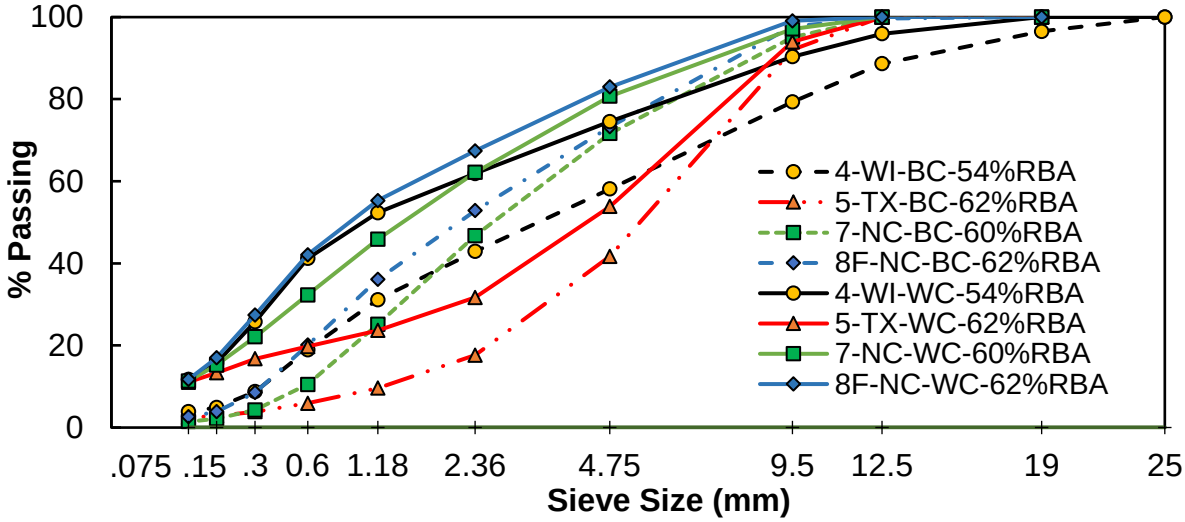

FIGURE 10 BC and WC for sources with RBA equal or above 60 percent (4, 5, 7 and 8F)

FIGURE 11 shows comparisons of the individual percent retained values for all the BC and WC gradations obtained using the control procedure. These plots provide another means to assess the impact of the RAP agglomerations on gradation. The BC has a greater percentage of the material retained on the coarser sieves while the WC has significantly more material retained on the finer sieves. Similar trends were observed for all RAP sources evaluated in this study, showing evidence of RAP agglomerations in all sources before mixing. Interestingly, FIGURE 11 indicates that the differences in individual percent retained values at the finest sieve sizes for the black and white gradations is greater for the fine rather than coarse stockpile crushed from the same source millings (i.e., by comparison (h) vs. (i) and (j) vs. (k)). Thus, initially, by only inspecting the gradation results alone a lower RBA may be expected. However, due to the overall gradation of the coarse versus fine stockpiles, the coarse stockpiles have a greater percentage of the total mastic volume contained within the fine sieve sizes (due to the higher proportion of the aggregate surface area contained), thus yielding a higher percentage of the total mastic that is deemed unavailable for a given differences in the percent retained on a given sieve fine size. There does not appear to be a general trend in RBA among collective fine versus coarse stockpiles from different sources. While Source 5-TX is also a coarse RAP, it exhibits notably higher RBA compared to Sources 8C-NC and 9C-NC. This observation is consistent with many of the fine RAP sources.

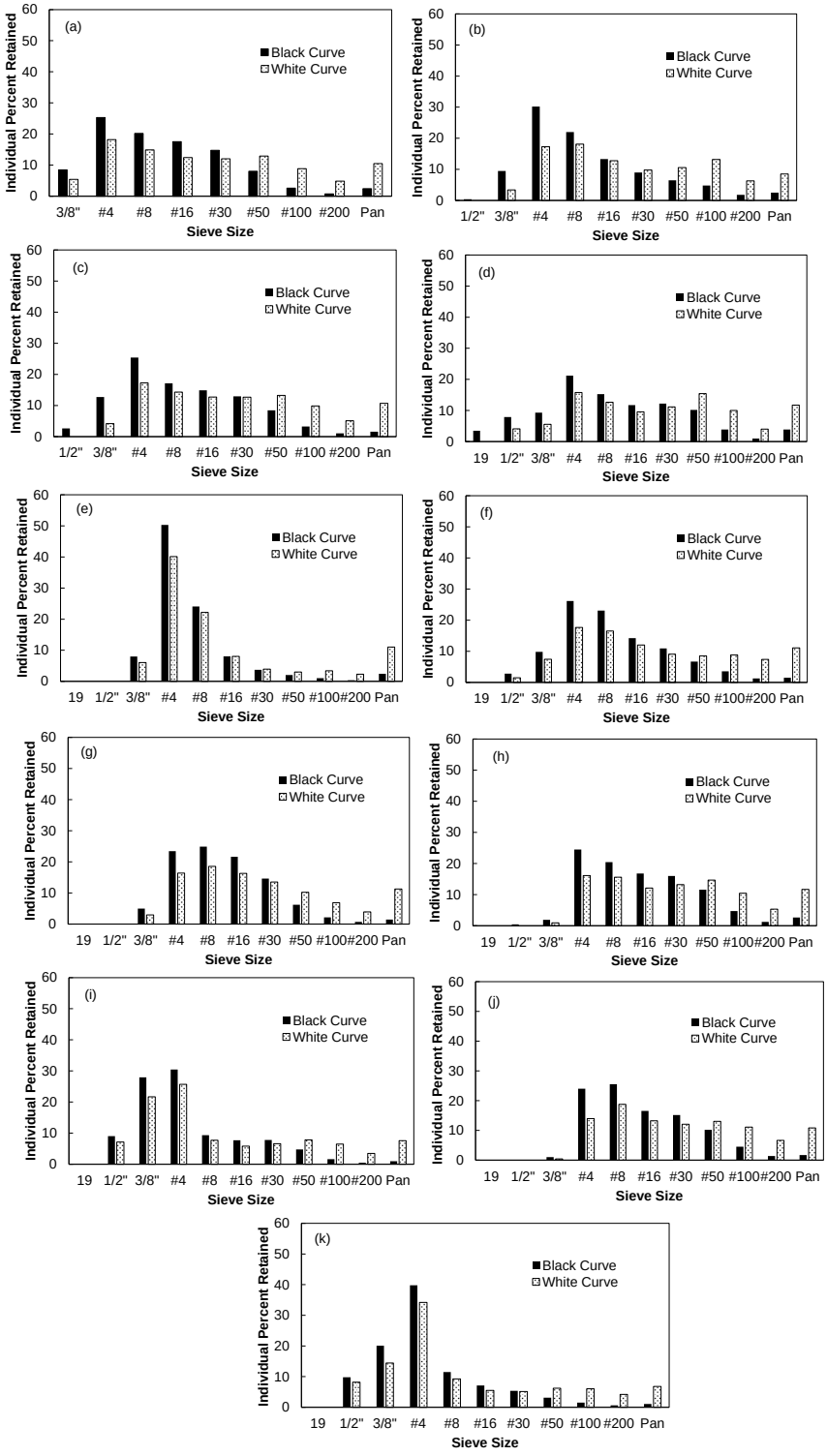

FIGURE 11 Black and white curves percent retained comparison for Sources: (a) 1-NC, (b) 2-NC, (c) 3-NC, (d) 4-WI, (e) 5-TX, (f) 6-NC, (g) 7-ME, (h) 8F-NC, (i) 8C-NC, (j) 9F-NC, and (k) 9C-NC

Evaluation of Temperature Effects

FIGURE 7 shows that the preheating temperature of the RAP resulted in similar RBA results with one exception. To further evaluate preheating temperatures, visual observations of the RAP samples were

made and the BCs were compared. FIGURE 12, FIGURE 13, and FIGURE 14 present visual representations of the RAP samples at distinct stages: (a) when in a dry state at 25°C but previously heated at 60°C during drying, (b) subsequent to washing and drying at 100°C, and (c) following conditioning to the mixing temperature for Sources 1-NC, 4-WI, and 5-TX, respectively. In each case, a noticeable escalation in binder activity was visually observed with the increase in temperature despite the relatively small effect of temperature on the RBA results. Particularly noteworthy is the observation in Source 5-TX, where some agglomerations exhibited signs of melting.

(a) (b) (c)

FIGURE 12 Sources 1-NC samples at (a) 25°C, (b) 100°C, and (c) 152°C

(a) (b) (c)

FIGURE 13 Source 4-WI samples at (a) 25°C, (b) 100°C, and (c) 146°C

(a) (b) (c)

FIGURE 14 Source 5-TX samples at (a) 25°C, (b) 100°C, and (c) 152°C

During the manual separation of weak agglomerations at 100°C and T_{mix}, it became apparent that very few agglomerations broke for Source 1-NC samples, while a significantly greater number of agglomerations broke for Source 4-WI samples. Given that these agglomerations were easily broken by manual separation, they are also expected to break during mixture production and thus, heating beyond 60°C is deemed necessary. Upon closer examination, it became apparent that the agglomerations exhibiting sensitivity to conditioning temperature in the samples from both Sources 1-NC and 4-WI were

rich in binder and their internal composition consisted exclusively of fine particles, as illustrated in FIGURE 15. The binder of these binder-rich agglomerations became soft and consequently, the agglomeration exhibited a propensity to easily break upon heating. This finding suggests that the sensitivity of the agglomerations to temperature depends on their internal structure. Additionally, it was also observed that these agglomerations often fragmented into smaller-sized agglomerations rather than returning to their original particle size. The propensity for the agglomerations to break appeared similar visually at 100°C and T_{mix} for the Source 1-NC and Source 4-WI materials.

FIGURE 15 Fragmented binder-rich agglomerations from Source 4(WI)

In contrast, the Source 5-TX agglomerations demonstrated distinct behavior upon conditioning at T_{mix} compared to Sources 1-NC and 5-WI. A notable visual observation was the prevalence of agglomeration formation rather than breakage, attributed to the activation of the available RAP binder in certain particles. Consequently, these particles started adhering to one another, giving rise to the formation of agglomerations, as depicted in FIGURE 16. However, these agglomerations were weak and easily broken manually. Thus, the new agglomerations are not expected to persist during mixture production. Therefore, it is important to separate these new agglomerations to accurately quantify RBA. It is vital to emphasize that the formation of such new agglomerations may not occur when the RAP is incorporated into the asphalt mixture because the active binder will also interact with adjacent virgin aggregates and binder that prevent contact with other RAP particles. Heating the RAP to 100°C rather than T_{mix} helps mitigate the formation of these weak agglomerations.

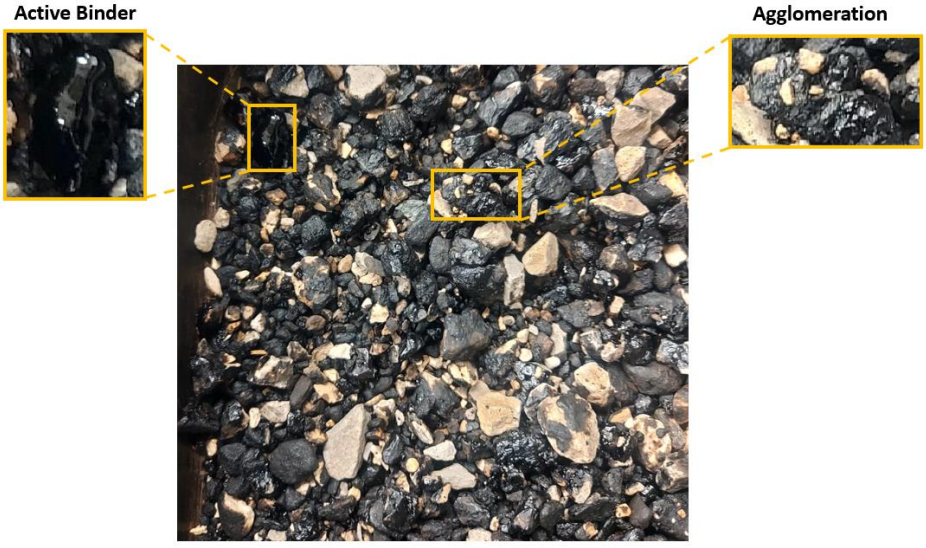

FIGURE 16 RAP particles from Source 5-TX agglomerating after conditioned at mixing temperature

FIGURE 17, FIGURE 18, and FIGURE 19 show the comparisons between the BCs obtained

using the different preheating temperatures for Sources 1-NC, 4-WI, and 5-TX, respectively. Please take note that the T_{mix} BC was obtained after acquiring the 100°C BC from the same sample. As a result, the observed change in gradation cannot be exclusively ascribed to temperature variations; it is also indicative of the sample undergoing a secondary conditioning process, involving the breaking of agglomerations once again.

For Source 1-NC, the T_{mix} BC resulted in a slightly finer gradation when compared to 60°C BC and 100°C BC. However, the changes in gradation were marginal and did not have any impact on RBA which shows that 100°C was hot enough to break the majority of the weak agglomerations. A more pronounced change was observed among the three BCs evaluated for Source 4-WI where the T_{mix} BC was the finest. However, the alterations in gradation resulted in only a three percent increase in RBA when comparing 100°C RBA and T_{mix} RBA. Notably, when Source 4-WI was not subjected to washing and heating (i.e., 60°C BC), the BC was significantly coarser, leading to a 10 percent decrease in RBA as shown in FIGURE 18. The observed changes in RBA for Source 4-WI align with the visual observations that indicated a greater number of agglomerations breaking after heating for this particular source, which may be due to a second round of manual breaking of the agglomerations and/or the increase in temperature.

In the case of Source 5-TX, minimal changes in the BC were observed among the scenarios evaluated. However, unlike Sources 1-NC and 4-WI, the T_{mix} BC became slightly coarser due to the formation of agglomerations when this source was heated to the mixing temperature as shown in FIGURE 16. Moreover, the 60°C BC was the coarsest among the three gradations, indicating that few agglomerations were broken in the process of washing and heating. However, in general, the agglomerations from Source 5-TX demonstrated insignificant sensitivity to washing and heating.

In all instances, preheating the RAP to the mixing temperature before sieving had a marginal impact on the RBA compared to preheating it at 100°C. This suggests that the increase in temperature primarily corresponds to a rise in recycled binder activity rather than a significant enhancement in RBA. The only notable case where a substantial difference was imparted by the RAP sieving procedure was observed in the 60°C BC from Source 4-WI, indicating that the RBA of this source was influenced by the washing and subsequent preheating processes and the disruption of agglomerates prior to sieving the RAP. Although the T_{mix} BC resulted in a higher RBA for this source, as there was not a significant disparity noted in the ability to disintegrate agglomerations between the 100°C and T_{mix} conditions, the observed shift in gradation could be attributed to a subsequent round of agglomeration breakage and not only to the temperature itself. Given the notable prevalence of temperature-sensitive agglomerations in Source 4-WI, it is plausible to assume that the sample cooled down before achieving complete breakage for the measurement of the 100°C BC.

Different from Source 4-WI, for Sources 1-NC and 5-TX, solely performing the dry sieve analysis of the RAP would provide a satisfactory indication of their RBA. Simultaneously, conditioning the RAP at the mixing temperature (T_{mix} BC) resulted in the activation of the binder in Source 5, leading to the formation of additional agglomerates rather than the intended breakage of existing agglomerates. Reflecting that 60°C proved insufficient for the required agglomeration breakage in Source 4-WI and that T_{mix} induced binder activation for 5-TX, the control procedure emerges as the most effective approach overall where the temperature is hot enough to break the agglomerations but too cold to cause significant binder activation.

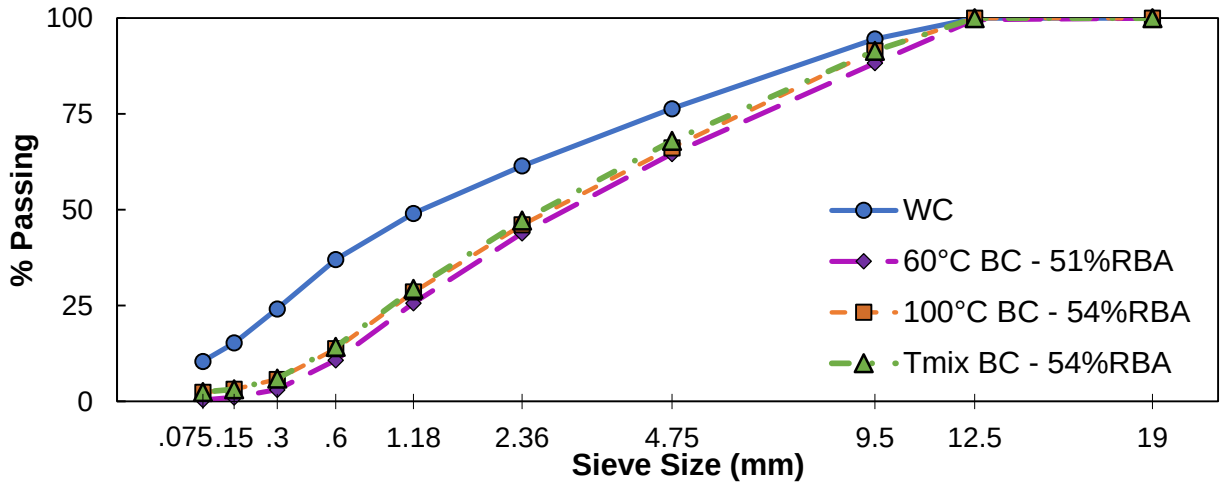

FIGURE 17 Source 1-NC 60°C, 100°C, and T_{mix} black curves with their correspondent WC

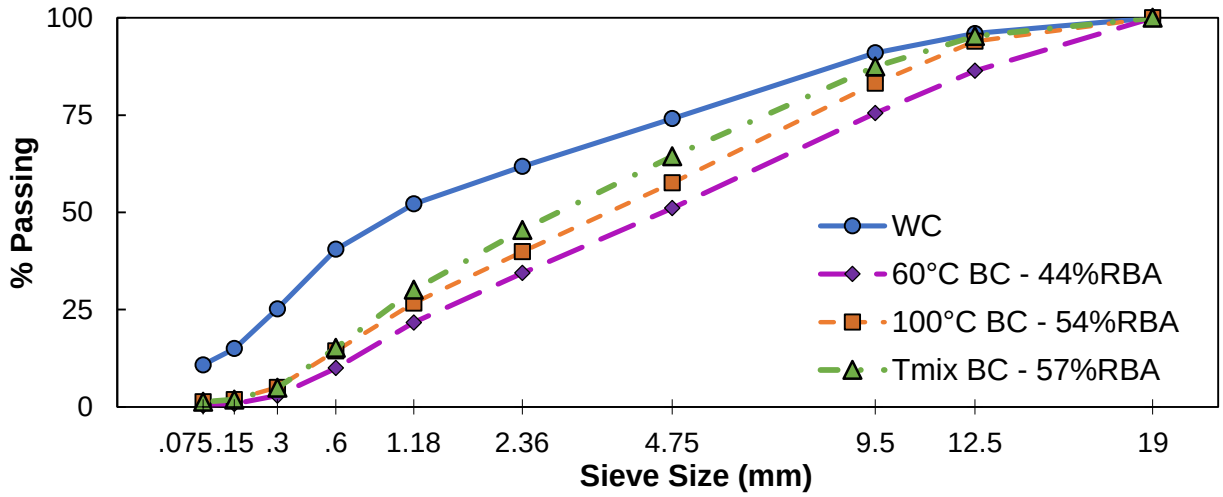

FIGURE 18 Source 4-WI 60°C, 100°C, and T_{mix} black curves with their correspondent WC

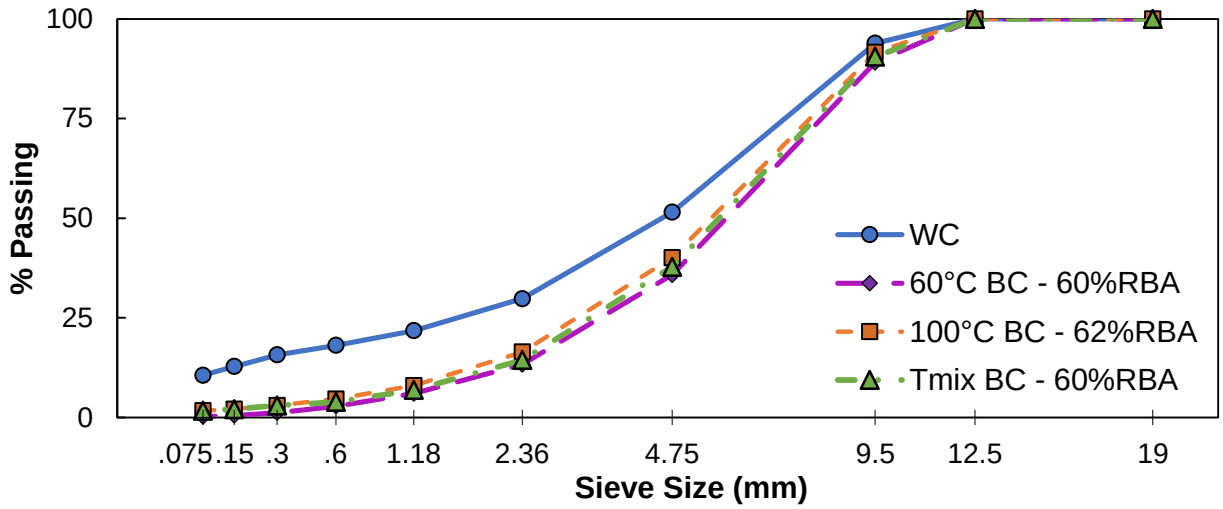

FIGURE 19 Source 5-TX 60°C, 100°C, and T_{mix} black curves with their correspondent WC

Tracer-based Microscopy Results

Control Fabrication Procedure

Tracer-based microscopy was conducted on mixtures prepared for all RAP sources using the control fabrication procedure to evaluate the ability of RBA measurements to reflect RBC in asphalt mixtures. RAP agglomerations were observed via tracer-based microscopy in all mixtures evaluated, consistent with past studies (*5-8*, *12-13*). The local RBC measurements vary within a given mixture sample but no clear trends with increasing distance from a RAP agglomeration were observed. Partial binder diffusion would yield a decreasing RAP binder concentration with increasing distance from the RAP particle surface. However, the observed heterogeneity was random. Thus, the microscopy analysis suggests that partial RBA is a consequence of RAP agglomerations rather than partial binder diffusion.

RBC results ranged from approximately 44 to 66 percent for the different nine mixtures. These results indicate that complete RBC is not achieved when fabricating asphalt mixtures samples in the laboratory and highlight that an assessment of RBA is critically needed. Additionally, the microscopy results suggest that different mixture sources can yield different RBC values.

FIGURE 20 shows a comparison between the RBC results from tracer-based microscopy and the control procedure RBA results from sieve analysis. All mixture RBC results shown in FIGURE 20 correspond to specimens fabricated using the control procedure. FIGURE 20 includes the results of past research that investigated four fine RAP sources from North Carolina (*6*). The past research implemented the control asphalt mixture fabrication and 100°C sieve analysis procedures used herein. FIGURE 20 demonstrates a strong correlation (R^2 = 0.70) between the control (100°C) sieve analysis procedure and RBC for the study materials and similar agreement when the results of past research are combined with those acquired in this study (R^2 = 0.74). Moreover, the results are centered along the line of equality (slope = 1.025 for the study materials) suggesting calibration of the RBA calculation procedure to yield accurate RBC is unnecessary. The greatest differences observed between control RBA and RBC values in this study were 8 and 6 percent for Sources 2-NC and 7-ME, respectively. The average difference between RBA and RBC results when using the control procedure was 3 percent. The impact of these differences on the inferred effective binder content of a high RAP content (30 to 50 percent) would be negligible (less than 0.1 percent). Accordingly, these results are in agreement with the ones found by Pape and Castorena (*6*) and support the use of the sieve analysis to quantify RBA.

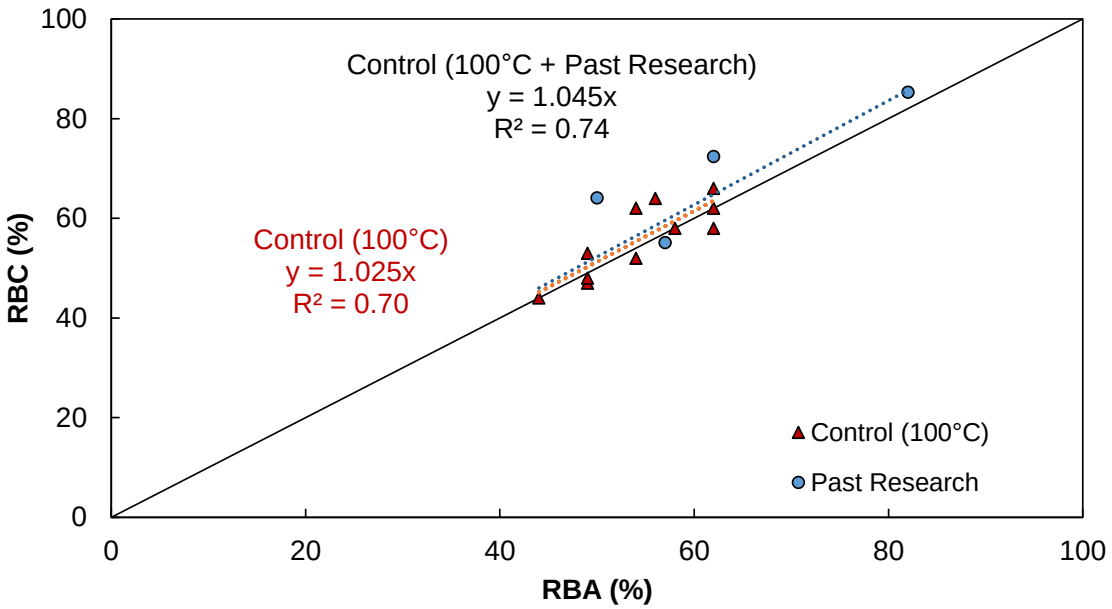

FIGURE 20 Comparison between RBA results from sieve analysis and RBC results from tracer-based microscopy analysis of asphalt mixtures

Comparison of the Alternative Fabrication Procedures

RBC measurements were also used to evaluate the potential impacts of temperature and conditioning on DoA. This evaluation was important to assess if RBA measurements can be used to estimate the RBC in asphalt mixtures produced under variable conditions. FIGURE 21 shows the effect of mixing temperature, the use of superheating virgin aggregates as opposed to preheating both RAP and virgin aggregate, and simulated silo storage on the RBC for mixtures produced using Sources 1-NC, 4-WI, and 5-TX. FIGURE 21 shows that different preheating procedures and simulated silo storage yielded very small differences in RBC, suggesting little variation in DoA or RBA among the production conditions evaluated. Tukey's HSD (Honest Significance Difference) tests were used to evaluate the significance of differences in RBC imparted by variations in the laboratory fabrication procedure. A confidence level of 95 percent was used in the Tukey's HSD tests. In all cases, the p-values are much higher than 0.05, with 0.62 as the minimum. Thus, the fabrication procedures had a statistically insignificant effect on the mean RBC for a given mixture. These results support the hypothesis that agglomerations generally do not form or break apart during production undermining the use of sieve analysis to quantify RBA. Furthermore, the lack of sensitivity of RBC to the laboratory production variables indicates that DoA in the asphalt mixtures did not vary substantially with the mixing temperature or conditioning procedure.

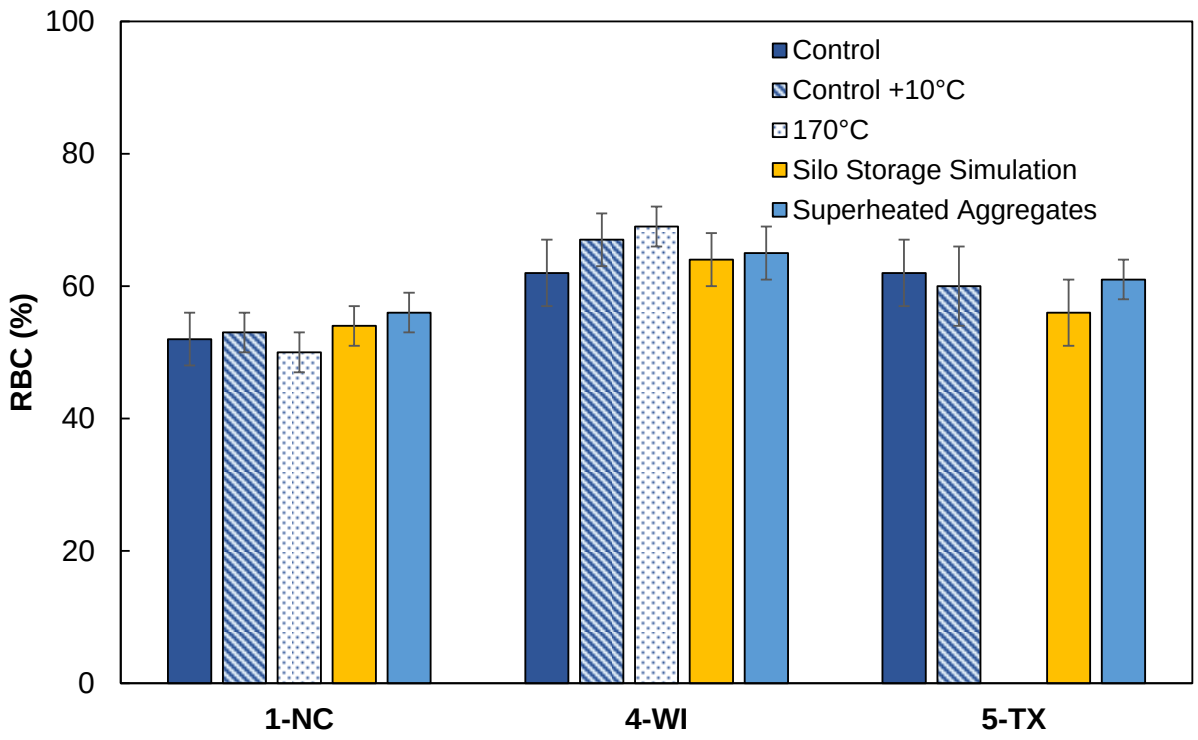

FIGURE 21 Effect of fabrication procedures on RBC (error bars reflect standard errors)

Pape and Castorena (*13*) used the same tracer-based microscopy method but different asphalt mixtures and observed that superheating the virgin aggregates and combining them with room temperature RAP can impact RBC compared to conventional, laboratory preheating procedures. However, superheating only imparted a statistically significant difference when it invoked an excessive RAP temperature of 188°C, which greatly exceeded the mixing temperature. In the case of this study, the virgin aggregate superheating temperature was selected to yield a RAP temperature equal to the mixing temperature upon mixing.

DoA Results from ITS of 100 percent RAP specimens

The ITS-based DoA experiments were used to further evaluate temperature effects and potential sources of variation in the DoA. FIGURE 22, FIGURE 23, and FIGURE 24 show the DoA experiment results for Sources 1-NC, 4-WI, and 5-TX, respectively. A consistent trend was observed across all sources, indicating that the ITS, and consequently the DoA, increased as the temperature rose from 100°C to 140°C, confirming the visual observations from the sieve analysis experiments. In contrast, FIGURE 22(a) and FIGURE 23(a) show that the alteration of the conditioning temperature from 140°C to 155°C had no discernible impact on the ITS and air voids of Sources 1-NC and 4-WI. Conversely, a notable decrease in ITS along with an increase in air voids were observed for Sources 1-NC and 4-WI when the material was conditioned at 170°C. This observation aligns with similar findings reported in the existing literature. Epps et al. (*9*) and Menegusso et al. (*11*) both noted an initial increase in ITS up to an optimum temperature, dependent on the RAP source, followed by a subsequent decrease. In most cases, the increase in ITS with temperature was observed until either 140°C or 170°C. This upward trend can be attributed to the fact that the viscosity of the binder at 70°C and 100°C is excessively high, impeding the activation of the RAP binder. Epps et al. (*9*) proposed that the decline in ITS at high temperature is likely a result of the RAP particles' inability to adhere to one another due to the hardening of the material after being subjected to high conditioning temperatures. However, it is crucial to acknowledge that aging the RAP for four hours at 170°C in the oven may not accurately replicate production conditions where any

extended conditioning at elevated temperature (e.g., silo storage) would occur after the RAP is mixed with the virgin materials.

In the case of Source 5-TX, the average ITS exhibited an average increase with rising conditioning temperature; however, the error bars indicate that no statistically significant difference exists among 140°C, 155°C and 170°C measurements. It is noteworthy that, this particular source exhibited only marginal variations in air voids among the specimens conditioned at different temperatures except with the exception of 100°C. This suggests that there was no significant improvement in workability between 140°C and 170°C for this source. Additionally, unlike Sources 1-NC and 4-WI, no decrease in ITS was observed for Source 5-TX at 170°C.

FIGURE 22(b), FIGURE 23(b), and FIGURE 24(b) present the calculated DoA for Sources 1-NC, 4-WI, and 5-TX, respectively. The DoA values were determined by dividing the ITS values of each RAP source by the maximum ITS recorded across multiple conditioning temperatures. As the temperature increased from 70°C to 140°C, the DoA showed a significant increase from 60 to 100 percent for Source 1-NC, and from 54 to 100 percent for Source 4-WI. However, between 140°C and 155°C, no significant change in DoA was observed for Sources 1-NC and 4-WI, as the DoA remained approximately 100 percent at 155°C. In contrast, a notable decrease in DoA was evident at 170°C.

Source 5-TX exhibited average DoA values of 55 percent, 80 percent, 92 percent, and 100 percent at temperatures of 100°C, 140°C, 155°C, and 170°C, respectively. Notably, there is a consistent increase in average DoA as the temperature rises. However, due to the lack of statistical significance in the differences between the DoA measurements for 140°C, 155°C, and 170°C, it is not possible to conclusively establish an increase in DoA between these temperature for Source 5-TX. It is essential to highlight that the specimens from this source showed greater visual variability and had a lower effective binder content, which might have contributed to the increased variability observed in the results.

Overall, there were no noticeable variations observed in the DoA of Sources 1-NC and 4-WI when comparing the samples conditioned at 140°C and 155°C. Similarly, no discernible differences were observed for Source 5-TX between the temperatures of 140°C, 155°C, and 170°C. These results imply that there is no singular optimal temperature that provides maximum DoA for a given RAP source, but rather an optimal temperature range that appears to align with typical mixture production temperatures. When the temperature falls below this range, the viscosity of the binder is higher precluding full activation (*9*). Conversely, prolonged conditioning at temperatures exceeding this range result in the aging and hardening of the binder, thereby diminishing its DoA.

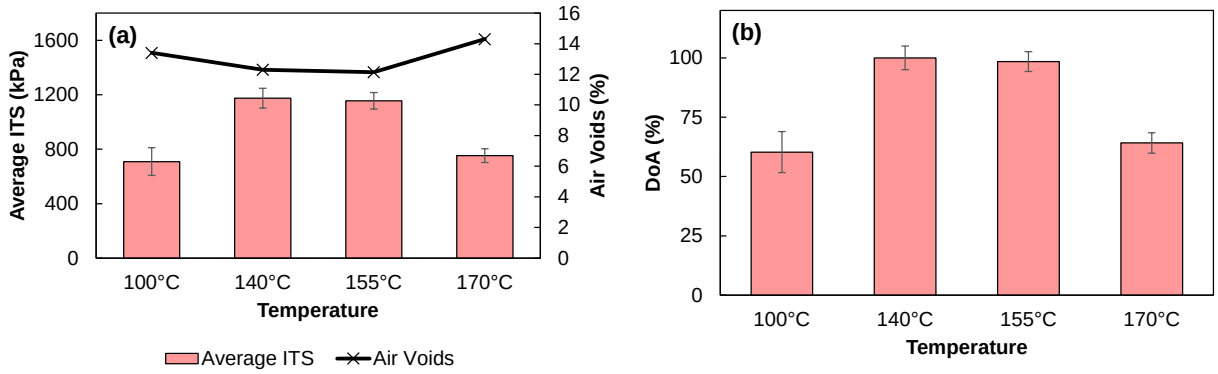

FIGURE 22 Source 1-NC (a) average ITS and air voids measurements, and (b) DoA results

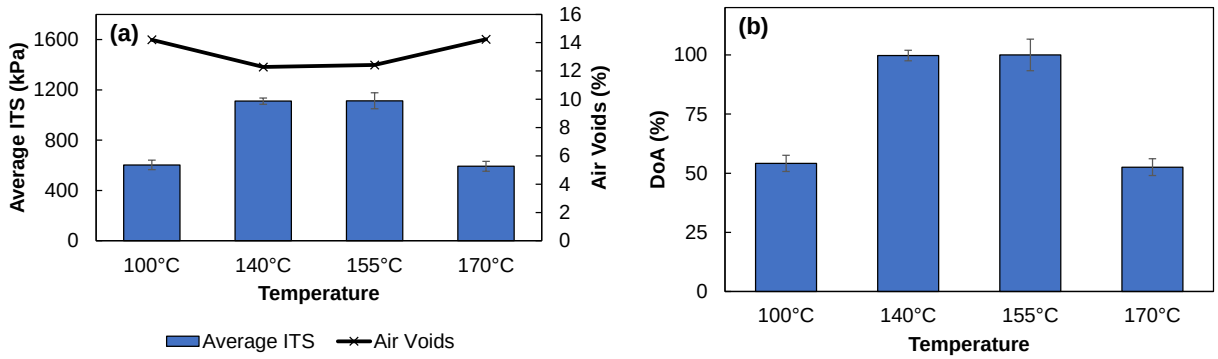

FIGURE 23 Source 4-WI (a) average ITS and air voids measurements and (b) DoA results

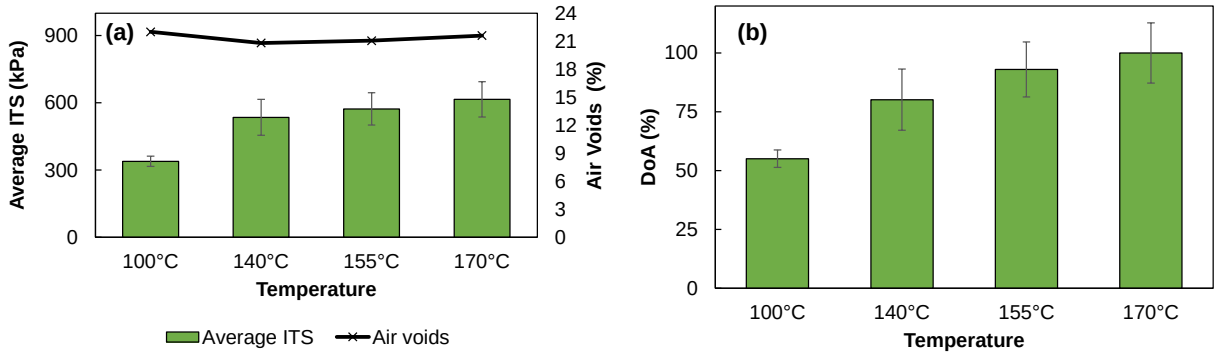

FIGURE 24 Source 5-TX (a) average ITS and air voids measurements (b) DoA results

Comparison of the RBA, DoA, and RBC Measurements

FIGURE 25 compare RBA, DoA and RBC measurements and their respective changes with temperature for Sources 1-NC, 4-WI and 5-TX. Here, the RBC results correspond to the control preheating procedure in all cases without simulated silo storage. The RBC measurements for Sources 1-NC and 5-TX closely match the RBA values obtained through sieve analysis. For Source 4-WI, the RBC derived from the control procedure was 62 percent, whereas the RBA from 100°C BC yielded 54 percent. Similar to the observations from sieve analysis, this particular source exhibited a higher susceptibility to break when subjected to heat, potentially leading to some additional breakdown of agglomerations during mixing. Nevertheless, although not as close as for Sources 1-NC and 5-TX, the RBA and RBC values remain comparable. Hence, these findings further suggest that sieve analysis could potentially reflect the RBC in asphalt mixtures produced at various temperatures.

Moreover, RBA and RBC were only marginally affected by temperature whereas ITS measurements indicated that DoA increased from 100°C to 140°C and significantly reduced at 170°C for Sources 1-NC and 4-WI. Despite this decrease in DoA at 170°C, no corresponding decrease in RBC was observed. Nevertheless, it is important to consider that the microscopy RAP samples were subjected to a brief 45-minute heating process prior to mixing with the virgin materials, while the samples used for calculating the DoA underwent a more extensive and unrealistic four-hour conditioning period in the oven at 170°C. As a result, the RAP material in the microscopy samples did not undergo the same aging process as the 100 percent RAP samples. Given that, the decrease in DoA at 170°C was attributed to aging rather than the temperature itself and it is hypothesized that the DoA was 100 percent for the samples mixed at 170°C.

As mentioned earlier, the RBC of a particular mix depends on the RBA and DoA of the RAP. Notably, the DoA was 100 percent at all the temperatures that RBC was measured, and a clear similarity

between RBA and RBC was observed across all the sources. This observation suggests that RBC becomes equivalent to RBA when the DoA reaches 100 percent, which suggests that RBA measurements can be used to reflect RBC in asphalt mixtures.

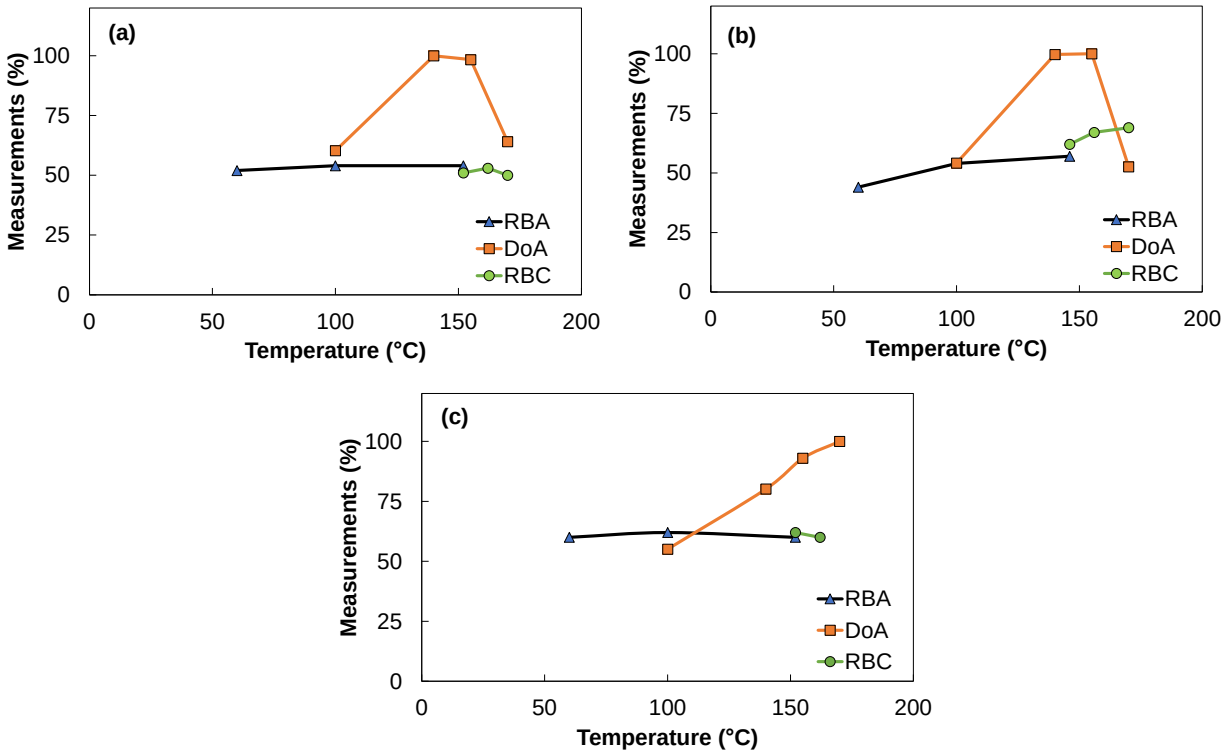

FIGURE 25 RBA, DoA and RBC measurements at different temperatures for (a) Source 1-NC, (b) Source 4-WI and (c) Source 5-TX

Sensitivity Analysis of the Calculated RBA to RAP Properties

A sensitivity analysis of the calculated RBA to Pba, RAP asphalt content, and RAP aggregate specific gravity was conducted for all the sources. The motivation for the sensitivity study is that there is uncertainty in the absorption characteristics and Gsb of RAP materials. Moreover, ignition oven and solvent extraction can yield different asphalt content results. Therefore, consideration of the sensitivity of the RBA results to variation in these characteristics is important to assess the ruggedness of the procedure under development. For the sensitivity analysis, two assumptions for Pba were conducted: zero absorption (i.e., Gsb = Gse) and 2 percent absorption. Note that changes in absorption affects both the inputted Pbe and Gsb values. To evaluate the effect of RAP asphalt content, the asphalt content used to calculate the RBA was taken to be one percent higher and one percent lower than the measured asphalt content from extraction (e.g., if the measured asphalt content was 5 percent, values of 4 and 6 percent were tried). Similarly, the effect of the aggregate specific gravity was assessed by increasing and decreasing the measured Gsb value by 0.3 (e.g., if the measured Gsb was 2.557, values of 2.277 and 2.877 were used). Note that only one variable was modified in a given calculation iteration and the gradation results were not changed.

FIGURE 26 shows the range of RBA results obtained for the RAP properties based on the described modifications to the input asphalt content, specific gravity, and binder content. The results reveal that the calculated RBA is not very sensitive to any of these input properties. Source 5 experienced the greatest change in RBA equal to 3 percent when the binder content was raised by one percent. These small changes in RBA would result in negligible differences in relation to the inferred effective binder content of an asphalt mixture design. Therefore, the uncertainty in the asphalt binder content, absorption,

and aggregate bulk specific gravity does not contribute substantially to increasing uncertainty in the RBA result from sieve analyses. Furthermore, these results indicate the possibility of simplifying the RBA calculation procedure to use G_{se} instead of G_{sb} and absorption of zero percent (i.e., use P_b instead of P_{be}) given the uncertainty in the P_{ba} and corresponding G_{sb} of RAP sources. Alternatively, a fixed G_{sb} and binder content could be used for RBA calculations.

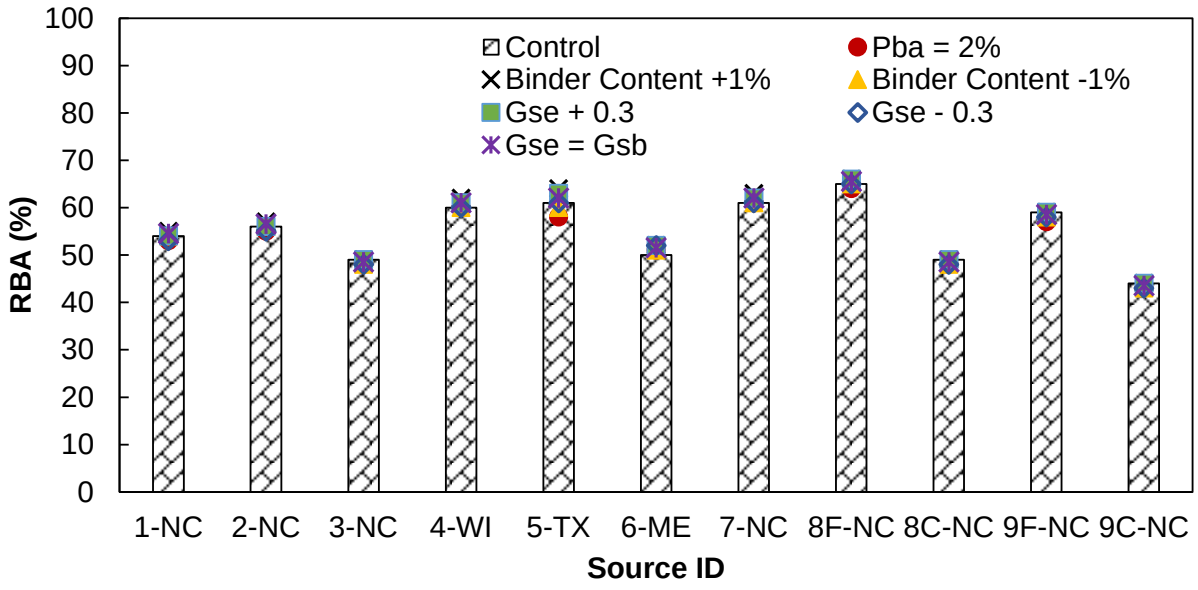

FIGURE 26 Sensitivity analysis results

Evaluation of the Effects of RAP Source and Composition on RBA

An analysis of variance (ANOVA) was conducted to evaluate if RBA results of the control procedure differ significantly among stockpiles. While in some cases, the mean RBA results fall within a relatively narrow range among sources, the results indicate that the RAP RBA does vary with the source with a confidence level of 95 percent. The detailed ANOVA results are presented in TABLE 5 and TABLE 6.

TABLE 5 Analysis of Variance of RAP Source Effect on RBA

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Ratio
Model	10	967	96.71	66.5
Error	11	16	1.45	**Prob > F**
Total	21	983		<.0001*

TABLE 6 Effect of RAP Source on RBA

Source	Degrees of Freedom	Sum of Squares	F Ratio	Prob > F
Source	10	967	66.5	<.0001*

To evaluate the effects of RAP material properties on RBA, the correlations between RBA and RAP high-temperature performance grade (HPG), asphalt content, and recovered aggregate gradation parameters were evaluated. Gradation parameters considered include particle size with 10 percent finer (D10), particle size with 30 percent finer (D30), particle size with 60 percent finer (D60), fineness modulus (FM), and uniformity coefficient (Cu). FIGURE 27 shows scatterplots of RBA versus the different properties evaluated where the pink shaded areas correspond to the 95 percent confidence interval. The correlation coefficients, denoted by r are presented in TABLE 7. TABLE 7 along with FIGURE 27 shows that D10, D60, and FM have marginal linear associations with the RBA. However, the

results indicate that the HPG, asphalt content, D30, and Cu are very weakly correlated with the RBA.

TABLE 7 Summary of correlation coefficients for RAP material properties with RBA

RAP material properties	Correlation coefficient (r)
RAP HPG	-0.19
Asphalt Content (%)	0.31
Aggregate D10	-0.69
Aggregate D30	-0.18
Aggregate D60	-0.54
Aggregate FM	-0.50
Aggregate Cu	-0.21

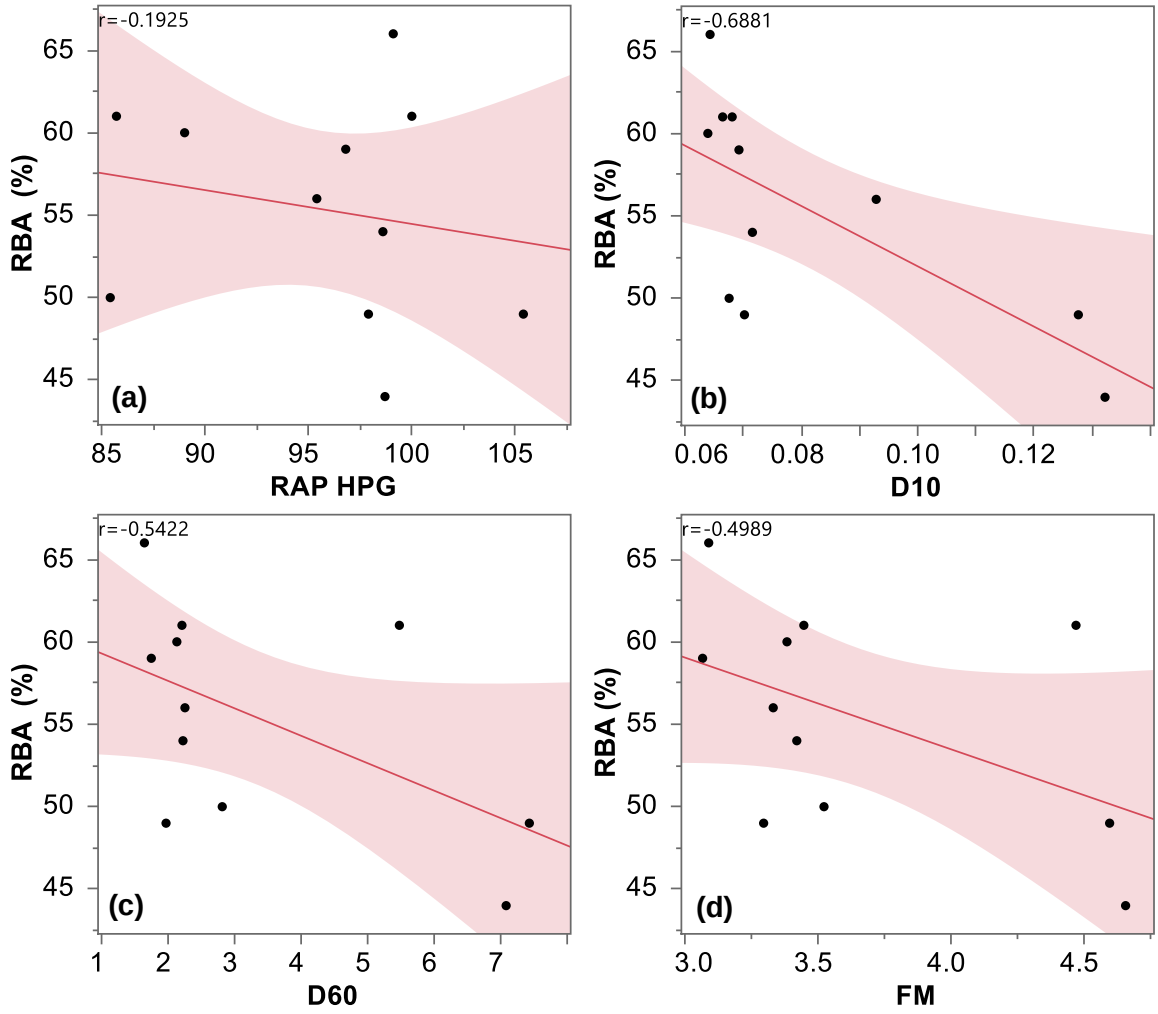

FIGURE 27 Correlation analysis between RBA and RAP material properties

Based on the correlation analysis results, a complementary multivariate linear regression analysis was conducted with four factors (i.e., HPG, AC, D10, and D60) to evaluate if RBA can be predicted using the constituent properties of a RAP stockpile. Note that D60 and FM are correlated so only D60 was included in the regression analysis. The regression model had a poor R^2 of 0.48, indicating that the RBA cannot be predicted from the constituent RAP properties evaluated and suggesting that comparative sieve

analysis of the RAP and recovered aggregate is needed to determine source specific RBA. The regression model is shown in FIGURE 28, along with Equation (12).

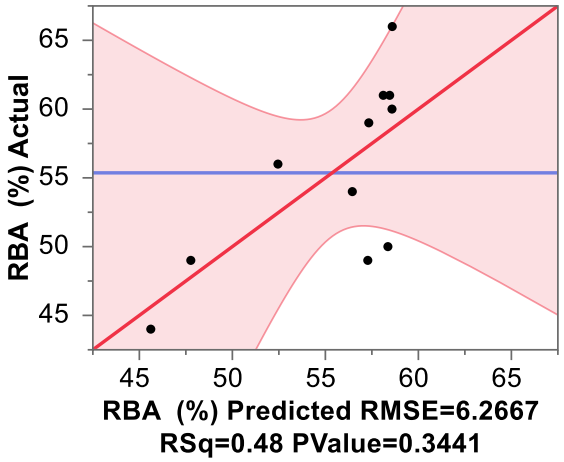

FIGURE 28 Actual versus predicted RBA plot

$$RBA(\%) = 70.721 - 202.232 \times D10 + 0.451 \times D60 - 0.059 \times HPG + 1.072 \times AC(\%) \qquad (12)$$

The relationship between RAP (black curve) gradation parameters and RBA was also investigated through correlation analysis. The corresponding correlation coefficients are denoted by r and presented in TABLE 8. FIGURE 29 shows scatterplots among the RAP gradation parameters and RBA where the pink shaded areas correspond to the 95 percent confidence interval. Table 9 along with FIGURE 29 reveals a marginal linear association between RBA D30, D60, and FM. The collective results of the correlation analysis suggest that source specific RBA depends on both the black and white curve gradations and cannot be readily predicted from a single gradation parameter.

TABLE 8 Summary of Correlation Coefficients for RAP Gradation Parameters with RBA

RAP gradation parameters	Correlation coefficient (r)
D10	-0.24
D30	-0.54
D60	-0.64
FM	-0.64
Cu	-0.15

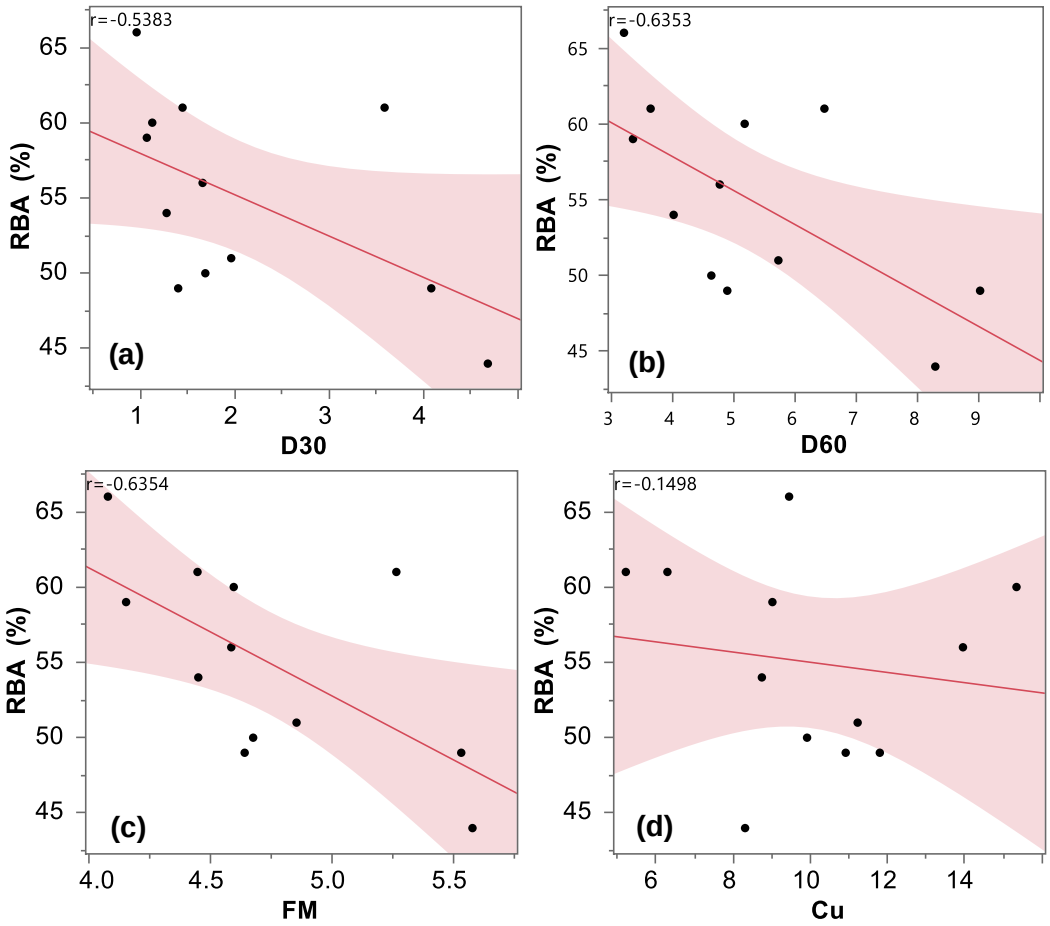

FIGURE 29 Correlation analysis between RBA and RAP gradation parameters

Comparison of the Control and AAMD Mixtures

Comparison of the Control and AAMD Mixtures with the Same RAP Content

FIGURE 30 presents the comparisons between the control and AAMD mixture blend gradations for the cases where the AAMD and respective control mixtures contained the same RAP content. Within these and subsequent graphs, the 'black curve' shows the blend gradation that is calculated when using the RAP black curve to reflect its gradation whereas the 'white curve' shows the blend gradation calculated when using the RAP white curve to reflect its gradation. FIGURE 30 shows that the control mixture white curves are similar to the corresponding AAMD mixture black curves, which was intentional to reflect what a mixture designer might do. Through the research project, this approach was found to generally yield an available VMA in the AAMD mixture that was close to the specified (i.e., intended) VMA of the corresponding control mixture. The AAMD mixture gradations show that the gradation interpreted using the RAP white curve is finer than the gradation interpreted using the RAP black curve for a given mixture due to the presence of agglomerations of adhered RAP particles. Thus, the AAMD mixtures have finer white curves than the corresponding control mixtures.

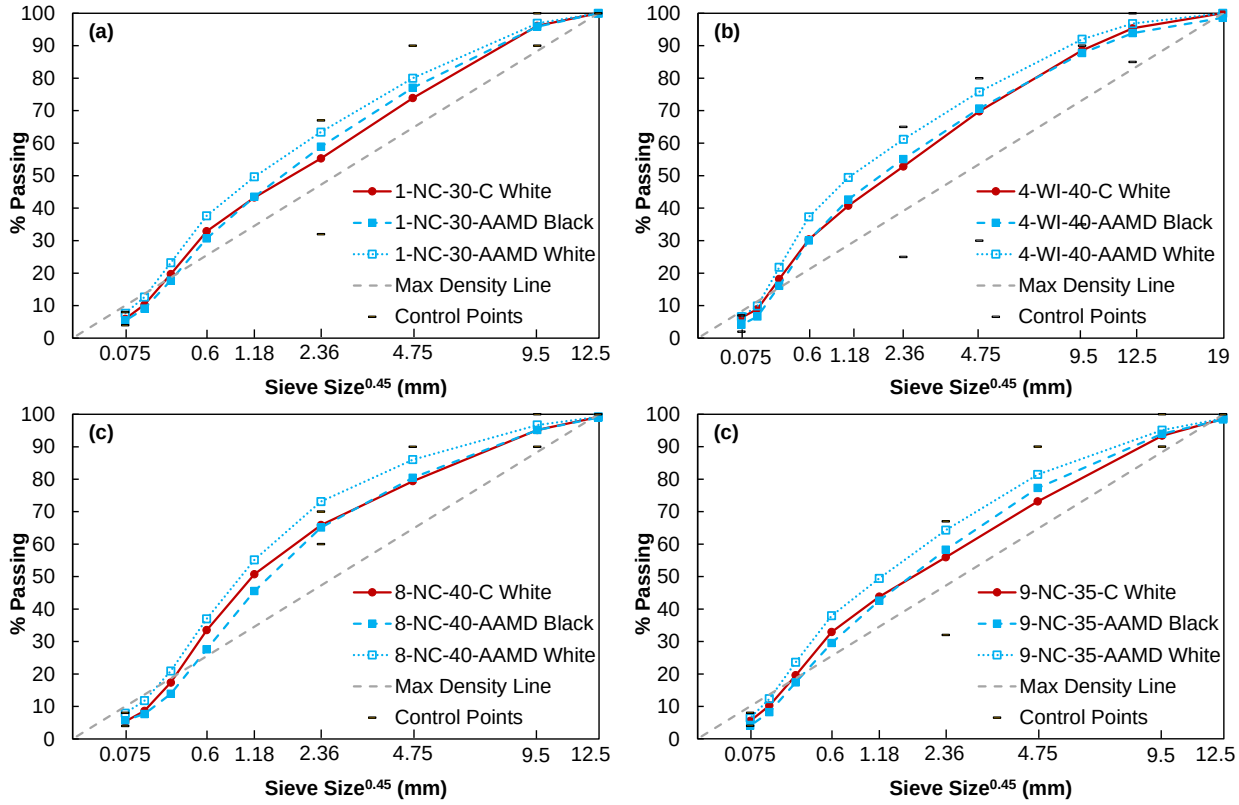

FIGURE 30 Blend gradations for the control and AAMD mixtures prepared with the same RAP content: (a) Source 1-NC, (b) Source 4-WI, (c) Source 8-NC, (d) Source 9-NC

TABLE 9 and TABLE 10 provide a comprehensive breakdown of the composition of the control and AAMD mixtures prepared with the same RAP contents. The quantities designated as 'specified' correspond to calculations made under the assumption of 100 percent RBA, aligning with the conventional practice. In contrast, the 'available' quantities align with calculations according to the AAMD method. With the exception of the 8-NC-40 case, TABLE 9 and TABLE 10 demonstrate that the AAMD method yielded higher asphalt contents for a given control mixture due to the changes to the aggregate structure which increased the VMA of the mixture. The marginal differences between the volumetric composition of the 8-NC-40-C and 8-NC-40-AAMD mixtures is attributed to the stringent constraints set by the NCDOT on the 2.36-mm sieve for RS9.5B mixtures. The other NC mixtures evaluated are all RS9.5C mixture types, which have less stringent limits on the 2.36-mm sieve. The 2.36-mm sieve is the primary control sieve for the 9.5-mm NMAS mixtures. The influence of the percentage passing the primary control sieve on VMA is well documented in the literature (*19*). Consequently, the relatively minor discrepancies in the percentage passing the 2.36-mm sieve between control and AAMD mixtures from Source 8-NC may account for the limited extent of changes observed in the volumetric properties of these mixtures.

TABLE 9 and TABLE 10 underscores the significant impact of discrediting unavailable binder on the interpretation of mixture volumetric properties. The AAMD method results in lower calculated values for RBR, VMA, VFA and DP than those calculated when assuming 100 percent RBA. Notably, the available VMA values for the 9-NC-35-C and 4-WI-40-C mixtures fall short of meeting the specified minimum limits, indicating that these mixtures would be rejected under the AAMD framework. Also, although the available VMA for 1-NC-30-C mixture does meet the minimum limit, it approaches the specified limit, which differs from the typical practice of North Carolina contractors who often aim for a higher VMA than the minimum to ensure compliance during plant production.

TABLE 9 Specified and Available Volumetric Properties of the NC RS9.5C Control and AAMD Mixtures with the Same RAP Content

Mix properties	Source 1-NC		Source 9-NC		Spec. limits
	1-NC-30-C	1-NC-30-AAMD	9-NC-35-C	9-NC-35-AAMD	
Specified binder content (%)	6.0	6.7	6.0	6.7	--
Available binder content (%)	5.4	6.1	5.2	5.9	--
Virgin binder content (%)	4.4	5.2	4.3	5.0	--
Specified RBR (%)	25.9	22.8	27.8	24.4	--
Available RBR (%)	17.1	14.8	17.3	14.9	--
Specified Binder Blend HPG	75.6	74.7	74.5	73.7	--
Available Binder Blend HPG	72.9	72.2	71.6	71.0	--
Specified VMA (%)	16.8	17.7	16.8	18.5	Min. 15.5
Available VMA (%)	15.9	16.9	15.2	17.1	
Specified VFA (%)	76.1	77.3	76.2	78.2	65-78
Available VFA (%)	74.9	76.3	73.6	76.4	
Specified DP	1.1	1.3	1.0	1.1	0.6-1.4
Available DP	0.7	1.0	0.7	0.8	

TABLE 10 Specified and Available Volumetric Properties of the Other Control and AAMD Mixtures with the Same RAP Content

Mix properties	Source 4-WI		Spec. limits	Source 8-NC		Spec. limits
	4-WI-40-C	4-WI-40-AAMD		8-NC-40-C	8-NC-40-AAMD	
Specified binder content (%)	5.6	6.1	--	6.6	6.6	--
Available binder content (%)	4.7	5.3	--	5.8	5.8	--
Virgin binder content (%)	3.4	3.9	--	4.6	4.7	--
Specified RBR (%)	39.3	35.9	--	29.8	29.7	--
Available RBR (%)	27.9	25.1	--	20.2	19.8	--
Specified Binder Blend HPG	68.4	67.3	--	72.3	72.3	--
Available Binder Blend HPG	64.6	63.6	--	68.8	68.8	--
Specified VMA (%)	15.0	16.2	Min 14.0	17.9	18.2	Min. 16.0
Available VMA (%)	13.9	14.9		17.0	17.3	
Specified VFA (%)	72.6	75.2	65-78	77.7	78.1	65-78
Available VFA (%)	70.3	73.1		76.4	76.9	
Specified DP	1.3	1.2	0.6-1.2	0.9	1.6	0.6-1.4
Available DP	0.9	0.9		0.6	1.3	

FIGURE 31 presents the IDEAL CT and rutting test results for the control and AAMD designs prepared at fixed RAP content. The error bars in the IDEAL CT graphs in FIGURE 31 and subsequent graphs represent the standard error of the test results. In some cases, the error bars are very small and thus, not visually discernable. The control mixtures exhibit CT_{index} values that are significantly lower than the respective AAMD mixtures, indicating that the AAMD mixtures have superior cracking resistance. Each NC AAMD mixture had statistically equal APA rut depths to the respective control mixture whereas the 4-WI-40-C mixture exhibited a marginally but statistically significant lower HWTT rut depth than the 4-WI-40-AAMD mixture. While the AAMD mixtures do have notably higher available binder content than the respective control mixtures, the gradation design changes on the basis of the RAP black curves implemented within the AAMD method appear to have mitigated the negative consequences of this additional binder on mixture rutting resistance with the exception of the 4-WI-40 case. However, all of the mixtures meet the rut depth requirements specified by the respective state agency.

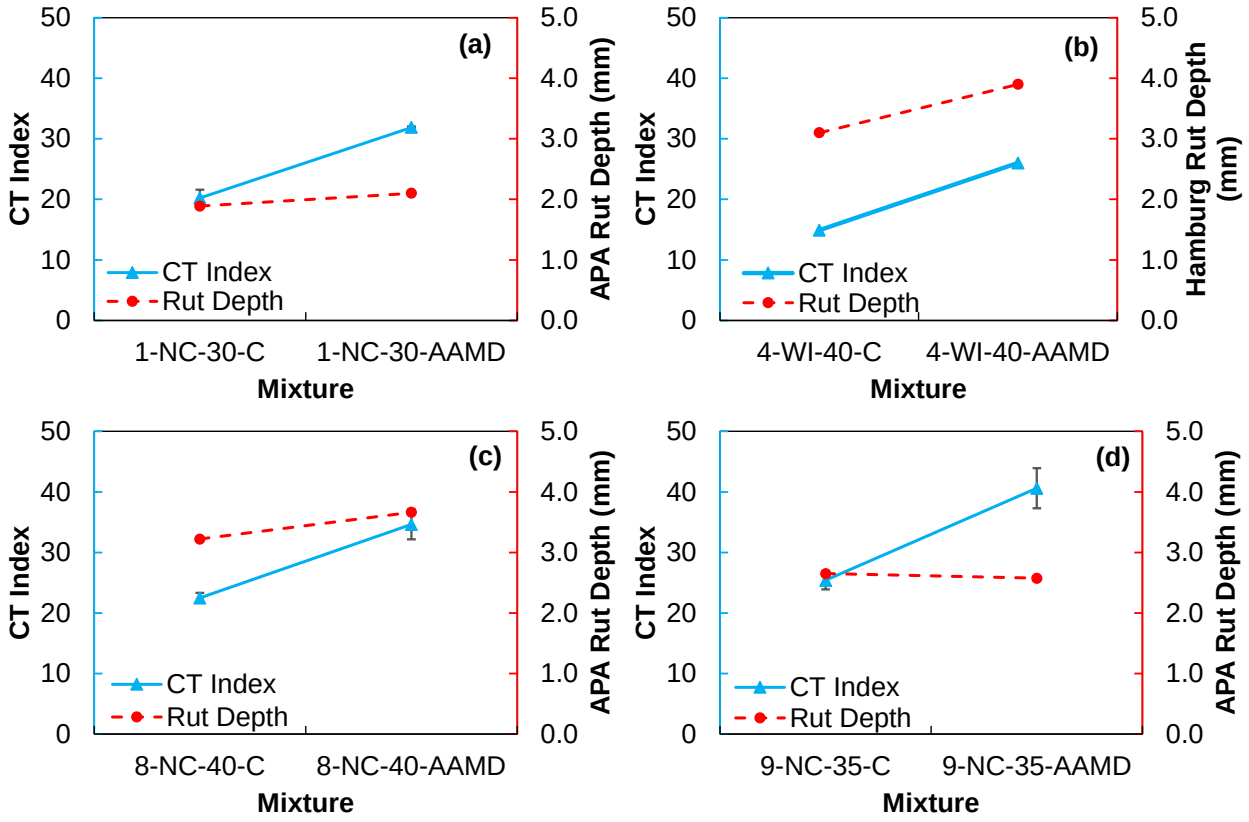

FIGURE 31 Cracking and rutting test results for the control and AAMD mixtures with the same RAP content: (a) Source 1-NC, (b) Source 4-WI, (c) Source 8-NC, (d) Source 9-NC

Comparison of the Control and AAMD Mixtures with Elevated RAP Content

FIGURE 32 presents the resultant blend gradations of the control and elevated RAP content mixtures. The RAP content of three control mixtures were increased to either 40 or 50 percent. To align with the NCDOT RBR specifications, a PG 58-28 virgin binder was used in the 1-NC-50-AAMD and 9-NC-50-AAMD designs. Similarly, the 7-ME-40-AAMD mixture included a PG 52-34 virgin binder whereas the 7-ME-20-C mixture used a PG 58-28 virgin binder. To increase the RAP content of the mixtures, the RAP black curves were used to reflect their gradations and the virgin aggregate stockpiles proportions were adjusted to accommodate the additional RAP content and achieve a similar blend gradation to that specified (i.e., the white curve) for the respective control mixture. All the virgin stockpiles used in the control mixtures were retained for the elevated RAP content AAMD mixtures. In general, the elevated RAP content mixture black curves are similar to the corresponding control mixture white curve. However, some differences are observed, particularly for the 7-ME-40-AAMD mixture. The high RAP content made it more difficult to manipulate the blend gradation through adjustment of the virgin stockpile proportions than the lower RAP content mixtures.

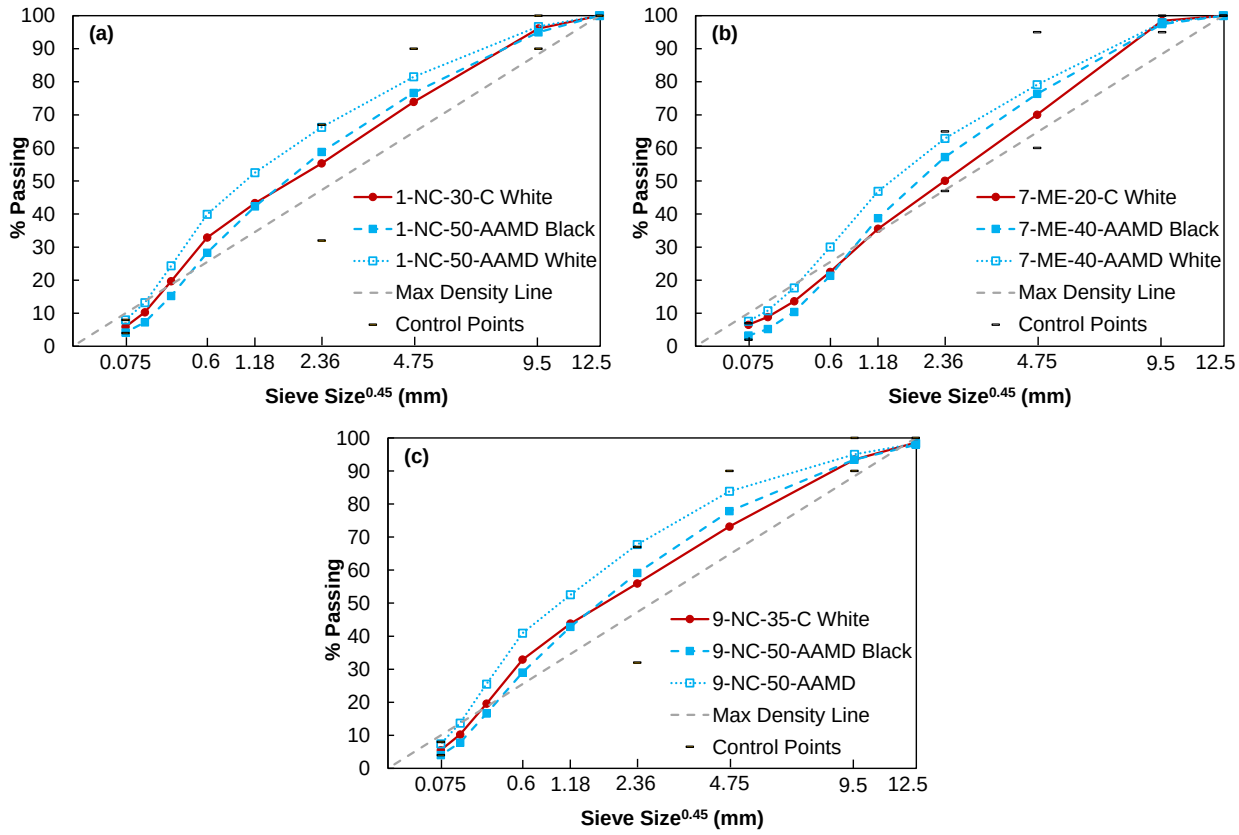

FIGURE 32 Blend gradations for the control and AAMD mixtures prepared with elevated RAP content: (a) Source 1-NC, (b) Source 7-ME, (c) Source 9-NC

TABLE 11 and TABLE 12 present the comparison of the volumetric properties of the control and elevated RAP content AAMD mixture designs. The available binder contents of the control and elevated RAP AAMD mixtures are similar for the three cases. However, the virgin binder contents of each elevated RAP content mixture is lower than the respective control mixture, suggesting the AAMD mixtures may be economically advantageous. TABLE 12 also shows that neither the 7-ME-20-C or 7-ME-40-AAMD mixtures have available VMAs that exceed the specified limit. The available DPs of the control and respective elevated RAP content AAMD mixtures are also all similar. The virgin binder used for all the mixtures with elevated RAP was softer than the respective control mixtures. With the use of a softer virgin binder, the estimated available binder blend HPG of the 50 percent RAP mixtures are 1°C to 4°C lower than the respective control mixtures.

TABLE 11 Specified and Available Volumetric Properties of the NC Control and AAMD Mixtures with Elevated RAP Content

Mix properties	Source 1-NC		Source 9-NC		Spec. limits
	1-NC-30-C	1-NC-50-AAMD	9-NC-35-C	9-NC-50-AAMD	
Specified binder content (%)	6.0	6.7	6.0	6.5	--
Available binder content (%)	5.4	5.7	5.2	5.5	--
Virgin binder content (%)	4.4	4.2	4.3	3.8	--
Specified RBR (%)	25.9	37.7	27.8	41.1	--
Effective RBR (%)	17.1	26.3	17.3	29.1	--
Specified Binder Blend HPG	75.6	74.3	74.5	73.9	--
Available Binder Blend HPG	72.9	69.9	71.6	69.9	--
Specified VMA (%)	16.8	17.2	16.8	18.0	Min. 15.5
Available VMA (%)	15.9	15.9	15.2	16.1	
Specified VFA (%)	76.1	76.8	76.2	77.8	65-78
Available VFA (%)	74.9	74.9	73.6	75.2	
Specified DP	1.1	1.4	1.02	1.33	0.6-1.4
Available DP	0.7	0.8	0.7	0.7	

TABLE 12 Specified and Available Volumetric Properties of the NC Control and AAMD Mixtures with Elevated RAP Content

Mix properties	Source 7-ME		Spec. limits
	7-ME-20-C	7-ME-40-AAMD	
Specified binder content (%)	5.7	6.1	--
Available binder content (%)	5.3	5.2	--
Virgin binder content (%)	4.7	4.2	--
Specified RBR (%)	17.2	32.1	--
Effective RBR (%)	10.2	20.2	--
Specified Binder Blend HPG	66.1	64.9	--
Available Binder Blend HPG	64.5	61.2	--
Specified VMA (%)	15.5	16.3	Min 16.0
Available VMA (%)	14.8	15.1	
Specified VFA (%)	74.4	76.6	65-80
Available VFA (%)	73.3	74.7	
Specified DP	1.3	1.5	0.6-1.2
Available DP	0.9	1.1	

FIGURE 33 presents the IDEAL CT and rutting test results for the control and AAMD designs prepared at elevated RAP content. The Source 1-NC-30 and 9-NC-35 control mixtures exhibit CT_{index} values that are significantly lower than the respective AAMD mixtures at 50 percent RAP content while the control and AAMD mixtures display similar APA rut depths. The superior cracking performance of the 1-NC-50-AAMD and 9-NC-50-AAMD mixtures compared to their respective controls is attributed to their slightly higher available binder contents and softer effective binder matrices. In contrast, FIGURE 33(b) shows that the 7-ME-20-C mixture exhibits a CT_{index} and HWTT rut depth compared to the 7-ME-40-AAMD mixture despite the two mixtures having similar available asphalt contents and effective binder HPGs. Furthermore, the specified binder content was substantially higher in the 7-ME-40-AAMD mixture than the 7-ME-20-C mixture, indicating that underestimation of the RBC in the asphalt mixture cannot explain the performance trends. Therefore, it was speculated that the virgin binder used in the 7-ME-20-C mixture have superior cracking resistance compared to the 7-ME-40-C mixture, which may not have been captured through the performance grade.

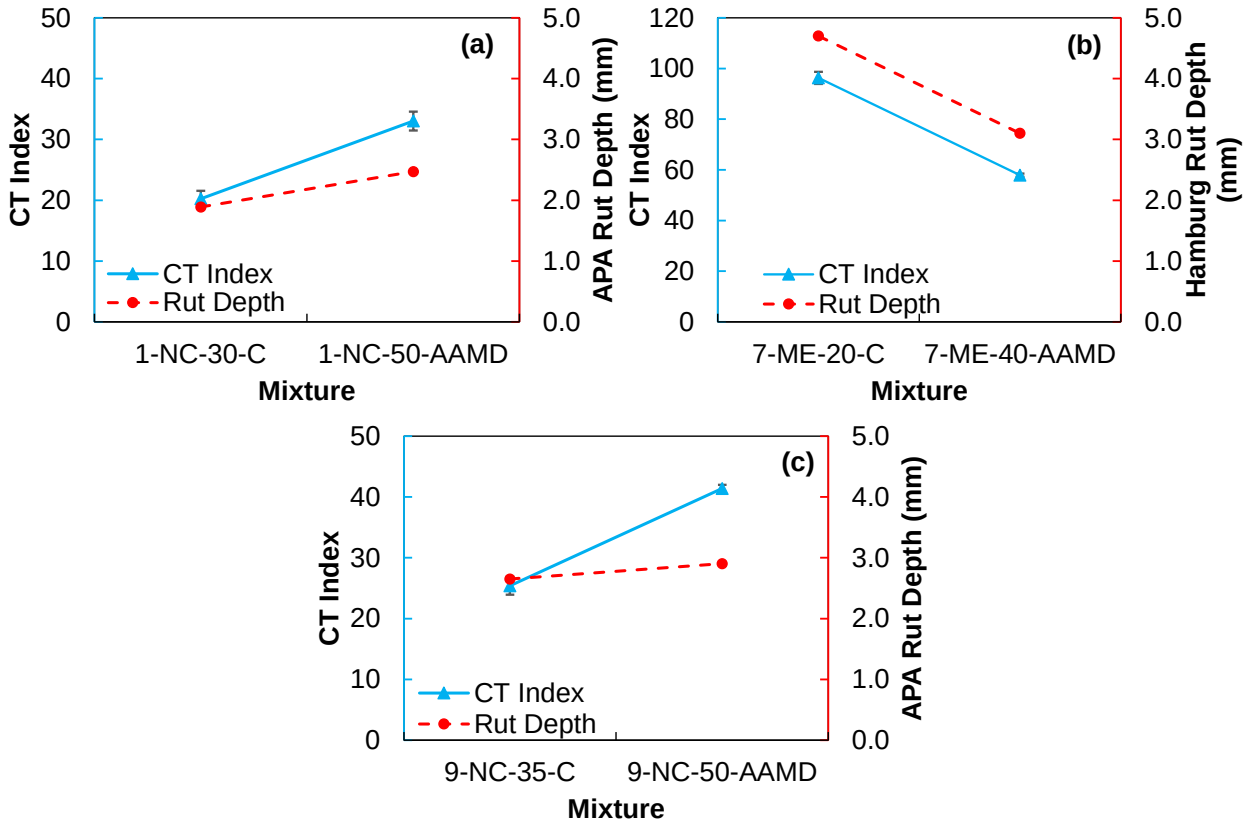

FIGURE 33 Cracking and rutting test results for the control and AAMD mixtures with elevated RAP content: (a) Source 1-NC, (b) Source 7-ME, (c) Source 9-NC

To further evaluate potential reasons for the CT_{index} results of the Source 7-ME mixtures, temperature-frequency sweep testing was conducted on the virgin binders used in the 7-ME-20-C mixture (PG 58-28) and 7-ME-40-AAMD mixture (PG 52-34) at the Rolling Thin Film Oven (RTFO) age level according to the testing procedure and pairwise interpolation method for master curve construction used by (*20*). FIGURE 34 shows the results. The dynamic shear modulus and phase angle master curves follow the expected trends based on the HPG results. That is, the PG 52-34 binder exhibits a lower dynamic modulus and phase angle than the PG 58-28 binder. The Glover-Rowe parameter (*21*) values were calculated using the temperature-frequency sweep results and found to be 0.17 kPa and 1.59 kPa for the PG 52-34 and PG 58-28 binders, respectively. A lower Glover-Rowe parameter value is indicative of higher ductility for non-polymer modified asphalt binders, also suggesting superior cracking resistance of the PG 52-34 virgin binder compared to the PG 58-28 virgin binder (*22*). However, FIGURE 34(c) shows that the two binders appear similar in the black space, suggesting a similar balance of modulus and relaxation characteristics, leading to similar rheological index (R) values of 1.73 and 1.85, calculated using the linear regression method in (*20*) for the PG 52-34 and PG 58-28 binders, respectively. Some studies have reported that the R value is an indicator of cracking resistance (e.g., *23*) and thus, this finding suggests that the two virgin binders could yield similar cracking resistance, offering a possible explanation for why the 7-ME-40-AAMD mixture exhibited poorer cracking resistance than the 7-ME-20-C mixture despite having a softer effective binder matrix. However, given that the other rheological indicators suggest superior cracking resistance of the PG 52-34 virgin binder, a definitive conclusion cannot be drawn. Chemical compatibility and interactions between the virgin and RAP binders may also have affected the performance of the mixtures, which was not evaluated. Collectively, these finding suggests that relying on performance-graded virgin and RAP properties may be insufficient to optimize the cracking performance of asphalt mixtures.

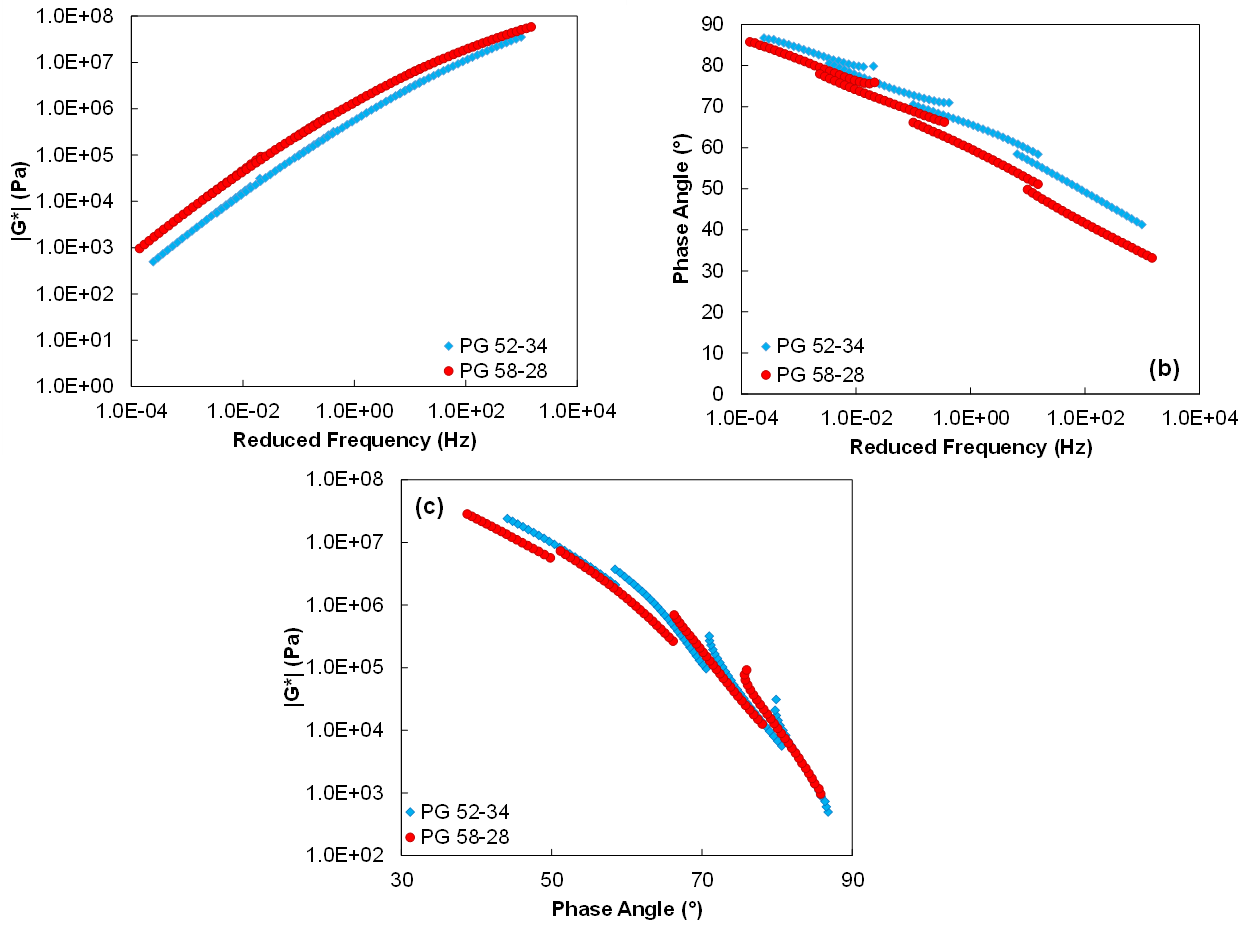

FIGURE 34 Source 7-ME mixture virgin binder temperature-frequency sweep test results: (a) dynamic shear modulus (|G*|) master curves, (b) phase angle master curves, and (c) black space

Comparison of the Comparative Virgin Mixtures and AAMD Mixtures

Virgin mixtures were designed using Source 1 and 8 virgin aggregate stockpiles to achieve similar available VMA and binder contents to the respective AAMD RAP mixtures (i.e., 1-NC-0-E was prepared to be similar to 1-NC-30-AAMD and 8-NC-0-E was prepared to achieve similar available properties to 8-NC-40-AAMD). The 1-NC-0-E and 8-NC-0-E mixtures adhered to NCDOT specifications for RS9.5C and RS9.5B mixtures, respectively, with the exception that the 8-NC-0-E mixture failed the gradation specification at 2.36 mm sieve. This was required to achieve a VMA relatively close to the available VMA of the 8-NC-40-AAMD mixture,

FIGURE 35 presents the blend gradations for the comparative virgin, control RAP, and AAMD RAP mixtures for Sources 1 and 8. The comparative virgin mixtures display coarser gradations compared to the respective AAMD mixtures, which was required to achieve similar available volumetric properties.

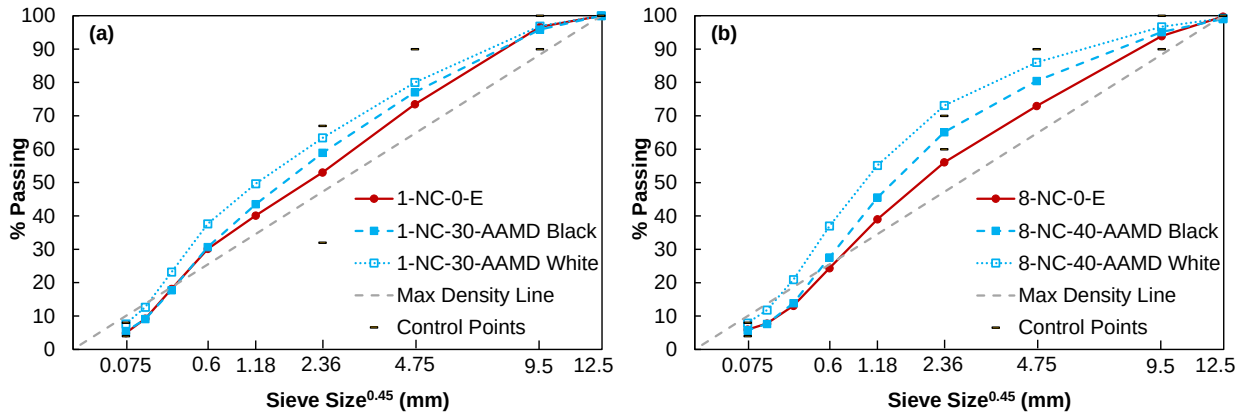

FIGURE 35 Blend gradations for the AAMD and comparative virgin mixtures: (a) Source 1-NC, (b) Source 8-NC

TABLE 13 presents the volumetric properties of the comparative virgin and AAMD RAP mixtures. The 1-NC-0-E mixture has similar available VMA, VFA, and binder content values to the 1-NC-30-AAMD mixture. Moreover, the 1-NC-0-E mixture has similar total VMA, VFA, and binder content to the 1-NC-30-C mixture. The 8-NC-0-E has similar available VMA and VFA values and 0.4 percent higher available binder content compared to both the 8-NC-30-AAMD and 8-NC-30-C mixtures. Recall that the VMA of the 8-NC-30-C could not be increased substantially when preparing the 8-NC-30-AAMD mixture due to the tight gradation restrictions on the 2.36 mm sieve for RS9.5B mixtures in NC. This restriction on the 2.36 mm sieve also made it difficult to achieve the same available VMA in the comparative virgin and RAP mixtures. TABLE 13 shows that the estimated available HPG values of the virgin and respective AAMD RAP mixtures are within 1.1°C in both cases, which was intentional. The virgin binder used for the virgin mixtures were also selected so that the HPG is close to the available blend HPG of the RAP mixtures. Correspondingly, a PG 70-22 virgin binder was used in the 1-NC-0-E mixture and a PG 64-22 was used in the 8-NC-0-E mixture.

TABLE 13 Specified and Available Volumetric Properties of the Comparative Virgin and AAMD Mixtures

Mix properties	Source 1-NC		Source 9-NC		Spec. limits
	1-NC-0-E	1-NC-30-AAMD	8-NC-0-E	8-NC-40-AAMD	
Specified binder content (%)	6.1	6.7	6.2	6.6	--
Available binder content (%)	6.1	6.1	6.2	5.8	--
Virgin binder content (%)	6.1	5.2	6.2	4.7	--
Total RBR (%)	0.0	22.8	0.0	29.7	--
Available RBR (%)	0.0	14.8	0.0	19.8	--
Total Binder Blend HPG	72.0	74.7	67.6	72.3	--
Available Binder Blend HPG	72.0	72.2	67.6	68.8	--
Specified VMA (%)	17.1	17.7	17.2	18.2	Min. 15.5 (1) Min 16.0 (8)
Available VMA (%)	17.1	16.9	17.2	17.3	
Specified VFA (%)	76.6	77.3	76.8	78.1	65-78
Available VFA (%)	76.6	76.3	76.8	76.9	
Specified DP	0.9	1.3	1.0	1.6	0.6-1.4
Available DP	0.9	1.0	1.0	1.3	

FIGURE 36 shows the comparison of the IDEAL CT and APA test results of the comparative virgin and respective RAP mixtures. The average CT_{index} results of the 1-NC-0-E and 1-NC-30-AAMD are statistically. Recall that the A-30/0-C mixture exhibits a significantly lower result. The 8-NC-0-E mixture has a marginally higher CT_{index} than the 8-NC-40-AAMD mixture, which is attributed to its 0.4 percent higher available binder content. The comparative virgin mixtures both have higher APA rut depths than the respective RAP mixtures, indicating that the RAP mixtures may have superior aggregate structures. However, all mixtures met NCDOT specifications for the APA rut depth. Collectively, the similar cracking performance achieved in the comparative virgin and AAMD mixture results suggest that the AAMD approach mitigated the adverse effects of RAP through the control of available volumetric and effective binder properties.

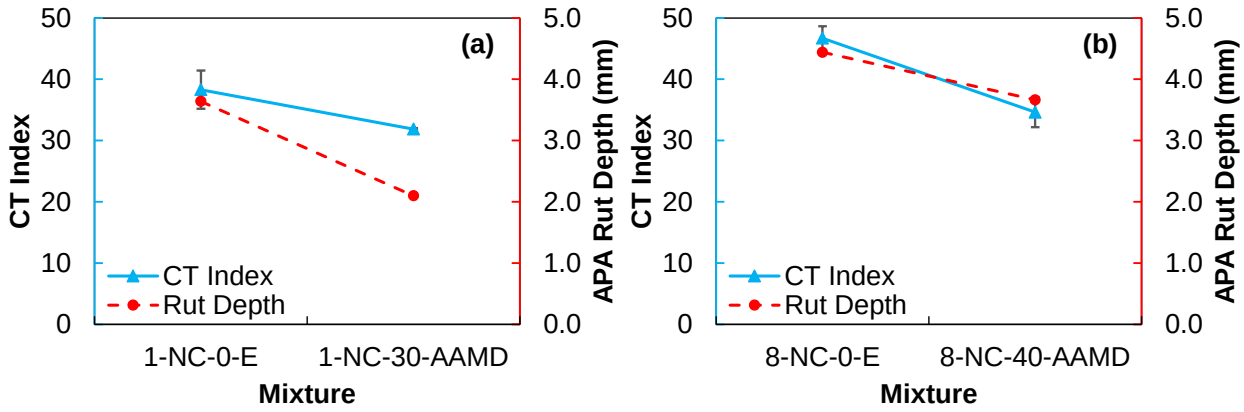

FIGURE 36 Cracking and rutting test results for the AAMD and comparative virgin mixtures: (a) Source 1-NC, (b) Source 8-NC

Summary of Findings

This study aimed to validate a sieve analysis method for quantifying RBA through evaluating the procedures' underlying assumptions that agglomerations do not fully break during asphalt mixture production and that RBA is an indicator of RBC in asphalt mixtures. In addition, this study sought to evaluate the effects of adjustments to mixture design procedures to address RBA on asphalt mixture performance.

Agglomerations were observed in all tracer-based microscopy asphalt mixtures samples, thereby verifying that RAP agglomerations do not completely disintegrate during the mixing process. Consequently, a portion of the RAP binder remains inaccessible for interaction with the virgin binder, leading to partial RBC in all mixtures evaluated.

Various conditioning procedures for the RAP were examined to determine which approach most effectively characterizes the RAP BC for quantifying RBA. Dry sieve analysis (60°C BC) of RBA measurements highlighted a significantly lower RBA for one source compared to the washed sieve analysis procedures evaluated, indicating that the performance of this source was influenced by the washing and subsequent heating processes and the corresponding disruption of agglomerates prior to sieving the RAP. Conditioning the RAP at the mixing temperature (T_{mix} BC) following washing resulted in the activation of the binder in a RAP source, leading to the formation of additional agglomerates rather than the intended breakage of existing agglomerates. The RBA determined from a washed sieve analysis of RAP that was conditioned at 100°C (100°C BC) yielded therefore was deemed optimal, allowing for similar breakage of weak agglomerations that would likely break down during asphalt mixture production while avoiding significant binder activation. This procedure generally yielded RBA results in close results to the RBC measurements (R^2 = 0.70, average difference = 2.5 percent). The alignment of RBA and RBC results indicates that DoA is 100 percent at and above 140°C for the cases evaluated. Additionally, the RBC remains stable under common production temperatures, RAP and virgin aggregate preheating procedure, or simulated silo storage, which supports the idea that RBA can mirror RBC in asphalt mixtures under varying conditions, demonstrating the extensibility of the tool for the design and evaluation of asphalt mixtures.

The effects of RBA on asphalt mixture design were evaluated by comparing the composition and performance of control asphalt mixtures designed under the assumption of 100 percent RBA with those redesigned according to the AAMD method. The AAMD method explicitly considers the role of RAP agglomerations and RBA on the design and evaluation of asphalt mixtures. The AAMD method generally produced mixtures with enhanced cracking performance and similar rutting resistance compared to the control mixtures with the same RAP or elevated content. However, in one case an AAMD mixture with elevated RAP content displayed inferior cracking resistance to the control mixture. While the reason for

this trend was not clearly identified, it is thought to be the result of potential differences in the cracking resistance of the virgin binders used in the mixtures that was not captured through performance-graded properties. Virgin mixtures and AAMD RAP mixtures prepared with similar available volumetric and effective properties yielded similar cracking performance, suggesting potential for applying the AAMD method to counteracts RAP's detrimental effects on cracking resistance.

PLANS FOR IMPLEMENTATION

Two state agency-sponsored research projects are evaluating the sieve analysis method developed to quantify RAP RBA for their respective states. An NCDOT-sponsored research project is evaluating the extensibility of the RBA findings of this project to plant-produced mixtures by conducting tracer-based microscopy measurements of RBC in mixtures produced using a laboratory pugmill that better mimics an asphalt plant than the conventional bucket mixture used in this project. A VDOT-sponsored research project is evaluating the sieve analysis method developed in this project to characterize the RBA of 10 to 14 RAP sources in Virginia and will use the results to evaluate the performance impacts of RBA on mixture design.

A draft AASHTO standard for the sieve analysis procedure has been prepared to further facilitate implementation. Microsoft Excel templates for calculating RBA using sieve analysis results and calculating available volumetric properties according to the AAMD method have been developed to also facilitate technology transfer and training. These templates have been shared with several state agencies, academic institutions, and mixture design laboratories. The research team has also presented the sieve analysis method through several invited presentations both domestically and internationally.

CONCLUSIONS

The following conclusions and recommendations are drawn from the results of this study:

- Partial RBA and RBC were observed for all sources, revealing the inaccuracy of assuming 100 percent contribution from the RAP binder.
- The RBA derived from a washed sieve analysis of RAP conditioned at 100°C (100°C BC) demonstrated favorable agreement with RBC measurements, making it the recommended procedure for implementation. The omission of washing and subsequent preheating fails to break weak agglomerations that may break during asphalt mixture production whereas the use of higher conditioning temperatures can cause new agglomerations to form that are unlikely to form during mixture production.
- The RBA calculated from sieve analysis results is relatively insensitive to the inputs of RAP binder content, absorption, and aggregate specific gravity. Correspondingly, it is recommended that the effective specific gravity and zero absorption be used when calculating RBA given that RAP aggregate absorption (and therefore, bulk specific gravity) is generally uncertain.
- The RBC remains stable under common production temperatures, RAP and virgin aggregate preheating procedure, or simulated silo storage, supporting the idea that RBA can mirror RBC in asphalt mixtures under varying conditions. However, this study only analyzed laboratory-mixed and laboratory-compacted asphalt samples. Further validation under actual plant conditions is recommended.
- According to DoA measurements from the ITS of RAP samples, there is no singular optimal temperature for binder activation in a specific RAP source; instead, an optimal temperature range exists that appears to align with the span of typical production temperatures.
- Statistical analyses indicate that RBA cannot be predicted from the constituent RAP properties (i.e., binder PG, asphalt content, recovered aggregate gradation), thereby suggesting that measurement of both the RAP gradation (black curve) and recovered aggregate gradation (white curve) is necessary to precisely quantify source-specific RBA.
- Although displaying statistical variances, most sources consistently presented RBA values near 60 percent. Also, the average RBC measurement was 60 percent across the sources evaluated. This suggests that adopting a fixed RBA value of 60 percent could be a practical alternative when sieve analysis measurements are not feasible.
- The AAMD method produced mixtures with enhanced cracking performance compared to control mixtures with the same or lower RAP content designed under the assumption of 100 percent RBAs in all but one case evaluated. The AAMD method also generally resulted in rut depths similar to the respective control mixtures. All AAMD mixtures met rutting requirements specified by the respective state agency.
- Virgin mixtures and AAMD RAP mixtures prepared with similar available volumetric and effective properties yielded similar cracking performance. The comparative virgin mixtures displayed inferior rutting resistance compared to the AAMD RAP mixtures.

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APPENDIX: RESEARCH RESULTS

Sidebar Info
Program Steering Committee: NCHRP IDEA
Title: A Practical Method to Determine Reclaimed Asphalt Pavement (RAP) Binder Availability
Project Number: 20/30-236
Start Date: 11/01/2021
Completion Date: 12/31/2023
Product Category: New or improved specification
Principal Investigator: Cassie Castorena, Professor
E-Mail: cahintz@ncsu.edu
Phone: 919-515-6411

TITLE:
Sieve Analysis to Quantify RAP Binder Availability

SUBHEAD:
A practical method to quantify RAP binder availability and improve asphalt mixture design procedures.

WHAT WAS THE NEED?
Recycled binder availability (RBA) is the proportion of total recycled binder in a RAP source that is available to blend with virgin asphalt. The vast majority of asphalt mixtures produced today contain RAP due to associated cost and environmental benefits. It is generally accepted that 100 percent RBA is not achieved in practice, which is not accounted for in the majority of state highway agency design procedures. Consequently, the innovation developed through this project serves an urgent need to address uncertainty in the performance of RAP asphalt mixtures designed under current procedures.

WHAT WAS THE GOAL?
The goal was to develop a practical method to quantify RBA predicated on prior research that demonstrates that RAP binder that is inside agglomerations of adhered RAP particles is ‘unavailable’ whereas peripheral binder coating RAP particles is ‘available’.

WHAT DID WE DO?
The project established a procedure to quantify RAP RBA using comparative sieve analysis of RAP and recovered RAP aggregate. The differences between the gradation of the RAP, termed the black curve, and there recovered RAP aggregate, termed the white curve, provides a measure of the extent of agglomeration in the RAP and hence, were used to calculate the RBA. The method was applied to nine RAP sources obtained from four states. Several sieve analysis procedural variables were evaluated, including the RAP drying and preheating procedures, use of washed versus dry sieve analysis of the RAP, and washing time. Furthermore, the RBA results of sieve analysis were compared to measurements of recycled binder contribution (RBC) in asphalt mixtures obtained through tracer-based microscopy. The effects of RBA on asphalt mixture design were evaluated by comparing the composition and performance of control asphalt mixtures designed under the assumption of 100 percent RBA with those redesigned according to the availability adjusted mixture design (AAMD) method. The AAMD method explicitly considers the role of RAP agglomerations and RBA on the design and evaluation of asphalt mixtures.

WHAT WAS THE OUTCOME?
The results indicate that conducting a washed sieve analysis of RAP using a drying temperature of 100°C after washing is optimal. The innovation was verified to accurately reflect RBC in asphalt mixtures through comparative tracer-based microscopy. Tracer-based microscopy analysis of asphalt mixtures fabricated using alternative preheating and conditioning procedures further indicates that RBC in asphalt mixtures

does not vary significantly with laboratory production conditions. Consequently, the results suggest promise for RBA results from sieve analysis to reflect RBC in asphalt mixtures produced under variable conditions. A draft AASHTO test procedure for the determination of RBA from sieve analysis was developed.

The AAMD method generally produced mixtures with enhanced cracking performance and generally similar rutting resistance compared to the control mixtures with the same or elevated RAP content. Also, virgin mixtures and AAMD RAP mixtures prepared with similar available volumetric and effective properties yielded similar cracking performance, suggesting potential for applying the AAMD method to counteracts RAP's detrimental effects on cracking resistance. These performance findings highlight the importance of integrating RBA considerations into mixture design.

WHAT IS THE BENEFIT?

The vast majority of asphalt mixtures produced today contain RAP due to associated cost and economic benefits. It is generally accepted that 100 percent RBA is not achieved in practice, which is not accounted for in the majority of state highway agency design procedures largely due to the lack of a method to quantify RBA. Consequently, the innovation developed through this project serves an urgent need to address uncertainty in the performance of RAP asphalt mixtures designed under current procedures. The results of this project suggest that considering RBA when designing asphalt mixtures has important performance implications.

IMAGES

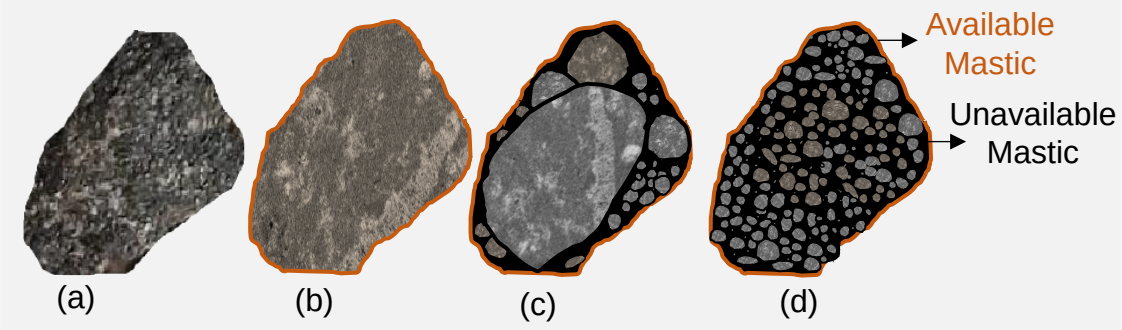

FIGURE 37 Depiction of RAP particles (a) photo of a RAP particle, (b) RAP particle with one core aggregate, (c) RAP particle containing a coarse aggregate particle surrounded by fine aggregates, and (d) RAP particle containing agglomerated fine aggregates