



Binder Availability in Recycled Materials: Review of Literature and Available Quantification Methods

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16. Abstract Increasing recycled material content in asphalt mixtures provides economic and environmental benefits, but each unique material combination of virgin and recycled materials and additives must be engineered to ensure adequate performance with proper selection of component materials and balanced proportioning, as well as consideration of recycled binder availability. The design of mixtures with recycled materials often assumes that 100 percent of the recycled binder is available to blend with the virgin binder, and the virgin binder content is reduced accordingly. In reality, when recycled binder availability is less than 100 percent for heavily aged materials, total binder contents are less than optimum from mix design, resulting in dry mixtures with insufficient coating and inadequate durability and cracking performance. In addition, recycled binder availability can be used to assess aging state and preclude the use of large quantities of these materials with stiff, brittle binders that contribute negatively to performance even if available. This synthesis project addressed these issues by reviewing the literature available on the topic of recycled binder availability, collecting information on the state of the practice regarding recycled binder availability, performing a detailed analysis on three different recycled binder availability quantification methods, and revising the Texas Department of Transportation balanced mix design spreadsheet for Superpave mixtures to incorporate recycled binder availability.					
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LITERATURE AND AVAILABLE QUANTIFICATION METHODS**

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DISCLAIMER

This research was performed in cooperation with the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of FHWA or TxDOT. This report does not constitute a standard, specification, or regulation.

This report is not intended for construction, bidding, or permit purposes. The engineer (researcher) in charge of the project was Amy Epps Martin, TX P.E. #91053.

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TABLE OF CONTENTS

	Page
List of Figures.....	viii
List of Tables	ix
Chapter 1 Introduction.....	1
Impact of Recycled Binder Availability	2
Objectives	4
Summary	5
Chapter 2 Literature Review	7
Studies on Binder Availability for Mixtures with RAP	7
Studies on Binder Availability for Mixtures with RAP and RAS	8
Studies on Binder Availability for Mixtures with RAS.....	8
Summary	9
Chapter 3 Information Gathering.....	11
Chapter 4 Methods to Estimate Recycled Binder Availability.....	15
Method I: NCHRP 09-58.....	16
Method II: RILEM TC RAP TG5.....	17
Method III: FHWA	23
Summary	25
Chapter 5 TxDOT Mix Design Revision.....	27
Chapter 6 Value of Research	31
Chapter 7 Summary and Recommendations	33
References	35
Appendix: Annotated Bibliography	41
Studies on Binder Availability for Mixtures with RAP.....	41
Studies on Binder Availability for Mixtures with RAP and RAS	55
Studies on Binder Availability for Mixtures with RAS.....	58

LIST OF FIGURES

	Page
Figure 1-1. Recycled binder availability scenarios: (a) no RAP/RAS binder availability or black rock; (b) partial availability of RAP/RAS binder and partial blending between recycled and virgin binders; (c) full RAP/RAS availability and full blending between recycled and virgin binders.	2
Figure 1-2. Coatability comparison for different recycling agent incorporation methods: (a) virgin aggregates, (b) replacement by full recycling agent amount, and (c) addition (no replacement) (Epps Martin et al. 2019; Arámbula-Mercado et al. 2018).....	4
Figure 1-3. Coatability index for rejuvenated asphalt mixtures with 0.4 RBR and 0.5 RBR with various recycling agent incorporation methods (Epps Martin et al. 2019; Arámbula-Mercado et al. 2018).	4
Figure 3-1. Web-based questionnaire.	11
Figure 3-2. RAP and RAS BAF values for nine states with reduced BAFs.	14
Figure 4-1. NCHRP 09-58 method to quantify recycled binder availability (Kaseer et al. 2019).	16
Figure 4-2. Relationship between RAP BAF and RAP PGH at (a) 140°C and (b) 150°C mixing temperatures.....	17
Figure 4-3. Equipment used to estimate recycled binder availability in the RILEM method: (a) SGC and (b) IDT.	18
Figure 4-4. Typical force-displacement curves obtained from the IDT strength test at different conditioning temperatures.	19
Figure 4-5. Typical load-displacement curve with parameters used in the CT_{Index} calculation (ASTM D8225).	20
Figure 4-6. DoA calculated by the RILEM method at different conditioning temperatures based on (a) S_T , and (b) CT_{Index}	21
Figure 4-7. The effect of recycled binder availability on mixture performance: (a) RAP BAF versus S_T , and (b) RAP BAF versus CT_{Index}	22
Figure 4-8. Comparison between NCHRP 09-58 method and RILEM method RAP binder availability results at 140°C.	23
Figure 4-9. Determination of DWT parameter (Dongré et al. 2015).....	24
Figure 4-10. RAP BAF at 150°C mixing temperature from NCHRP 09-58 compared to (a) DWT at 150°C and (b) predicted RAP PGH (°C).....	24
Figure 5-1. Revised TxDOT balanced mix design spreadsheet for Superpave mixtures to account for recycled binder availability.....	28

LIST OF TABLES

	Page
Table 1-1. Properties of mixtures in coatability study (Epps Martin et al. 2019; Arámbula-Mercado et al. 2018).	3
Table 3-1. Current state DOT recycled binder availability practices.	13
Table 4-1. Properties of RAP sources used in NCHRP 09-58, RILEM, and FHWA studies.	15
Table 4-2. Comparison of binder availability quantification methods.	26
Table 6-1. Estimated value of research (annual basis).	32
Table A-1. Recommended methods to estimate blending parameters.....	56

CHAPTER 1 INTRODUCTION

Economic and environmental benefits motivate state agencies to consider the use of reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS) in pavement construction. Employing recycled materials that are obtained from milling operations is cost effective because it reduces the need to mine and transport aggregates and to acquire virgin asphalt binder. In addition, by repurposing the use of recycled materials, the use of landfills for their disposal is minimized.

State agencies usually consider limiting the amount of recycled materials in new asphalt mixtures, and these limits typically vary depending on the layer of the pavement (i.e., surface, intermediate, or base) and experience (i.e., observed pavement performance) with the use of recycled materials. However, the asphalt industry in general is pushing toward increasing the amount of recycled materials that is allowed or included in asphalt mixtures in all layers of the pavement, which raises concerns regarding the future performance and longevity of pavements surfaced or resurfaced with these materials.

An important factor that controls the performance of these recycled asphalt mixtures is the amount of recycled binder that becomes available during production and construction. This amount of available recycled binder in recycled asphalt mixtures is affected by:

- Component materials—RAP and/or RAS aging state/source and original binder grade, binder content, and gradation; and additive type(s), including recycling agents or warm mix asphalt (WMA) additives.
- Proportioning—additive dose.
- Production and construction—mixing and storage times and temperatures.

Higher recycled binder availability in recycled asphalt mixtures can be realized when using less aged RAP/RAS, incorporating recycling agents or WMA additives, and employing higher mixing and storage temperatures. Recycled binder availability can be illustrated by three possible scenarios (D'Angelo et al. 2011; Kaseer et al. 2019; Huang et al. 2005; McDaniel and Anderson 2001):

- No availability/blending: the RAP/RAS acts as a black rock, and no recycled binder becomes available during the asphalt mixture production process, as illustrated in Figure 1-1(a).
- Full availability/blending: all the RAP/RAS binder becomes available during the asphalt mixture production process, yielding a blend of recycled and virgin binder that coats the virgin and recycled aggregate particles, as illustrated in Figure 1-1(c).
- Partial availability/blending: a case between Scenario 1 and 2, where a portion of the RAP/RAS binder becomes available and blends with the virgin binder, as illustrated in Figure 1-1(b).

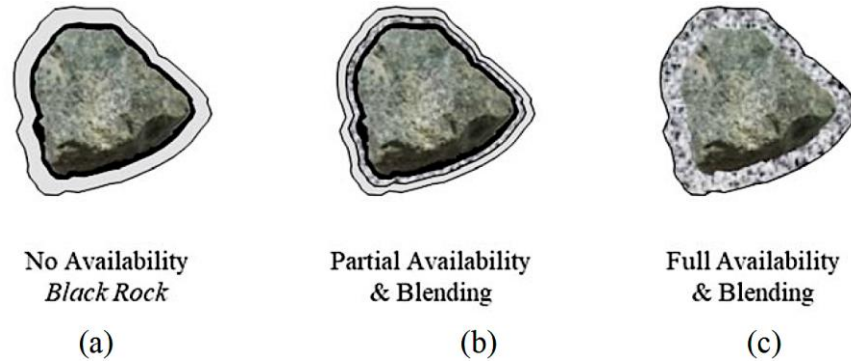


Figure 1-1. Recycled binder availability scenarios: (a) no RAP/RAS binder availability or black rock; (b) partial availability of RAP/RAS binder and partial blending between recycled and virgin binders; (c) full RAP/RAS availability and full blending between recycled and virgin binders.

It is currently widely accepted, based on the results of many past research studies, that when the RAP/RAS is incorporated in a hot mix asphalt (HMA) mixture, the recycled binder becomes partially available, and thus partial blending occurs, as shown in Figure 1-1(b).

Despite the knowledge that the recycled binder is partially available and partial blending occurs during HMA production, many current mix design procedures (including Texas Department of Transportation [TxDOT] Special Specification [SS] 3076, SS 3077, and SS 3074) estimate the recycled binder content using either ignition oven or extraction and assume all recycled binder is available and contributes to the total optimum binder content in the asphalt mixture. In other words, these mix design procedures assume Scenario 3 (Figure 1-1[c]).

IMPACT OF RECYCLED BINDER AVAILABILITY

It is important to quantify the recycled binder availability for mix design and to estimate the effect of partial blending on asphalt mixture properties. A wrong assumption regarding recycled binder availability could yield an insufficient amount of virgin binder in the asphalt mixture, with negative effects on pavement performance. If part of the recycled binder is not available during the asphalt mixture production process, the assumption of a 100 percent availability, and thus full blending, could lead to asphalt mixtures with less effective binder content. Mixtures with this characteristic, also called dry mixtures, will exhibit uncoated aggregates and will be prone to premature cracking and moisture damage distress. Conversely, assuming a lower recycled binder availability than the one that actually occurs in the asphalt mixture could lead to an excessive effective binder content, which could generate stability and compatibility issues during construction and rutting distress during service. This could be particularly problematic when softer virgin binders and/or rejuvenators are incorporated in the recycled asphalt mixture at high recycled material contents.

The selection of an appropriate recycled binder availability factor is critical to preclude insufficient aggregate coatability that could result in workability and durability issues. National

Cooperative Highway Research Program (NCHRP) Project 09-58, The Effects of Recycling Agents on Asphalt Mixtures with High RAS and RAP Binder Ratios, performed a limited study to evaluate the effect of recycling agents on aggregate coatability in recycled asphalt mixtures. The degree of coatability was assessed based on the method proposed by Newcomb et al. (2015) that measures coatability index (CI) as the difference in saturated surface dry water absorption for the uncoated and coated coarse aggregate fraction (larger than 9.5 mm) after 1 hour of soaking in water. The larger the CI, the better the aggregate coating (Epps Martin et al. 2019; Arámbula-Mercado et al. 2018).

The referenced study evaluated two mixtures with high recycling agent doses (9.5 percent and 12.5 percent) to mitigate high recycled binder ratios (RBRs) (Table 1-1). RBR represents the percentage by weight of total recycled binder (assuming 100 percent availability) to total binder weight in the asphalt mixture:

$$RBR = \frac{P_{b_{RAP}} \times P_{RAP}}{100 \times P_{b_{total}}} + \frac{P_{b_{RAS}} \times P_{RAS}}{100 \times P_{b_{total}}} \quad (\text{Equation 1.1})$$

Where

- $P_{b_{RAP}}$ = binder content of RAP,
- P_{RAP} = RAP content by weight of mixture,
- $P_{b_{RAS}}$ = binder content of RAS,
- P_{RAS} = RAS content by weight of mixture, and
- $P_{b_{total}}$ = total binder content of the combined mixture.

Table 1-1. Properties of mixtures in coatability study (Epps Martin et al. 2019; Arámbula-Mercado et al. 2018).

Mixture	Recycling Agent Dose	Recycling Agent Type	Virgin Binder	RBR
0.4 RBR	9.5%	Aromatic extract	Performance grade (PG) 64-22	0.4 RAP
0.5 RBR	12.5%	Tall oil	PG 64-28	0.25 RAP + 0.25 RAS

The recycling agents were incorporated in the mixtures using three methods to reflect the spectrum of possibilities when adding the recycling agent: (a) no replacement of the virgin binder (i.e., addition of the recycling agent), (b) replacement of the virgin binder by half of the recycling agent amount, and (c) replacement of the virgin binder by the full recycling agent amount. Figure 1-2 illustrates the effect of recycling agent incorporation methods (a) and (c) on aggregate coatability.

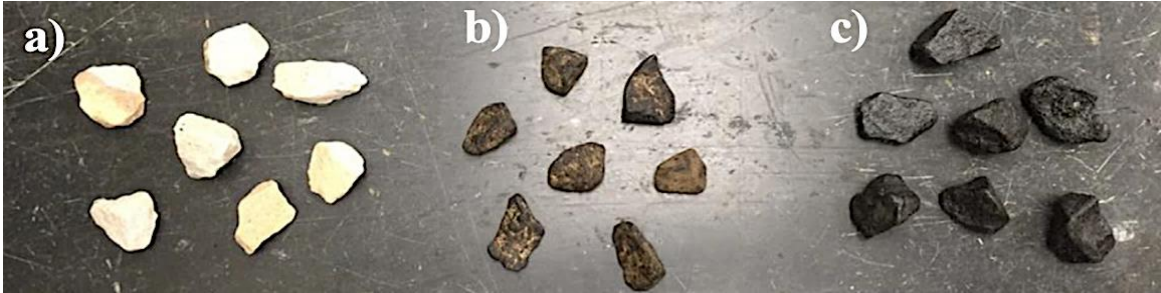


Figure 1-2. Coatability comparison for different recycling agent incorporation methods: (a) virgin aggregates, (b) replacement by full recycling agent amount, and (c) addition (no replacement) (Epps Martin et al. 2019; Arámbula-Mercado et al. 2018).

Calculated CI values for the two mixtures listed in Table 1-1 are shown in Figure 1-3. For both high RBR mixtures with high recycling agent doses, the coatability decreased when the full amount was used to replace virgin binder, and this decrease was more critical for the recycled mixture with both RAP and RAS. This suggests that these combinations of materials were not optimal for adequate performance, partially due to insufficient binder availability of recycled materials.

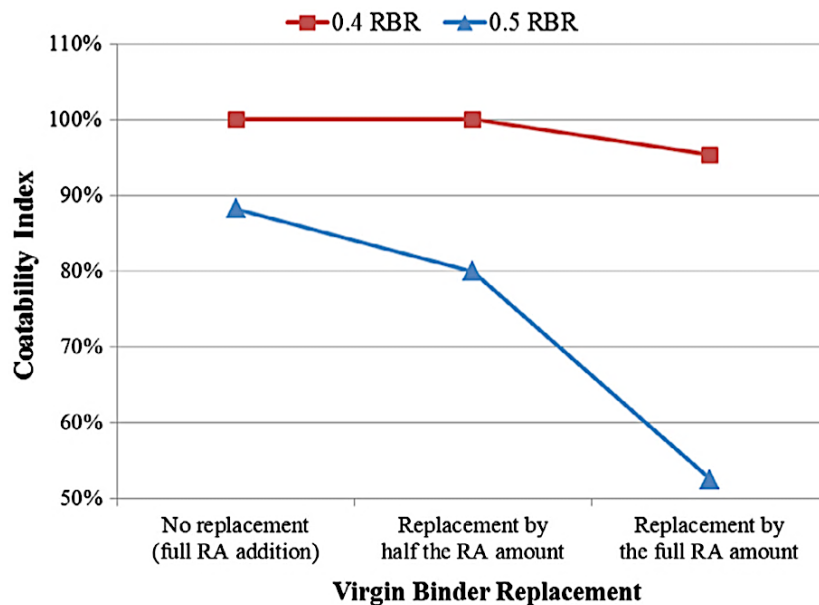


Figure 1-3. Coatability index for rejuvenated asphalt mixtures with 0.4 RBR and 0.5 RBR with various recycling agent incorporation methods (Epps Martin et al. 2019; Arámbula-Mercado et al. 2018).

OBJECTIVES

The objectives of this project were to explore the issue of recycled binder availability and provide recommendations for TxDOT to account for recycled binder availability in mix design for Superpave mixtures. These objectives were accomplished through the performance of the following tasks:

- Literature review on recycled binder availability.
- Information gathering on the state of the practice regarding recycled binder availability.
- Assessment of different methodologies to quantify recycled binder availability.
- Revision of TxDOT mix design spreadsheet for Superpave mixtures to include recycled binder availability.

SUMMARY

This chapter provided background information on the importance of quantifying recycled binder availability and factors affecting it. A discussion of the impacts of recycled binder availability was provided, with a focus on its effect on aggregate coatability. This chapter also summarized the objectives and the scope of work of this project. This report is composed of five chapters. This chapter (Chapter 1) includes background information, project objectives, and report organization. Chapter 2 provides a summary of the literature review performed on recycled binder availability. Chapter 3 summarizes the information gathered from state departments of transportation (DOTs) regarding recycled binder availability. Chapter 4 provides a detailed summary of methodologies reviewed to quantify recycled binder availability, including testing protocols, and equations to calculate recycled binder availability. Chapter 5 explains proposed revisions to the TxDOT mix design spreadsheet for Superpave mixtures to incorporate recycled binder availability. Chapter 6 summarizes the major findings of this project and lists future research needs.

CHAPTER 2 LITERATURE REVIEW

A literature review was performed on methods to quantify recycled binder availability using references gathered as part of the recently completed national research project NCHRP 09-58, a currently ongoing international effort focused on recycled binder availability and blending, and a thorough review of electronic databases performed by the Texas Transportation Institute's (TTI's) Library Services staff. The total number of references identified via these efforts were 252, and 51 of them were selected for further detailed review, out of which 42 were found relevant and summarized. The references were divided by the type of material described in the research study as follows: (a) RAP only, (b) combination of RAP and RAS, and (c) RAS only. In addition, a detailed summary in annotated bibliography format of the references selected for detailed review is included in the appendix.

STUDIES ON BINDER AVAILABILITY FOR MIXTURES WITH RAP

Most of the references, 32 out of the 42 that were found relevant and summarized, studied the availability of RAP binder in asphalt mixtures. A brief summary of each of these studies in annotated bibliography format is included in the appendix. About 15 of these references used extracted or staged extracted RAP binder or blended RAP and virgin binders to estimate the recycled binder availability/blending (AbuQtaish et al. 2018; Eddhahak-Ouni et al. 2012; Gottumukkala et al. 2018; Jiang et al. 2018; Liphardt et al. 2015; Mohammadafzali et al. 2019; Nahar et al. 2013; Shirodkar et al. 2011; Sreeram et al. 2018; Sreeram and Leng 2019; Vassaux et al. 2018; Xu et al. 2014; Xu et al. 2018; Yang et al. 2019; Yu et al. 2017). Techniques used to assess the extracted binder properties included rheology (complex modulus, phase angle, multiple stress creep recovery [MSCR] parameters), penetration, softening point, atomic force microscopy (AFM), Fourier transform infrared spectroscopy (FTIR), scanning electron microscope (SEM), gel permeation chromatography (GPC), and X-ray microcomputed tomography (CT) and imaging techniques.

Another 13 of the RAP references related to the study of mixture performance properties to estimate the recycled binder availability/blending with and without the presence of WMA additives or rejuvenators (Al-Qadi et al. 2009; Bennert & Asphalt, 2012; Booshehrian et al. 2013; Carbonneau et al. 2012; Coleri et al. 2018; Coffey et al. 2013; Daniel and Mogawer 2010; Faheem et al. 2018; Hajj et al. 2012; Menegusso Pires et al. 2019; Mogawer et al. 2012; Wen and Zhang 2016; Yu et al. 2017). Test methods used to assess the asphalt mixture properties included volumetric, workability, stability, semicircular bending (SCB), disc-shaped compact tension (DCT), dynamic modulus, indirect tensile (IDT) strength, flow number, flexural beam fatigue, and overlay. About five studies focused on the correlation between the complex modulus from extracted RAP/virgin blended binder and the dynamic modulus of recycled asphalt mixtures under the assumption that the dynamic modulus of the asphalt mixture was heavily dependent on the binder stiffness (Booshehrian et al. 2013; Carbonneau et al. 2012; Daniel and Mogawer 2010; Hajj et al. 2012; Mogawer et al. 2012). In addition, one of the references used asphalt mixture

dynamic modulus measurements to estimate pavement performance in the mechanistic-empirical pavement design guide (MEPDG) (Coffey et al. 2013).

About six of the references included in this subset focused on estimating the recycled binder availability/blending using distinct aggregate fractions, one fraction with RAP and the other with virgin aggregate. Four of those studies employed extracted binder properties to make the estimate (Gottumukkala et al. 2018; Shirodkar et al. 2011; Yang et al. 2019; Yu et al. 2017), one used surface area of the aggregates (Stimilli et al. 2015), and another used binder content determined with an ignition oven (Kasser et al. 2019).

Last, five references focused on studying the longer-term diffusion of the virgin binder into the RAP material using either the dynamic shear rheometer (DSR), X-ray CT, or IDT test methods (Kriz et al. 2014a; Kriz et al. 2014b; Mohammadafzali et al. 2019; Rad et al. 2014; Wen and Zhang 2016).

STUDIES ON BINDER AVAILABILITY FOR MIXTURES WITH RAP AND RAS

The studies that evaluated asphalt mixtures with RAP and RAS (6 out of the 42 that were found relevant and summarized) focused on degree of blending, availability, and activation. A brief summary of each of these studies in annotated bibliography format is included in the appendix. Some researchers evaluated degree of blending or activation by comparing predicted and measured dynamic moduli using models such the Hirsch model (Ashtiani et al. 2018; Mogawer et al. 2013). Others used blending charts to evaluate blending in RAS and RAP binders (Zhou et al. 2013). Only a few researchers quantified the amount of available RAS or RAP binder using chemical methods such as GPC (Zhao et al. 2015). Mixture tests including four-point bending beam fatigue, SCB, DCT, dynamic modulus, and IDT strength were also performed to evaluate degree of blending and activation in RAP and RAS mixtures (Ashtiani et al. 2018; Nazzal et al. 2017). In general, asphalt mixtures produced with RAP showed a greater amount of available binder when compared to those produced with RAS (Nazzal et al. 2017; Zhao et al. 2015). A national survey was conducted to determine binder availability factors for RAP and RAS used in different state agencies (Stroup-Gardiner 2016). The results of the surveys showed that the binder availability factor varied widely among different state agencies.

STUDIES ON BINDER AVAILABILITY FOR MIXTURES WITH RAS

Four studies, out of the 42 that were found relevant and summarized, evaluated the degree of blending in asphalt mixtures with RAS. A brief summary of each of these studies in annotated bibliography format is included in the appendix. Some of these studies evaluated blending using binder rheology tests such as DSR and bending beam rheometer (BBR) (Zhou et al. 2013; Zhao et al. 2014). Other studies evaluated blending using microscopic tools such as AFM (Zhao et al. 2015). Chemical approaches have also been implemented to evaluate blending by analyzing chemical composition of binders (Zhao et al. 2014). In addition, mixture tests have been

conducted to evaluate the degree of blending between RAS and virgin binder (Sharifi et al. 2019). Examples of mixture tests adopted in previous studies include four-point bending beam fatigue and SCB tests. Some of these studies demonstrated that blending occurs between RAS and virgin binder (Sharifi et al. 2019; Zhou et al. 2013; Zhao et al. 2014), while others concluded that blending does not occur (Zhao et al. 2015).

SUMMARY

The consensus from the studies that were summarized is that partial blending does occur during asphalt mixture production, and that many factors affect the recycled binder availability/blending, primarily virgin binder grade, RAP/RAS source (degree of oxidative aging), RAP/RAS content, RAP/RAS binder content, and mixing temperature. More recycled binder availability/blending was observed when softer virgin binders or rejuvenators were incorporated in the recycled asphalt mixture, less RAP/RAS content was introduced, or elevated asphalt mixture mixing and storage temperatures were considered. Not all references measured or reported a numerical value for the recycled binder availability/blending factor, and most references gave a range depending on recycled binder content.

For the RAP studies, the reported recycled binder availability values ranged from 16 percent to 96 percent (Coleri et al. 2018; Gottumukkala et al. 2018; Jiang et al. 2018; Kaseer et al. 2019; Menegusso Pires et al. 2019; Shirodkar et al. 2011; Stimilli et al. 2015; Yu et al. 2017). In addition, a couple of studies focused on assessing only the RAP availability by combining heated RAP material with virgin aggregate without added virgin binder and reported lower recycled binder availability values of around 10 percent to 24 percent (Gottumukkala et al. 2018; Shirodkar et al. 2011).

The wide range in recycled binder availability values reported in the literature, and the diversity in methods used to quantify it, highlight the importance of understanding this phenomenon and developing values that are applicable to Texas RAP, RAS, and virgin binder sources. This understanding will facilitate improvement of the mix design procedure and ensure better asphalt mixture performance and longer pavement service life.

CHAPTER 3 INFORMATION GATHERING

Information on the state of the practice regarding recycled binder availability was gathered by submitting a short web-based questionnaire to TxDOT personnel, who then distributed it to DOT members of the American Association of State Highway and Transportation Officials (AASHTO) Committee on Materials and Pavements (COMP). State DOTs that indicated that they utilize a reduced recycled binder availability, also called binder availability factor (BAF), were interviewed in follow-up telephone conversations. The simple, single-question web-based questionnaire shown in Figure 3-1 was distributed with TxDOT assistance to members of the AASHTO COMP to determine which state DOTs utilize a BAF less than 1.0 (or 100 percent) for RAP and/or RAS. A strong and rapid response rate from 38 of 50 states (76 percent) indicated that 10 states reduce their recycled binder availability. These states include Delaware (DE), Illinois (IL), Georgia (GA), Tennessee (TN), New York (NY), Ohio (OH), South Carolina (SC), Kentucky (KY), Louisiana (LA), and Arkansas (AR).

The Texas A&M Transportation Institute (TTI) is conducting research to assess the current state-of-the-practice regarding recycled asphalt mix design procedures and binder availability factors, for the TxDOT project 0-7062 *Synthesis for Quantification of Binder Availability in Recycled Materials*. Please complete the following based on your organization's current specifications and procedures by **January 6, 2020**:

Do your state specifications or procedures consider a recycled materials binder availability factor less than 1.0 (or 100%) for RAP and/or RAS?

YES

NO

When you select a response to the question above, a webpage will be displayed in your browser, where you will confirm your selection and enter your contact information and available times for a short follow-up interview if necessary.

If you are not the best person to respond, please forward this email to the appropriate person. Questions or comments can be directed to the principal investigator of the TxDOT research project, Amy Epps Martin (a-eppsmartin@tamu.edu).

- **Binder Availability** refers to the amount of recycled binder from reclaimed asphalt pavement (RAP) or recycled asphalt shingles (RAS) that activates and contributes to the total effective binder content in an asphalt mixture.
- Mix design of asphalt mixtures with recycled materials often assumes 100% recycled binder availability; however, in reality, the binder availability is often less than 100%, especially for heavily aged materials.
- Assuming 100% recycled binder availability often results in a dry asphalt mixture with a total binder content less than optimum, insufficient aggregate coating, and inadequate durability and cracking performance.

Figure 3-1. Web-based questionnaire.

Short follow-up interviews were conducted by phone with those 10 states that responded affirmatively to the questionnaire to determine the following and request any additional references (presentations, links, documents):

1. What are the RAP and RAS binder availability factor(s) utilized in your state?
 - a. How were they determined?
 - b. When and how were they introduced?
2. Have you adjusted them? When and why?
3. What are the typical RAP and RAS PG grades in your state?
 - a. What are the typical target PG grades in your state?
 - b. What are the typical base binder (substitute) PG grades in your state?
4. How are RAP and RAS binder contents determined?

Results from the follow-up interviews are summarized in Table 3-1, with data for only nine states provided because AR indicated a reduced BAF in error on the questionnaire.

Different methods are utilized by the different state DOTs to ensure sufficient binder in recycled asphalt mixtures for cracking resistance and durability. Most reduce the credit for the recycled (RAP and/or RAS) binder content as part of the total binder content, while others increase the required total binder content or correct the original optimum binder content from mix design to obtain a corrected optimum asphalt content (COAC). This COAC method was developed by Georgia DOT (GDOT) and documented in NCHRP Synthesis 495 (Stroup-Gardiner 2016). GDOT's research was adopted by nearby South Carolina and Kentucky. Delaware DOT (DelDOT) adopted recommendations from AASHTO PP78 and results from NCHRP Project 09-58 (Epps Martin et al. 2019) in its revised RAP Calculator spreadsheet, and Illinois DOT (IDOT) reduced the G_{sb} for RAS by 0.2 based on AASHTO PP78 and requirement by FHWA. New York State DOT (NYSDOT) increased total binder content by 0.2 percent when more than 10 percent RAP is used, and developed an engineering instruction for a maximum of 20 percent RBR when RAS is utilized (with a requirement that RAP also be included). Kentucky DOT (KYDOT) also increased total binder content from mixtures designed at 3.5 percent air voids and $N=65$ to address premature failures and the increased use of RAP and RAS.

Figure 3-2 plots the RAP and RAS BAF values for the nine state DOTs with factors less than 100 percent. Seven state DOTs reduce the RAS BAF, while only four of these same state DOTs provide a reduced RAP BAF. In addition, the RAS BAF is always lower than the corresponding RAP BAF. Most of these factors were introduced 1–5 years ago, but KYDOT and Oregon DOT (ODOT) introduced theirs in 2011 and 2012, respectively. Most DOTs have not revised their factors, although GDOT, ODOT, and DelDOT have recently made revisions based on additional data.

Table 3-1. Current state DOT recycled binder availability practices.

State	RAP BAF (%)	RAS BAF (%)	Latest Revision	Method	Typical Target PG	Substitute PG	Recycled P_b
DE	90	80	2020	Reduced recycled P _b in spreadsheet	PG 64-22	PG 58-28 PG 64-28	Extraction & recovery, ignition
IL	100	85	2019	Reduced G _{sb}	PG 58-28 PG 64-22	PG 58-28	Extraction & recovery, ignition
GA	60	— ^{\$}	2019	COAC	PG 64-22	No	Ignition primarily
TN	100	75 [^]	2015	Reduced recycled P _b	PG 64-22 PG 67-22		Extraction & recovery, ignition
NY	—	60	2015	Increased total P _b	PG 64-22		Extraction & recovery
OH	100	60 [*]	2019	Reduced recycled P _b	PG 58-28 PG 64-22	Yes	Extraction & recovery
SC	75	75 [^]	~2017	Reduced recycled P _b	PG 64-22		Ignition
KY	100	75	2012	Reduced recycled P _b , increased total P _b	PG 64-22	PG 58-28	Extraction & recovery
LA	92 [*]	— ^{\$}	2018	Decreased RAP P _b by 0.4 from ignition	PG 67-22	PG 58-28	Ignition

* Estimated: 12% max (=60% of total estimated 20% RAS P_b); 0.4% decrease (=92% of total estimated 5% RAP P_b).

[^] Limited RAS.

^{\$} No RAS.

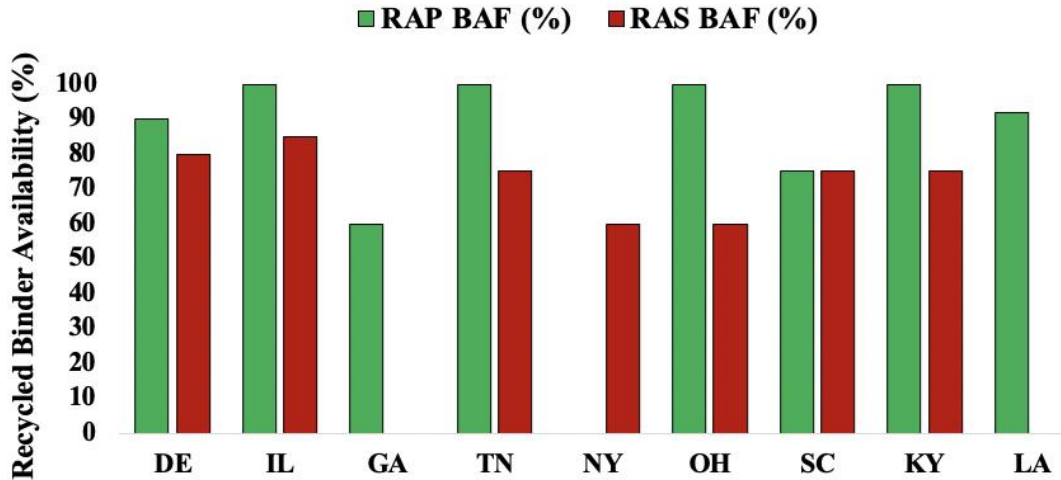


Figure 3-2. RAP and RAS BAF values for nine states with reduced BAFs.

In summary, this chapter summarized the information gathered from state DOTs regarding recycled binder availability. Results from the web-based questionnaire and follow-up interviews suggest the following:

- Recycled binder from RAP and RAS is not completely available for blending, and thus RAP and RAS BAF values should be less than 100 percent. This effect is exacerbated as recycled material content increases.
- RAP binder is more available than RAS binder due to differences in stiffness at common mixing temperatures, and thus the RAS BAF should be less than the RAP BAF.
- Ongoing interaction with contractors, asphalt binder user-producer groups, and the state asphalt pavement association is recommended to facilitate compromise with industry.

CHAPTER 4 METHODS TO ESTIMATE RECYCLED BINDER AVAILABILITY

Three methods to quantify RAP binder availability were compared by reviewing the results from three studies: (a) recently completed NCHRP 09-58, which quantified RAP binder availability for seven sources; (b) an ongoing International Union of Laboratories and Experts in Construction Materials, Systems and Structures (RILEM) Technical Committee (TC) RAP Task Group (TG5) coordinated effort in which TTI is participating by characterizing five of the same RAP sources; and (c) a Federal Highway Administration (FHWA) initiative where six of the same RAP sources were analyzed. The properties and location of the RAP sources used in these studies are summarized in Table 4-1.

Table 4-1. Properties of RAP sources used in NCHRP 09-58, RILEM, and FHWA studies.

RAP Source	Continuous PG Grade (°C)	Binder Content
Indiana (IN)	90-13	5.2%
Delaware (DE)	86-13	4.4%
Wisconsin (WI)	83-10	4.7%
Florida (FL)	99-19	4.8%
New Hampshire (NH)	90-20	4.6%
Henderson, Texas (TX1)	106-2	5.3%
Austin, Texas (TX2)	98-8	4.3%
Nevada (NV)	84-20	4.4%

This section describes the methods that can be employed to quantify recycled binder availability (NCHRP 09-58, RILEM, and FHWA). In addition, a comparison of results is provided.

METHOD I: NCHRP 09-58

NCHRP Project 09-58 quantified recycled binder availability using RAP from seven distinct locations: TX1, NH, WI, DE, IN, NV, and FL. In this method, the BAF of RAP is estimated by preparing two mixtures: (a) virgin mixture, and (b) RAP mixture. The virgin mixture is prepared using virgin binder and virgin aggregates with three specified sizes (coarse, intermediate, and fine particles), as shown in Figure 4-1. The mixture is short-term oven aged for 2 hours at the desired mixing temperature of 140°C or 150°C. After aging, the loose mixture is sieved to separate the aggregates coated with binder into the three fractions. The binder content of these fractions is then determined using the ignition oven per AASHTO T 308, and the binder content of the intermediate aggregates is used as a reference (Reference P_b) without correcting for fines lost. The RAP mixture is next prepared using three components: (a) virgin binder, (b) virgin aggregate (coarse and fine particles), and (c) RAP aggregates (intermediate particles). Like the virgin mixture, the loose mixture is short-term aged and sieved, and the binder content of the intermediate RAP particles is determined (RAP' P_b).

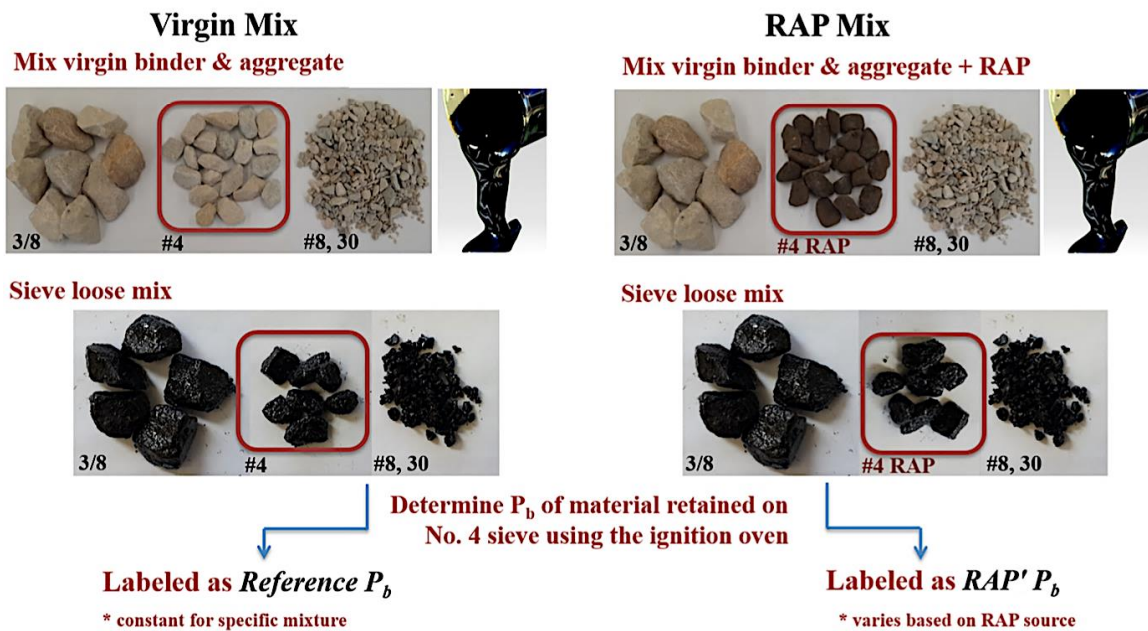


Figure 4-1. NCHRP 09-58 method to quantify recycled binder availability (Kaseer et al. 2019).

The Reference P_b and RAP' P_b values are used to estimate the percent of RAP binder availability by considering the following three scenarios:

- **Scenario 1:** $RAP' P_b = Reference P_b$ indicates full release of the RAP binder, which implies 100 percent RAP binder availability.
- **Scenario 2:** $RAP' P_b = ([1 - RBR] \times Reference P_b + RAP \text{ binder content})$ indicates that the RAP binder is acting as a black rock with 0 percent binder availability.

- **Scenario 3:** $Reference\ Pb < RAP'\ Pb < ([1 - RBR] \times Reference\ Pb + RAP\ binder\ content)$ indicates that the RAP binder is partially available.

The relationship between recycled binder availability and high-temperature performance grade (PGH) of the binder was explored by plotting RAP BAF against RAP binder PGH at 140°C and 150°C mixing temperatures, as shown in Figure 4-2. The results indicated that some relationship exists between the two variables. The lower the PGH of the RAP binder, the higher the BAF. This agrees with expected behavior for a more heavily aged RAP with a higher PGH and thus a higher stiffness of the binder coating the RAP particle. RAP binder availability is also affected by mixing temperature. Increasing the mixing temperature from 140°C to 150°C increased the RAP binder availability. For example, the NH RAP binder was 75 percent available at 140°C mixing temperature and became 91 percent available at 150°C.

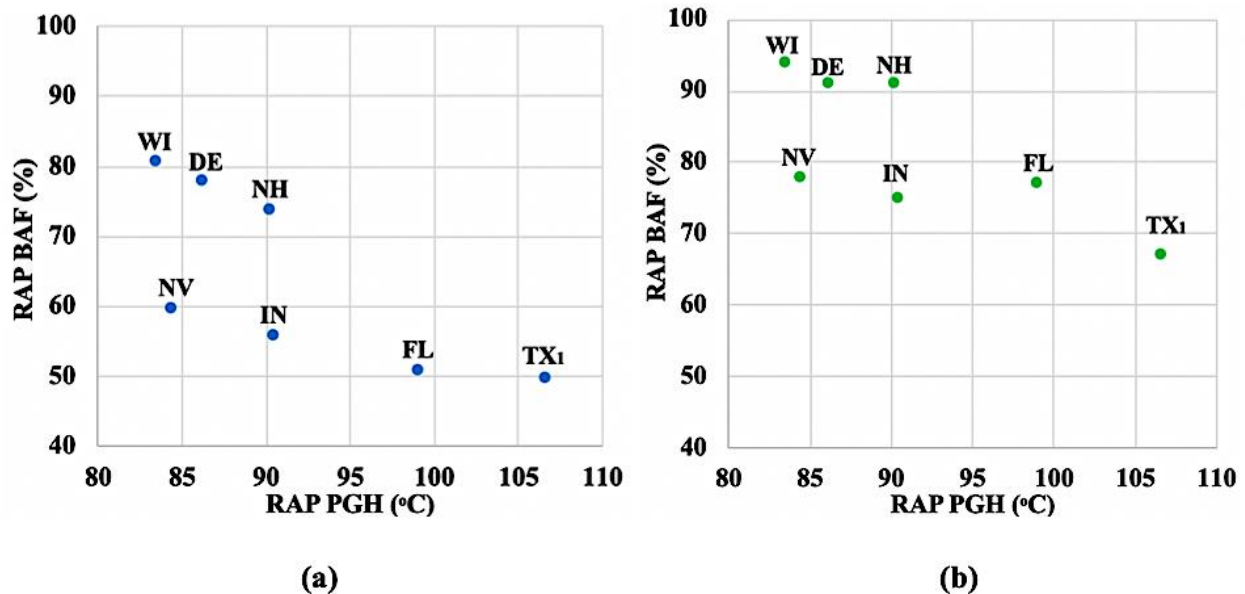


Figure 4-2. Relationship between RAP BAF and RAP PGH at (a) 140°C and (b) 150°C mixing temperatures.

Kaseer et al. (2019) indicated that the NCHRP 09-58 method could provide a reasonable estimate of recycled binder availability. However, this method requires extensive laboratory work and the use of selected virgin and recycled materials. Other shortcomings of this method are that it only considers intermediate RAP retained on the No. 4 sieve to represent the entire RAP gradation and it only applies to RAP.

METHOD II: RILEM TC RAP TG5

The ongoing RILEM effort evaluates the effect of recycled binder availability using RAP obtained from six sources: TX2, NH, WI, DE, IN, and FL. In this method, RAP availability is evaluated by performing IDT tests on 100 percent RAP mixtures to determine the IDT strength (ST) and cracking tolerance index (CT_{Index}). First, RAP is dried in the oven for 48 hours at 40°C.

Then, the material is conditioned in the oven for 4 hours prior to compaction at one of five temperatures (70°C, 100°C, 140°C, 170°C, and 190°C) selected to represent recycled mixture production temperatures and capture the range of potential RAP binder availability. After conditioning, the material is mixed by hand and specimens are compacted in the Superpave gyratory compactor (SGC) (Figure 4-3[a]). The IDT strength test (Figure 4-3[b]) is then performed at room temperature with at least five different replicates tested for each mixture.

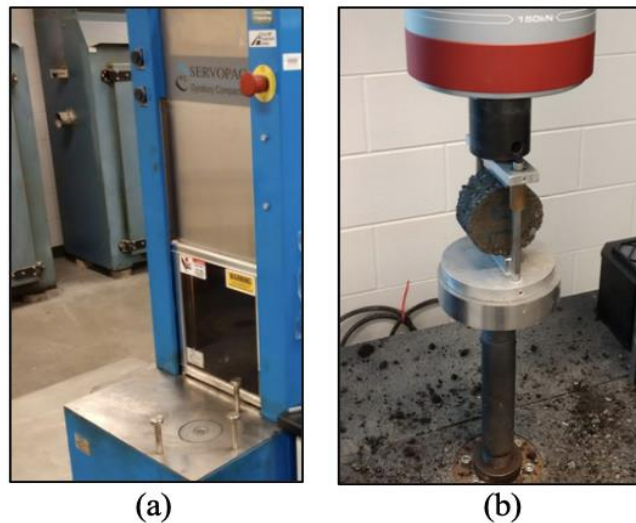


Figure 4-3. Equipment used to estimate recycled binder availability in the RILEM method: (a) SGC and (b) IDT.

To analyze the IDT data, force-displacement diagrams are evaluated for the 100 percent RAP mixtures. Figure 4-4 shows an example of force-displacement curves at the different conditioning temperatures. With increasing conditioning temperature (up to 140°C or 170°C for some RAP sources), the peak force and stiffness increase. Beyond this temperature, the peak force and stiffness decrease. It is assumed that the increase in peak force is due to more RAP binder becoming available at higher temperature, which improves the performance of the RAP specimen. However, the reason for the reduction in peak force after the conditioning temperature increased to 170°C or 190°C is likely due to a phenomenon known as clustering. Clustering refers to the adherence of RAP particles of various sizes to each other. Previous research by Bressi et al. (2015) evaluated the effect of mixing temperature on asphalt mixtures with 50 percent RAP content and found that RAP particles did not cluster at excessively high temperatures. The reason for this is because at extremely high mixing temperatures, the RAP particles lose volatiles and become excessively hardened. The inability of RAP particles to cluster at such high temperatures reduces the amount of available recycled binder in the RAP, and thus the peak force or the stiffness of the mixture is also reduced.

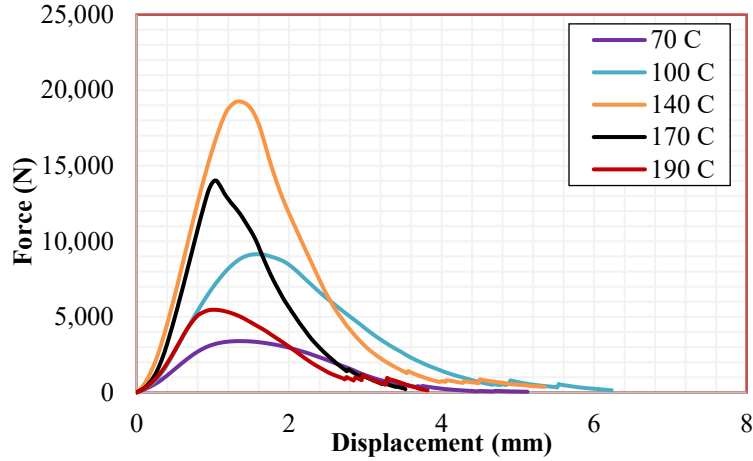


Figure 4-4. Typical force-displacement curves obtained from the IDT strength test at different conditioning temperatures.

S_T is calculated based on the peak force (Tex-226-F):

$$S_T = \frac{2F}{\pi \times (hd)} \quad (\text{Equation 4.1})$$

Where

F = vertical load at failure,
 h = specimen height, and
 d = specimen diameter.

The results of the IDT tests can also be used to calculate the CT_{Index} , which is a cracking tolerance parameter (ASTM D8225). The higher the CT_{Index} , the better the cracking resistance of the mixture. CT_{Index} can be computed from force-displacement curves obtained from IDT strength tests. As shown in Equation 4.2, the index is calculated based on specimen dimensions and three parameters: G_f , $|m_{75}|$, and l_{75}/D . G_f represents the fracture energy and can be calculated by dividing the total work under the force-displacement curve by the area of the cracking surface of the specimen (Figure 4-5). The parameters $|m_{75}|$ and l_{75}/D are calculated based on the post-peak point (PPP₇₅) where the load reduces to 75 percent of the peak load (Zhou et al. 2017).

$$CT_{\text{Index}} = \frac{t}{62} \times \frac{G_f}{|m_{75}|} \times \left(\frac{l_{75}}{D} \right) \quad (\text{Equation 4.2})$$

Where

G_f = total fracture energy,
 l = displacement,
 D = specimen diameter, and
 t = specimen thickness.

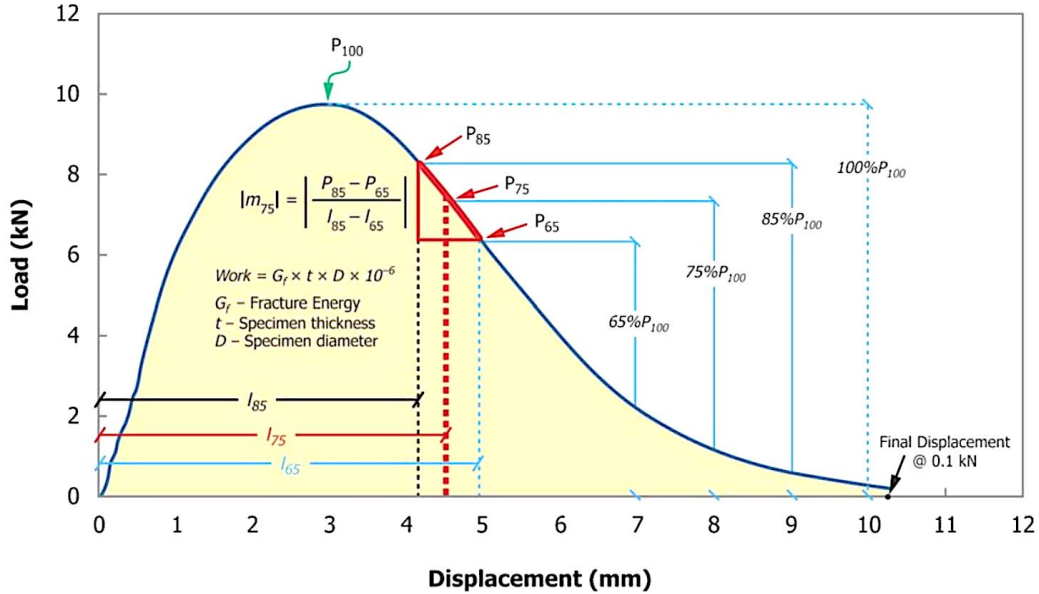


Figure 4-5. Typical load-displacement curve with parameters used in the CT_{Index} calculation (ASTM D8225).

After determining S_T and CT_{Index} , the recycled binder availability is estimated by calculating a parameter defined as the degree of activation (DoA). DoA is calculated using Equation 4.3. The higher the S_T or CT_{Index} of the mixture, the higher the DoA.

$$DoA (\%) = 100 \times \frac{X_{RAP}(T, test)}{\max X_{RAP}} \quad (\text{Equation 4.3})$$

Where

X_{RAP} = the mixture performance test result of RAP conditioned at a specific temperature T , and

$\max X_{RAP}$ = the maximum value observed among the temperatures evaluated.

Note that DoA is calculated using 100 percent RAP specimens and is used to estimate recycled binder availability in this comparison, but RILEM defines a different parameter as degree of availability (DoAv) when considering RAP in recycled asphalt mixtures.

Figure 4-6 represents the average DoA calculated by S_T and CT_{Index} for the RAP sources at the five different conditioning temperatures. DoA was calculated by dividing the S_T or CT_{Index} of each RAP source obtained from the best-fit curves by the average maximum S_T or CT_{Index} observed among all six RAP sources at the different conditioning temperatures. DoA values calculated by S_T followed the same trend observed in the force-displacement diagrams; DoA increased until it reached a maximum value at 140°C or 170°C, and then it started to decrease beyond this temperature. As mentioned previously, the reduction in DoA at high temperatures could be due to the inability of the RAP particles to cluster or adhere to each other at these high temperatures due to the excessive hardening and the loss of volatiles. Thus, there appears to be

an optimum DoA that is realized at common mixture production temperatures. Conversely, DoA calculated by CT_{Index} showed the opposite trend when compared to S_T , with a decreasing trend to 140°C or 170°C followed by an increase beyond this temperature. The difference in DoA trends between the two parameters results from the fact that CT_{Index} is an energy parameter that is related to the ductility of the mixture, while S_T is related to the stiffness or brittleness (i.e., fracture resistance).

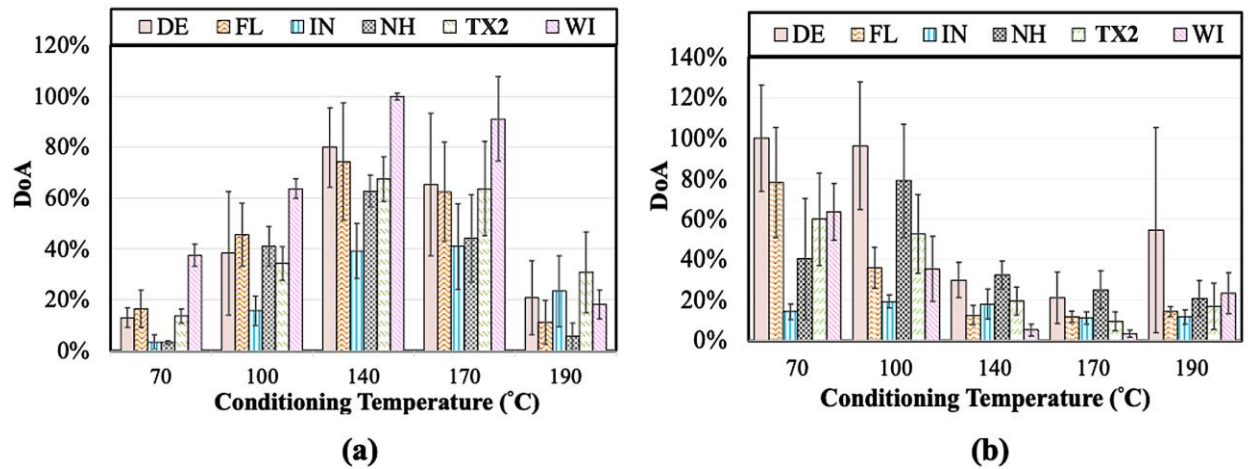


Figure 4-6. DoA calculated by the RILEM method at different conditioning temperatures based on (a) S_T , and (b) CT_{Index} .

The RILEM effort selected to focus on DoA calculated by S_T based on a comparison by Menegusso Pires et al. (2019) of a traditional recycled asphalt mixture and a corresponding artificial recycled asphalt mixture produced with 100 percent virgin materials but with similar characteristics (binder properties, aggregate types and gradation, and binder content) and an assumed 100 percent availability. The comparison found good correlation of the two mixtures with DoA by S_T but poor correlation with DoA by energy parameters such as CT_{Index} .

In this task, an artificial recycled asphalt mixture was not available, so BAF determined by the NCHRP 09-58 method was compared to DoA by both parameters. Figure 4-7 shows that no strong correlations were found between BAF and either parameter. For the relationship with DoA by S_T recommended as the best available by Menegusso Pires et al. (2019), the FL RAP exhibited high stiffness (based on PGH) of those with BAF data available but exhibited a relatively high S_T value (Table 4-1, Figure 4-7). Therefore, when the results from all RAP sources were combined, the FL RAP did not follow the expected trend or the trend followed by the other RAP sources (i.e., stiff RAP = high PGH = low BAF = low S_T). This comparison and those by others indicate that these parameters (i.e., S_T and CT_{Index}) may not capture all interacting factors that influence recycled binder availability.

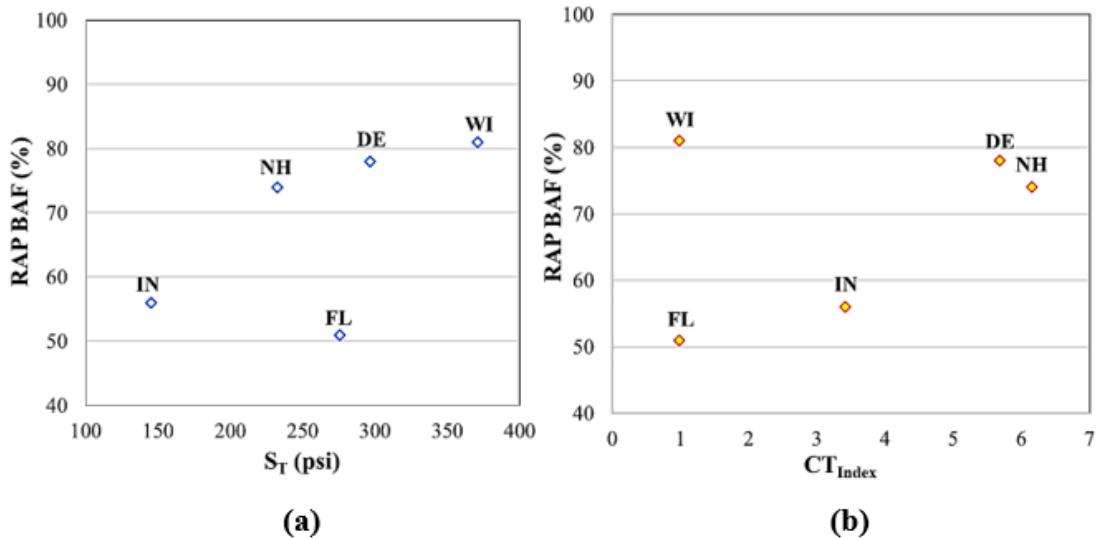


Figure 4-7. The effect of recycled binder availability on mixture performance: (a) RAP BAF versus S_T , and (b) RAP BAF versus CT_{Index} .

The ranking of DoA calculated by S_T and the BAF calculated by the NCHRP 09-58 method are summarized in Figure 4-8. TX1 and TX2 RAP sources were included separately since they were obtained from different locations in the state. Recycled binder availability values obtained from the two methods were ranked using 1 to indicate the highest recycled binder availability and 6 to indicate the lowest. The comparison is based on RAP sources conditioned at a temperature of 140°C, which is common to both methods. DoA and BAF showed a reasonable correlation for most RAP sources. Both methods indicated that WI and DE RAP sources exhibit the highest recycled binder availability. The slight differences in ranking between the two methods is due to the difference in the methods used to calculate BAF and DoA. The RILEM method calculates binder availability based on S_T of the RAP source; a high S_T indicates higher binder availability, but this may not be representative of how the RAP behaves in the recycled asphalt mixture, which is captured in the NCHRP 09-58 method. Furthermore, the effect of aggregate gradation and effective binder content is considered in the RILEM method but not in the NCHRP 09-58 method.

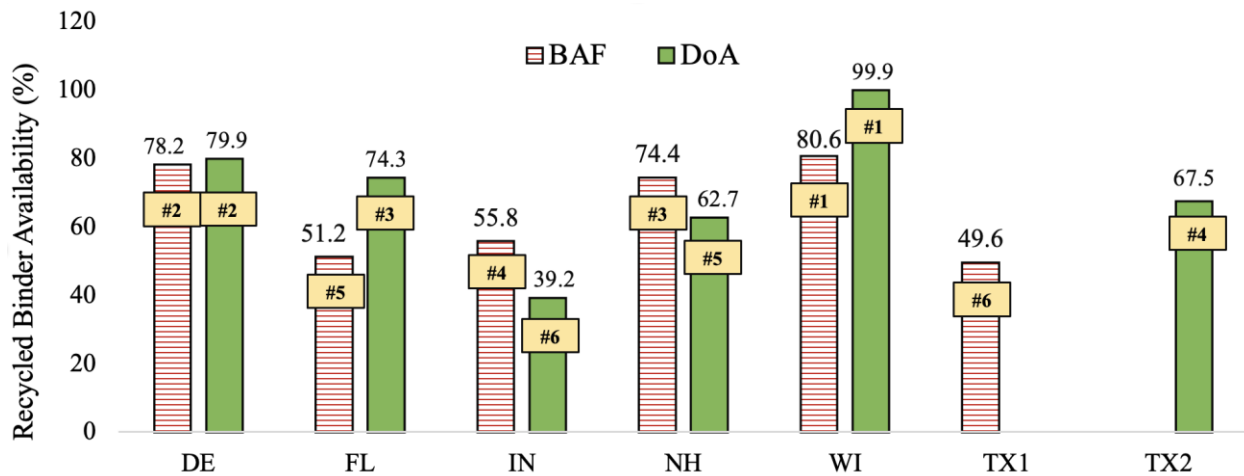


Figure 4-8. Comparison between NCHRP 09-58 method and RILEM method RAP binder availability results at 140°C.

The RILEM method is notably simpler than the NCHRP 09-58 method and does not require selected specific virgin materials; however, it requires performance testing and must be done on various sources and at multiple conditioning temperatures in order to obtain a relative ranking, which can be time consuming.

METHOD III: FHWA

The FHWA initiative evaluated recycled binder availability using RAP obtained from six sources: NV, NH, WI, DE, IN, and FL. In this method, an SGC is used to determine the workability of 100 percent RAP samples using modified hardware and software. The test is performed by subjecting a given amount of loose RAP to a constant displacement of 0.05 mm/s in the SGC with no gyrations. Testing is conducted at four temperatures varying from 25°C to 149°C.

The test generates a nonlinear compressive stress versus strain curve that can be used to assess the workability of the mixture using a parameter known as Dongre workability test index (DWT). The DWT parameter is determined by taking the slope of this curve at a stress level of 600 kPa, as shown in Equation 4.4 and Figure 4-9.

$$\text{DWT, kPa} = \frac{(650-550) \text{ kPa}}{(\text{Strain at } 650 - \text{strain at } 550)} \quad (\text{Equation 4.4})$$

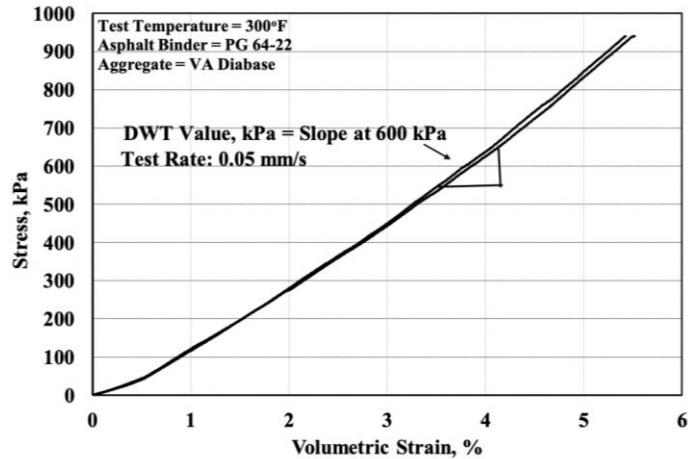


Figure 4-9. Determination of DWT parameter (Dongré et al. 2015).

The idea of this initiative is to determine if the workability of the RAP mixtures can be used to estimate recycled binder availability. Generally, mixtures with a higher DWT parameter are expected to have higher recycled binder availability.

Besides determining DWT, the FHWA initiative also explored if PGH of the RAP binder was correlated with recycled binder availability. For this initiative, PGH of the RAP binder was successfully determined using an artificial neural network (ANN) model based on several inputs, including aggregate gradation, binder content, DWT value, and the area under the stress-strain curve up to 600 kPa stress (Nrg600). Figure 4-10 compares both the DWT obtained at 150°C and the ANN-predicted PGH of the RAP binder to the RAP BAF from NCHRP 09-58 at 150°C mixing temperature. The results indicated no correlation for either parameter to representative recycled binder availability.

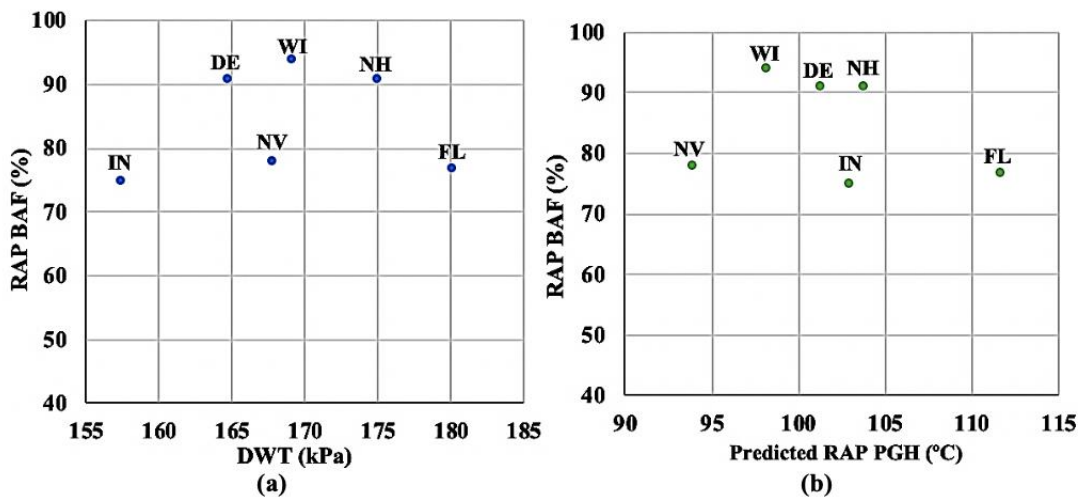


Figure 4-10. RAP BAF at 150°C mixing temperature from NCHRP 09-58 compared to (a) DWT at 150°C and (b) predicted RAP PGH (°C).

SUMMARY

This chapter assessed three different methodologies to quantify recycled binder availability (NCHRP 09-58, RILEM, and FHWA). A summary of the advantages and disadvantages of each of the three methods is provided in Table 4-2. The NCHRP 09-58 method provides the most realistic quantification of recycled binder availability compared to the other two methods and does not require performance testing or testing at multiple temperatures. Yet, it requires extensive laboratory work including virgin and RAP binder content quantification and the use of specific virgin materials. Additionally, the method quantifies recycled binder availability by considering only RAP retained on the No. 4 sieve, which does not represent field conditions. The RILEM method is the most comprehensive and practical approach because it captures the effects of gradation and effective binder content and is performed on 100 percent RAP mixtures at relevant conditioning temperatures. In addition, DoA calculated by the RILEM method showed a reasonable agreement with the BAF obtained from NCHRP 09-58. However, to determine a reasonable DoA for a specific RAP mixture, various RAP sources need to be compared. The FHWA method is the simplest technique since it does not require RAP binder content quantification, specimen preparation, or performance testing. However, DWT determined from this method did not correlate with the BAF obtained from NCHRP 09-58. In addition, all three methods are currently limited to the analysis of RAP materials and cannot accommodate RAS.

Table 4-2. Comparison of binder availability quantification methods.

Method	NCHRP 09-58	RILEM	FHWA
Advantages	Has better simulation of field	Only requires RAP	Only requires RAP
	Does not require performance testing at multiple temperatures	Utilizes relevant conditioning temperatures	
		Correlates well with BAF	Does not require performance testing
		Captures gradation effects and effective binder content	
Limitations	Requires ignition oven to determine RAP binder content	Requires performance testing at multiple temperatures	Requires using SGC with modified control software
	Uses only specific virgin materials	Must compare many RAP sources for relative RAP binder availability ranking	Has no correlation between DWT or predicted RAP PGH and BAF
	Only considers RAP retained on the No. 4 sieve		Requires multiple testing temperatures for ANN model

CHAPTER 5 TXDOT MIX DESIGN REVISION

The final part of this project involved proposing revisions to the TxDOT mix design spreadsheet for Superpave mixtures to account for recycled binder availability. The current special specification for balanced mix design (BMD) (SS 3074) allows the highest recycled materials content with up to 35 percent fractioned RAP, 30 percent RBR, and 5 percent RAS for surface mixtures. Assuming 100 percent recycled binder availability at such high percentages of recycled materials can result in dry mixtures that are prone to cracking and moisture damage. Thus, the proposed revisions to the spreadsheet were done to account for recycled binder availability by reducing the contribution of recycled asphalt binder by 25 percent if any of the following four conditions were met:

- Fractioned RAP content exceeds 20 percent.
- RBR exceeds 20 percent.
- RAS content exceeds 3 percent.
- RAP PGH exceeds 100°C (if data available).

These four thresholds were chosen considering the national recommended guidelines for Superpave mixtures containing RAP (McDaniel and Anderson 2001) and the recommendations of the national research project NCHRP 09-58 (Epps Martin et al. 2019). The national guidelines for using RAP in Superpave mixtures states that at low RAP percentages (10–20 percent), the characterization of the recovered RAP binder is not mandatory because there is not enough RAP present to cause issues. When using more than 20 percent RAP content in the mixture, characterization of RAP binder and use of blending charts are recommended because there is enough RAP to cause a change in the properties of the asphalt binder. Based on these recommendations, the thresholds for the RAP content and RBR were set to 20 percent for consideration of recycled binder availability. The threshold chosen for RAS content (3 percent) is based on the recommended limit in the NCHRP 09-58 project to prevent inadequate cracking resistance. The threshold for RAP PGH (100°C) is also based on the recommendations of the NCHRP 09-58 project as a limit for excessively aged RAP binders. The percent reduction in recycled binder availability was selected based on the RAP BAF implemented by GDOT initially in 2012.

The proposed revisions to the mix design spreadsheet are described in Figure 5-1. To account for recycled binder availability, the recycled asphalt binder and the recycled-to-total-binder ratio under the “combined gradation” tab was divided into two categories: (a) measured and (b) adjusted. The measured values are based on the percentage of total recycled binder content determined in the laboratory. The adjusted values are based on the percentage of recycled binder after taking into account the reduced recycled binder availability. The adjusted recycled asphalt binder can be determined as follows:

- First, the type of recycled material is selected, and the amount of recycled material and measured recycled asphalt binder content is entered for each material.
- Then, the measured PGH of RAP is entered, if available (although not required).
- The adjusted recycled asphalt binder is calculated automatically, taking into account the RBR, recycled material content by weight of total mix, and PGH of RAP. If any of the four conditions listed previously are met, the adjusted recycled asphalt binder is reduced by 25 percent from its measured value; otherwise, it remains the same.

		"RECYCLED MATERIALS"							
Bin No.6	Bin No.7	Bin No.8		Bin No.9		Bin No.10			
		Fractionated RAP		Fractionated RAP		RAS		Material Type	
								Material Source	
								RAS Type	
								RAP/RAS Producer	
								Sample ID	
Recycled Asphalt Binder (%)									
		3.0		2.5		20.0			
		15.0	% of Tot. Mix	5.0	% of Tot. Mix	5.0	% of Tot. Mix	Total Bin	

		"RECYCLED MATERIALS"							
Bin No.6	Bin No.7	Bin No.8		Bin No.9		Bin No.10			
		Fractionated RAP		Fractionated RAP		RAS		Material Type	
								Material Source	
								RAS Type	
								RAP/RAS Producer	
								Sample ID	
Recycled Asphalt Binder (%)									
Measured PGH of RAP (if available)		85		85					
Measured Recycled Asphalt Binder (%)		3.0		2.5		20.0			
Adjusted Recycled Asphalt Binder (%)		2.3		1.9		15.0			
		15.0	% of Tot. Mix	5.0	% of Tot. Mix	5.0	% of Tot. Mix	Total Bin	

Ratio of Recycled to Total Binder, % <i>(based on binder percent (%) entered below in this worksheet)</i>	
29.7	

Ratio of Recycled to Total Binder, % <i>(based on binder percent (%) entered below in this worksheet)</i>	
Adjusted	22.3
Measured	29.7

Figure 5-1. Revised TxDOT balanced mix design spreadsheet for Superpave mixtures to account for recycled binder availability.

Furthermore, to ensure that the correct optimum asphalt content value is used in production, an adjusted optimum asphalt content for quality control/ quality assurance (QC/QA) cell was added in the Summary sheet. This cell calculates the optimum asphalt content based on the virgin binder content and the original or total recycled binder percentage. Notes corresponding to these changes were also added to the Instructions sheet.

There are other methods to account for reduced recycled binder availability of recycled materials instead of directly incorporating it in the mix design. Other approaches to account for recycled binder availability include increasing the total binder content by requirement or by coarsening aggregate gradation, decreasing air voids, increasing voids in the mineral aggregate (VMA), or decreasing the number of gyrations. An improved estimate of recycled binder availability could help to evaluate performance (with aging) at the binder or binder level and screen poor material combinations, therefore reducing the number of required mix designs to achieve optimum cracking and rutting (i.e., balanced) recycled mixture performance.

In summary, this chapter described proposed revisions to the TxDOT mix design spreadsheet for Superpave mixtures to account for recycled binder availability. This chapter also identified other available approaches to account for recycled binder availability besides directly accounting for it in the mix design.

CHAPTER 6 VALUE OF RESEARCH

The benefits of properly accounting for recycled binder availability are three-fold: environmental, economic, and engineering related. Thus, these three aspects provide the basis for estimating the value of research associated with this synthesis project.

The environmental benefits can be quantified based on the results of the annual asphalt pavement industry survey on recycled materials and WMA usage conducted by the National Asphalt Pavement Association (NAPA). Data from the latest year available (2018) indicate that nationally, 82 million tons of RAP and 1 million tons of RAS replaced virgin materials. In Texas during this same year, based on responses from six companies representing 51 HMA/WMA production plants, approximately 2.9 million tons of RAP and 131 thousand tons of RAS were recycled in HMA/WMA. The primary environmental benefit is the savings in landfill space and associated fees, and the NAPA survey indicated that approximately 62 million cubic yards and \$5 billion were saved nationally. Based on total estimated production of 390 million tons of HMA/WMA nationally and 17.2 million tons in Texas, annual environmental savings total approximately \$22 million for disposal fees and 2.7 million cubic yards of landfill space. If RAP contents can be increased from the average of 18.9 percent in TxDOT mixtures, possibly even doubling them to approximately 40 percent, by understanding both the volumetric and performance contributions of the recycled materials to engineer each unique material combination, these savings are expected to double.

Economic savings can also be quantified based on the 2018 NAPA survey that indicated that \$2.9 billion was saved in virgin material costs. For the same ratio of total estimated production nationally and in Texas, this amount results in annual economic savings of approximately \$113 million, or \$6.50 per ton. A more detailed economic analysis of the use of RAP in asphalt mixtures was conducted as part of the national research project NCHRP 09-58 (Epps Martin et al. 2019). This analysis considered two different scenarios: (a) a low economic incentive scenario where the virgin material costs are relatively low compared to the RAP and additive costs and the available recycled binder is relatively low, and (b) a high economic incentive scenario where the virgin material costs are relatively high compared to the RAP and additive costs and the available recycled binder is relatively high. In addition, a contractor reviewed the cost data and assumptions utilized in this analysis for reasonableness. The results indicated that RAP contents can be doubled from 20 percent to 40 percent with the use of appropriate mitigation strategies (softer virgin binder or the use of additives including rejuvenators or WMA additives) for savings that range from \$6 to \$8 per ton HMA/WMA or from \$0.30 to \$0.40 per 1 percent RAP when virgin material costs are relatively high. These savings represent approximately 10 percent to 15 percent of plant production prices and about 7 percent to 10 percent of in-place prices for HMA/WMA. This analysis provided first costs and assumed that the mitigation strategies produce equivalent performance. Thus, life-cycle costs were reflected in the first cost savings. With a total estimated production of 15 million tons of

HMA/WMA based on the past year of TxDOT letting, annual economic savings of doubling the RAP content by understanding both the volumetric and performance contributions of the recycled materials to engineer each unique material combination are substantial and total approximately \$105 million.

Engineering-related benefits of understanding both the volumetric and performance contributions of the recycled materials were more difficult to quantify. Reports and presentations from GDOT were reviewed since GDOT conducted research and implemented a COAC approach to address insufficient density, dry mixtures, and premature failure by cracking. Follow-up contact via email also provided additional insight. Based on a review of more than 200 proprietary mix designs, GDOT is pleased with this approach and the resulting improvements in constructability and durability. In summary, GDOT was only able to obtain adequate performance after properly accounting for recycled binder availability. Thus, the annual engineering-related savings could be estimated based on the requirements of maintaining and/or rehabilitating pavements that prematurely failed prior to implementation of the COAC approach, but even without these benefits, the overwhelming environmental and economic savings compared to the budget for this project provide a significant value of research in terms of cost-benefit ratio of \$1:\$1954, as shown in Table 6-1.

Table 6-1. Estimated value of research (annual basis).

Environmental Savings	Economic Savings	Engineering-Related Savings	TxDOT Synthesis Budget
\$22,000,000.00	\$105,000,000.00	Unknown	\$64,988.00

Estimated Value of Research (Annual Basis) = Cost-Benefit Ratio (CBR) ≥ \$1:\$1954

In summary, this chapter described the environmental, economic, and engineering-related benefits associated with quantifying recycled binder availability in recycled asphalt mixtures. The environmental and economic savings were estimated based on the 2018 NAPA survey, and the engineering-related benefits were recognized as substantial based on the extensive work done by GDOT to account for recycled binder availability. Quantifying recycled binder availability can help in saving disposal fees, landfill space, and virgin material costs.

CHAPTER 7 SUMMARY AND RECOMMENDATIONS

This project explored recycled binder availability in recycled asphalt mixtures by performing a literature review, gathering information on current methods and practices adopted by state DOTs to account for recycled binder availability, conducting a detailed analysis of three different recycled binder availability quantification methods, and proposing revisions to the TxDOT mix design spreadsheet for Superpave mixtures to incorporate recycled binder availability.

The results of the review of previous studies indicated that recycled binders are partially available under normal asphalt mixture production conditions. Recycled binder availability estimated for RAP varied from 16 percent to 96 percent, while RAS showed lower recycled binder availability (36 percent to 61 percent). Although previous studies reported that recycled binders are partially available, the information gathered from state DOTs indicated that the majority of states assume full (100 percent) availability for both RAP and RAS, including 29 of 38 respondents to the questionnaire conducted as part of this project.

Three different recycled binder availability quantification methods were evaluated in detail, and the results of these methods were compared. One of the methods (NCHRP 09-58) quantified recycled binder availability using mixtures of RAP and virgin materials, while the other two methods (RILEM and FHWA) quantified it using 100 percent RAP. The results of this evaluation suggested that none of the three methods are ideal and that each one of these methods has its advantages and limitations. Quantifying recycled binder availability using mixtures of virgin and RAP materials can result in the most realistic quantification; however, this approach requires extensive laboratory work. Utilizing 100 percent RAP is a more practical approach; however, additional research is needed to understand how recycled binder availability obtained from these methods can be utilized for design of mixtures that contain both virgin and RAP materials.

This project also evaluated the effect of recycled binder availability on mixture performance and aggregate coating based on other research efforts. The results indicated that mixture performance parameters (S_T and CT_{Index}) may not always capture recycled binder availability that is influenced by multiple interacting factors. Aggregate coatability is not likely to be an issue at economical doses of recycling agents; however, at high recycling agent doses, coatability issues could arise, especially if the recycling agent is added by replacing the virgin binder by full recycling agent amount.

Finally, this project proposed revisions to the TxDOT mix design spreadsheet for Superpave mixtures to reduce the contribution of the recycled asphalt binder by 25 percent if the RAP content or RBR exceeded 20 percent, the RAS content was more than 3 percent, or the PGH of the RAP was greater than 100°C. These limits were selected by considering national guidelines for using RAP in Superpave mixtures and the recommendations of national research project NCHRP 09-58. The implementation of these proposed revisions would help reduce the issues of

dry mixtures or uncoated aggregates in recycled asphalt mixtures with high RAP/RAS content, and therefore achieve more durable, longer-lasting recycled asphalt mixtures.

Based on these previous observations, the following recommendations are made for consideration by TxDOT:

- Use a recycled BAF of 75 percent for RAP and RAS in recycled asphalt mixtures with higher RAP and/or RAS contents (and thus larger RBR) or heavily aged RAP.
- Explore alternate approaches to account for reduced recycled binder availability of recycled materials, including increasing total binder content by requirement or by changing aggregate gradation, decreasing design air voids, increasing VMA, or decreasing the number of gyrations.
- Consider quantifying recycled binder availability of TX RAP sources by performing an abbreviated form of the RILEM method at a reduced number of conditioning temperatures (e.g., 140°C and 170°C) and comparing results to the NCHRP 09-58 method.

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APPENDIX: ANNOTATED BIBLIOGRAPHY

STUDIES ON BINDER AVAILABILITY FOR MIXTURES WITH RAP

AbuQtaish, L., Nazzal, M. D., Kaya, S., Kim, S. S., Abbas, A., & Abu Hassan, Y. (2018). *AFM-based approach to study blending between RAP and virgin asphalt binders. Journal of Materials in Civil Engineering, 30(3), 04017300.*

The authors employed AFM stiffness measurements and bonding energy to evaluate interface blending between RAP and virgin binders and its characteristics. Virgin binders from the same source but with distinct performance grades (i.e., PG 58-28, PG 64-28, and PG 64-22) were employed, along with extracted binder from two sources of RAP. Specimens were prepared on glass slides, of which half were occupied by the virgin binder and half by the RAP binder. After bringing the two halves of the slides together, each half containing a type of binder, the specimens were heated on top of a hot plate for 3 minutes at 154°C. This procedure resulted in melting and spreading of both binders on the two sides of the glass slide. Afterward, the specimens were refrigerated to prevent further diffusion between the two types of binders. The AFM nanoindentation experiments were performed at intermediate temperatures. The results showed that the RAP binder and virgin binder types affected the reduced modulus of the blending zone. However, the adhesive bond characteristics were mainly dependent on the virgin binder type only. A linear regression model was used to predict the reduced modulus and bond energy of the blending zone in terms of the reduced modulus and bond energy of the individual RAP and virgin binders.

Al-Qadi, I. L., Carpenter, S. H., Roberts, G., Ozer, H., Aurangzeb, Q., Elseifi, M., & Trepanier, J. (2009). *Determination of Usable Residual Asphalt Binder in RAP. Illinois Center for Transportation (ICT).*

The authors explored the amount of available RAP binder when used in recycled mixtures in an effort to improve the Illinois Department of Transportation (IDOT) mix design method that assumed 100 percent contribution from the RAP binder. Recycled mixtures with 0 percent, 20 percent, and 40 percent RAP were prepared following the conventional method, and a companion set was prepared using recovered RAP binder and aggregate. The proportion of the recovered RAP binder used during the fabrication of the asphalt mixture varied from 0 percent, 50 percent, and 100 percent to simulate different amounts of available RAP binder. The mixture performance tests conducted included dynamic modulus, IDT strength and tensile strength ratio, SCB test, and DCT. In addition, tests on the virgin binder, recovered binders, and blended binders were also conducted using the DSR. The authors were unable to determine the actual blending percentages of the RAP binder in the mixture. Therefore, the authors recommended considering all the RAP binder content during mix design for mixtures with up to 20 percent RAP content and reducing the high and low-temperature PG of the virgin binder for recycled mixtures with 40 percent RAP content.

Bennert, T., & Asphalt, R. (2012). *Advanced Characterization Testing of RAP Mixtures Designed and Produced Using a “RAP Binder Contribution Percentage”* (No. 12-01). New York State Department of Transportation, Materials Bureau.

The authors, on behalf of NYSDOT, worked under the assumption that during production, not all the RAP binder is available to combine with the virgin aggregate and virgin binder and develop a RAP binder contribution percentage. The assumed contributions of the RAP binder used in the experiment were 100 percent, 75 percent, and 50 percent. When the RAP binder contribution was less than 100 percent, the virgin binder was increased proportionally. Laboratory tests were performed on reheated plant loose mix and included dynamic modulus, flow number, flexural beam fatigue, and overlay tester. The authors observed similar mixture stiffness and rutting performance, but in terms of the cracking tests, the 100 percent RAP contribution performed the worst, while the 75 percent and 50 percent RAP contribution mixtures had similar properties. The authors did not offer a specific recommendation, but based on the results, a reduced RAP contribution of 75 percent or less could assure better performance in terms of cracking resistance.

Booshehrian, A., Mogawer, W. S., & Bonaquist, R. (2013). *How to construct an asphalt binder master curve and assess the degree of blending between RAP and virgin binders. Journal of Materials in Civil Engineering, 25(12), 1813–1821.*

The authors developed a method to determine the degree of blending between virgin and RAP binders in recycled asphalt mixtures by measuring the dynamic modulus of the asphalt mixtures (i.e., actual blending) and the complex shear modulus of the recovered asphalt binders (i.e., full blending). The dynamic modulus values were estimated from the complex shear modulus values measurements using the Hirsch model for full blending conditions. Then, the estimated values were compared against measured dynamic modulus values and the degree of blending calculated based on the difference between the two. This methodology was used with plant-produced mixtures containing 0 percent, 20 percent, 30 percent, and 40 percent RAP. The mixture with 30 percent RAP and softer virgin binder exhibited the least degree of blending.

Carbonneau, X., Lubineau, F., Yvinec, B., & Michaut, J. P. (2012, May). *Binder mobilization in RAP and its contribution to mix performance. Proceedings of the International Conference on Road and Rail Infrastructure CETRA.*

The authors tested virgin and recycled asphalt mixtures with various RAP contents (i.e., 20 percent, 30 percent, and 40 percent) to determine the influence of RAP on the performance of the mixture. They prepared the mixtures with fully blended RAP and virgin binders and added the RAP as a mixture component. They used the dynamic modulus to test the asphalt mixtures, given its proven relationship to the stiffness of the binder. In addition, they obtained the complex modulus of the virgin binder, RAP binder, and the blended binder. They established that the RAP binder mobilization was the primary factor affecting the asphalt mixture performance. The

authors observed important impacts on performance when there was a high proportion of extracted RAP binder that was fully blended in the mixture or there was a significant difference between the stiffness of the virgin binder and the RAP binder. The difference in performance was not as significant when the RAP was used as a mixture component.

Coffey, S., Dubois, E., Mehta, Y. A., & Purdy, C. (2013). *Determining Impact of Degree of Blending Between Virgin and Reclaimed Asphalt Binder on Predicted Pavement Performance Using Mechanistic-Empirical Pavement Design Guide* (No. 13-0571).

The authors explored the impact of a reduced degree of blending on pavement rutting and fatigue performance using the MEPDG and conditions for New Jersey. Recycled asphalt mixtures with 25 percent RAP from three sources were employed in the study. The degree of blending was assumed to be 70 percent based on prior studies; next, dynamic modulus was performed on recycled mixtures prepared with the assumed degree of blending and full blending conditions; finally, the mixture properties were used in the MEPDG to predict performance. The authors concluded that for lower DoB the differences in performance were more significant, but if the DoB was 85 percent or higher, the effect on fatigue and rutting based on the MEPDG analysis would be negligible.

Coleri, E., Lewis, S., & Sreedhar, S. (2018). *Quantification of Rap Binder Blending to Provide Recommendations for Asphalt Mix Design* (No. 18-01228).

The authors estimated the amount of RAP binder that blended into the asphalt mixture by extracting and recovering the RAP binder; preparing a blend of virgin and RAP binder; using the binder blend to prepare asphalt mixture specimens with 0 percent, 50 percent, and 100 percent blending; and testing the specimens in the SCB test. The results were compared against asphalt mixtures with actual blending, meaning mixtures with RAP and virgin binder (without extracted and recovered RAP). Two RAP sources and a coarse and fine gradation were considered. Coarser aggregate gradations had higher flexibility index values in the SCB and thus better cracking resistance. The authors estimated that between 40 percent to 55 percent of the RAP binder was not available to blend in the asphalt mixture. Lower RAP blending resulted in less active binder content and lower cracking resistance.

Daniel, J. S., & Mogawer, W. S. (2010). *Determining the Effective PG Grade of Binder in RAP Mixes* (No. NETCR78).

The authors developed a method to estimate the binder PG from mixture properties. They employed asphalt mixtures with 0 percent, 10 percent, 25 percent, and 40 percent RAP and a single virgin PG of 64-28. In addition, they employed various virgin binder PGs (i.e., 58-28, 70-22, and 76-22) with 0 percent RAP. The test methods used included dynamic modulus, creep compliance, and IDT strength. The authors evaluated several methods to estimate the effective binder PG in the mixture and concluded that the Hirsch model was the most appropriate to back-

calculate binder stiffness from mixture dynamic modulus. Better accuracy was obtained for the low-temperature PG since the range of test temperatures for PG and dynamic modulus are the same; however, some difficulties were encountered with the high-temperature PG because of the difference between test temperatures and PG temperatures.

Eddhahak-Ouni, A., Dony, A., Colin, J., Mendez, S., Navaro, J., Drouadaine, I., & Bruneau, D. (2012). Experimental investigation of the homogeneity of the blended binder of a high rate recycled asphalt. *Road Materials and Pavement Design*, 13(3), 566–575.

The authors developed an experimental approach to characterize the level of blending of RAP and virgin binders in a hot recycled asphalt mixture with 70 percent RAP content. They employed staged extraction and analyzed the resulting binder with the ring and ball (i.e., softening point) temperature test and Fourier transform infrared spectroscopy (FTIR) to estimate the degree of blending. The authors determined the RAP content from each extraction stage and estimated between 32 percent to 38 percent RAP binder in the outermost layer, 58 percent to 65 percent in the intermediate layer, and around 70 percent in the innermost layer (i.e., binder coating the RAP material). They recommended the use of this experimental approach to perform qualitative tests during asphalt mixture production.

Faheem, A., Abboud, B., Coe, J., & Alsalihi, M. (2018). *Effect of Warm Mix Asphalt (WMA) Low Mixing and Compaction Temperatures on Recycled Asphalt Pavement (RAP) Binder Replacement* (No. FHWA-PA-2018-002-TEM WO 008). Pennsylvania Dept. of Transportation, Bureau of Planning and Research.

The authors studied the effect of WMA additives in asphalt mixtures with high RAP contents, especially in regard to mixing and compaction temperature and cracking resistance based on the RAP binder replacement. The binder replacement was measured indirectly by varying the amount of RAP in the asphalt mixture. In the first phase of the study, asphalt mixtures with two binder types were prepared at various mixing and compaction temperatures and conditioned for 2 and 4 hours after mixing. The RAP content also varied from 15 percent to 30 percent, and the RAP was obtained from two suppliers (i.e., sources). Last, two WMA additives were employed in the preparation of the asphalt mixtures. The results indicated that the WMA additive type and conditioning time yielded statistically similar volumetric, workability, and stability properties, and thus were eliminated from further analysis. In the second phase of the study, the remaining factors (i.e., binder type, RAP source, RAP content, and mixing temperature) were varied to prepare specimens and test them in the SCB test.

Gottumukkala, B., Kusam, S. R., Tandon, V., & Muppireddy, A. R. (2018). Estimation of Blending of Rap Binder in a Recycled Asphalt Pavement Mix. *Journal of Materials in Civil Engineering*, 30(8), 04018181.

The authors studied the degree of blending between RAP and virgin binders using recycled asphalt mixtures with 20 and 35 percent RAP and two types of virgin binders. They employed $G^*/\sin\delta$ penetration, and the softening point to evaluate the effective properties of the blended binder. They prepared specimens with RAP material passing sieve No. 4 and virgin aggregates larger than 9.5 mm and quantified the material transferred from the RAP binder to the virgin aggregates, which resulted in about 12 percent for the 20 percent RAP mixture and 10 percent for the 35 percent RAP mixture. In addition, they mixed the same gap-graded RAP and virgin aggregates with virgin binder. They extracted the binder from the RAP and virgin aggregates after mixing, determined its properties, and compared it against the properties of the virgin binder and RAP binder to estimate the degree of blending, which ranged from 16 to 87 percent. The authors concluded that the interaction between the RAP and virgin binders depended on the type of virgin binder and the RAP content.

Hajj, E. Y., Salazar, L. G. L., & Sebaaly, P. E. (2012). Methodologies for estimating effective performance grade of asphalt binders in mixtures with high recycled asphalt pavement content: Case study. *Transportation Research Record*, 2294(1), 53–63.

The authors investigated the effective binder properties of binders from field-recycled asphalt mixtures with various RAP contents (i.e., 0 percent, 15 percent, and 50 percent) via grading of recovered binders, blending chart, mortar procedure, and back-calculation of binder properties from mixture dynamic modulus. Overall, good correlations were observed between the estimated PG from blending charts and the ones measured from the recovered binder. However, as the RAP content increased (i.e., 50 percent), the low-temperature PG was warmer than the target binder grade. The authors established that this difference was due to the assumption of full RAP and virgin binder blending. Likewise, the mortar procedure also resulted in lower critical PG temperatures than the ones obtained from the recovered binders, which could also be due to the partial blending between virgin and RAP binders.

Jiang, Y., Gu, X., Zhou, Z., Ni, F., & Dong, Q. (2018). Laboratory observation and evaluation of asphalt blends of reclaimed asphalt pavement binder with virgin binder using SEM/EDS. *Transportation Research Record*, 2672(28), 69–78.

The authors used a scanning electron microscope/energy dispersive spectrometer (SEM/EDS) to observe and evaluate the degree of blending between RAP binder and virgin binder. The virgin binder was traced using titanium dioxide (TiO₂) powder, and the element mass ratio of titanium over sulfur, Ti:S, was the quantitative parameter indicating the blending ratio between the two binders. The results of this study showed that when the RAP content increased (from 15 percent

to 30 percent or 50 percent), the blending between the RAP binder and virgin binder decreased from around 95 percent to 40 percent for normal conditions (i.e., conditioning the loose mix for 45 minutes), 55 percent after short-term aging (i.e., conditioning the loose mix for 4 hours), and around 80 percent for long-term aging (i.e., conditioning the loose mix for 12 hours); in addition, the homogeneity of the blended binder was less. With aging and/or the addition of a recycling agent, the efficiency of the blend between RAP and virgin binders improved when enough time was allowed for the diffusion to take place.

Kaseer, F., Arámbula-Mercado, E., & Martin, A. E. (2019). A method to quantify reclaimed asphalt pavement binder availability (effective RAP binder) in recycled asphalt mixes. *Transportation Research Record*, 2673(1), 205–216.

The authors proposed a method to estimate the percent of active RAP binder in an asphalt mixture and investigated factors that affected RAP availability. Their proposed method consisted in preparing asphalt mixtures with three distinct aggregate fractions: coarse, intermediate, and fine. One mixture was virgin, while the other substituted the intermediate aggregate fraction with RAP. The mixtures were short-term oven aged after mixing and sieved, and then the binder content of each aggregate fraction was determined via the ignition oven. The binder availability was determined by comparing the binder content of the virgin and RAP intermediate aggregate fractions and assuming a linear relationship between the two extreme scenarios (i.e., complete availability versus black rock). Despite some limitations of the method, it was verified using artificial (i.e., laboratory aged) RAP with good results. Further, the influence of mixing temperature, short-term conditioning period, RAP source, RAP binder stiffness, and recycling agent on the binder availability of actual RAP samples was explored. The RAP availability ranged from about 50 percent to 95 percent depending on the RAP source and mixing temperature. The softer the RAP (i.e., lower PG), the higher the binder availability; in fact, the authors developed a relationship between binder availability and RAP PG that can be used to estimate availability for other RAP sources. The use of rejuvenators increased the RAP binder availability in some cases.

Kriz, P., Grant, D. L., Gale, M. J., Lavorato, S., & Pahalan, A. (2014a). Reclaimed asphalt pavement-virgin binder diffusion in asphalt mixes. *Proceedings of the Fifty-Ninth Annual Conference of the Canadian Technical Asphalt Association (CTAA)* (pp. 375–400).

The authors acknowledged two major RAP binder/virgin binder blending processes during mixture production: (1) contact between the virgin binder and the RAP material during mixing, and (2) diffusion of the virgin binder into the RAP binder after mixing. They focused on measuring the diffusion between virgin and RAP binders during asphalt mixture production and storage at elevated temperatures. They fabricated fully blended binder specimens and two-layer (RAP binder on top and virgin binder on the bottom) DSR specimens and confirmed that the viscosity was lower for the two-layer specimen, given that the virgin binder offered less

resistance to the shear force during testing. For asphalt mixture testing, the authors prepared virgin and RAP control mixtures, used a blended binder (with equivalent virgin and extracted RAP binder to simulate 30 percent RAP in the mixture) to prepare the blend control mixture, and used a fourth mixture with virgin binder and 30 percent RAP to assess the diffusion between the RAP and virgin binder. Partial blending between RAP and virgin binders was observed after production and storage. With elapsed time, the complex viscosity of the specimens increased, signaling increased diffusion between binders, but a considerable amount of time was required to reach a stable limit, even at elevated temperatures.

Kriz, P., Grant, D. L., Veloza, B. A., Gale, M. J., Blahey, A. G., Brownie, J. H., . . . Maccarrone, S. (2014b). Blending and diffusion of reclaimed asphalt pavement and virgin asphalt binders. *Road Materials and Pavement Design*, 15(sup1), 78–112.

The authors performed both blending and diffusion studies in RAP and virgin binders using the DSR. The degree of blending between RAP and virgin binders was studied under different times and temperatures. In their study, samples were prepared by blending RAP and virgin binders at 15 percent, 25 percent, and 50 percent RAP. Results indicated that for both HMA and WMA, when a film thickness of 20 μm was assumed, blending was completed within minutes. However, when thicker film was assumed (100 μm), blending time significantly increased, and only 90 percent DoB was reached for HMA and 65 percent for WMA. In such a case, it can take months or years for blending to be completed.

Liphardt, A., Radziszewski, P., & Król, J. (2015). Binder blending estimation method in hot mix asphalt with reclaimed asphalt. *Procedia Engineering*, 111(TFoCE), 502–509.

The authors used a method that measured the degree of miscibility between binders based on staged extraction. They employed 100 percent RAP stone mastic asphalt mixture specimens with added virgin binder. After preparing the specimens, the mixture was separated using a 1mm sieve, followed by a process of staged extraction. The staged extraction consisted in submerging the asphalt mixture in tetrachloroethylene solvent for 20 seconds three consecutive times, obtaining a sample after each step. The assumption was that, by following this process, after the first step the binder from the external layer was obtained, then from the middle layer, and finally from the internal layer (i.e., layer closest to the RAP). The extracted binder at each step was recovered and characterized in the DSR via complex modulus, phase angle, and MSCR. The authors confirmed partial blending and observed how the properties of the binder extracted from the external layer were closest to the properties of the virgin binder but still affected by the RAP binder.

Menegusso Pires, G., Lo Presti, D., & Airey, G. D. (2019). A practical approach to estimate the degree of binder activity of reclaimed asphalt materials. *Road Materials and Pavement Design*, 1–24.

The authors proposed an approach known as the cohesion test to estimate the degree of binder activity or DoA of reclaimed asphalt (i.e., amount of RAP binder that is activated during mixing) as a function of processing time and temperature to improve the value assumed during mix design of recycled mixtures (i.e., full blending). The authors made a specific distinction between the portion of the RAP binder that is activated and available to blend versus the RAP binder that blends in the presence of virgin binder or rejuvenators; they called the former DoA and classified it as an intrinsic property of the RAP material. The cohesion test employs the IDT strength test on 100 percent RAP Marshall specimens conditioned at various temperatures. The authors manufactured two asphalt mixtures—one with 100 percent field RAP and another with 100 percent artificial (i.e., laboratory aged but achieving similar penetration, softening point, viscosity, and stiffness as the recovered RAP binder) RAP—for which they assumed 100 percent activation. By comparing the cohesion test results of the two types of mixtures, they developed an index to estimate DoA. The results showed an increasing DoA with higher mixing temperature, ranging from about 51 percent at 70°C up to more than 100 percent at 170°C.

Mogawer, W., Bennert, T., Daniel, J. S., Bonaquist, R., Austerman, A., & Booshehrian, A. (2012). Performance characteristics of plant produced high RAP mixtures. *Road Materials and Pavement Design*, 13(sup1), 183–208.

The authors established the effect of mixture production parameters on the degree of blending between RAP and virgin binders using stiffness, cracking, rutting, moisture susceptibility, and workability of the asphalt mixtures. The authors acknowledged actual partial blending between the RAP and virgin binders but explored how different production factors affected the degree of blending, including RAP source and amount, virgin binder grade, mixing/discharge temperature, and storage time. Via master curve, the authors characterized extracted and recovered binders from asphalt mixtures with 0 percent, 20 percent, 30 percent, and 40 percent RAP contents and measured the dynamic modulus of the mixtures. They predicted the dynamic modulus of the mixture with the binder master curve and compared it against the measured values to obtain the degree of blending estimate. They reported that the most crucial factor affecting the degree of blending was the production/discharge temperature. However, the authors did not provide a quantitative estimate of the degree of blending between RAP and virgin binders.

Mohammadafzali, M., Ali, H., Sholar, G. A., Rilko, W. A., & Baqersad, M. (2019). Effects of rejuvenation and aging on binder homogeneity of recycled asphalt mixtures. *Journal of Transportation Engineering, Part B: Pavements*, 145(1), 04018066.

The authors investigated the effect of two types of rejuvenators (i.e., paraffinic oil and water-based emulsion) on two sources of RAP in terms of the homogeneity of the rejuvenated binder.

By extracting separate layers of the asphalt film covering the aggregates (i.e., staged extraction) and measuring its rheological properties, the authors were able to quantify the diffusion of the rejuvenator using a stiffness gradient factor and a homogeneity index. Based on their observations, they determined that shortly after mixing, the rejuvenated binder was not homogeneous, with the outer layer absorbing most of the rejuvenator and the inner layer remaining stiffer. With aging, the diffusion of the rejuvenator accelerates and results in a more homogeneous characteristic of the rejuvenated binder. In addition, rejuvenated mixtures were more homogeneous after aging when compared to similar virgin mixtures.

Nahar, S. N., Mohajeri, M., Schmets, A. J. M., Scarpas, A., Van de Ven, M. F. C., & Schitter, G. (2013). First observation of blending-zone morphology at interface of reclaimed asphalt binder and virgin bitumen. *Transportation Research Record*, 2370(1), 1–9.

The authors focused on the interaction and extent of blending between RAP and virgin binders using AFM in tapping mode. The authors extracted and recovered RAP binder and characterized it—along with the virgin binder—as blended RAP and virgin binder using penetration, softening point, mass density, and DSR rheological properties. They also measured the topography, phase contrast and amplitude error of the microstructure of these same binders with AFM. The AFM specimens consisted of samples of RAP and virgin binder placed side-by-side in a metal substrate (i.e., one binder on the top and the other on the bottom) and heated for 40 seconds at 130°C in a heater plate. This procedure melted the two binders and created a fused interfacial middle zone. The AFM measurements were done in a series of lines along the two types of binders and their interface. The authors quantified the size distribution, shape, and phase fraction of the elliptical domains in the AFM images, which were more prevalent in the virgin binder. The authors estimated the extent of the blending zone around 50 µm in length and dependent on mixing temperature, contact time, and binder grade. They also concluded that true blending occurred in this zone (as opposed to simply mixing two component materials, i.e., RAP binder and virgin binder), although they also acknowledged that if RAP aggregate was used (as opposed to extracted RAP binder), the behavior could be different.

Rad, F. Y., Sefidmazgi, N. R., & Bahia, H. (2014). Application of diffusion mechanism: Degree of blending between fresh and recycled asphalt pavement binder in dynamic shear rheometer. *Transportation Research Record*, 2444(1), 71–77.

The authors explored the rate of diffusion of virgin binder into RAP binder and the effect of time, temperature (i.e., binder viscosity), and film thickness on this process. The experiment was conducted using the DSR on artificial RAP/virgin binder specimens and verified with actual fine RAP/virgin binder mortar. The specimens consisted of 1-mm thick wafers of RAP binder and virgin binder placed in contact with each other at a high temperature to promote diffusion of the two materials. After a specified period, the specimens were allowed to cool down to slow the

diffusion process. Then, the binder samples were tested in the DSR at 64°C, and G*contact was the measured response. The authors concluded that the diffusion rate increased with temperature and that the source of the virgin binder influenced the diffusion rates. The experiment results also indicated that major blending occurred during mixing a short time thereafter at mixing temperatures higher than 100°C.

Shirodkar, P., Mehta, Y., Nolan, A., Sonpal, K., Norton, A., Tomlinson, C., ... Sauber, R. (2011). A study to determine the degree of partial blending of reclaimed asphalt pavement (RAP) binder for high RAP hot mix asphalt. *Construction and Building Materials*, 25(1), 150–155.

The authors developed a methodology to estimate the degree of blending of RAP binder in an asphalt mixture and estimated it for recycled mixtures with 25 percent and 35 percent RAP contents. The RAP was sieved below the No. 8 sieve, and the virgin aggregates were all above the No. 4 sieve. An initial assessment of the degree of blending was done by combining the RAP with the virgin aggregates without virgin binder, but the authors concluded that this estimate was not realistic given that some of the RAP binder coated the RAP aggregates or was lost on the mixing bucket and arm. Then, they conducted a subsequent analysis using RAP, virgin aggregates, and virgin binder. They extracted and recovered the binder after mixing and determined the high-temperature PG of the binder. Their assumption was that if there were 100 percent blending, the properties of the extracted binder from the RAP and virgin aggregate would be similar; however, if no blending occurred, the properties of the extracted binder from the RAP and virgin aggregates would be different. Their results showed degrees of partial blending of 70 percent and 96 percent for the recycled mixtures, with 25 percent and 35 percent RAP, respectively. The recycled mixture with 35 percent RAP used a softer virgin binder.

Sreeram, A., Leng, Z., Zhang, Y., & Padhan, R. K. (2018). Evaluation of RAP binder mobilisation and blending efficiency in bituminous mixtures: An approach using ATR-FTIR and artificial aggregate. *Construction and Building Materials*, 179, 245–253.

Authors used attenuated, total reflectance Fourier transform infrared (ATR-TIR) spectroscopy as an assessment tool. Mixtures with various percentages of RAP were prepared under different mixing conditions, and the resulting binder recovered from glass beads was used in place of aggregates. The recovered binder was characterized using DSR and GPC. Warm mix additives were also incorporated into the asphalt mixtures. The results indicated that the mobilization of the RAP binder was highly dependent on the mixing temperature and the presence of WMA additives.

Sreeram, A., & Leng, Z. (2019). Variability of RAP binder mobilisation in hot mix asphalt mixtures. *Construction and Building Materials*, 201, 502–509.

The authors recognized the uncertainty in the amount of RAP binder mobilized during the mixing process and quantified RAP binder mobilization using attenuated, total reflectance Fourier transform infrared (ATR-FTIR) spectroscopy. In general, the RAP binders exhibit a larger carbonyl band at around 1700 cm⁻¹ in the FTIR spectra. Three sources of RAP were employed in mixtures with 15 percent, 30 percent, and 50 percent RAP. A portion of the virgin aggregate was replaced with glass beads of various sizes to allow quantifying the RAP binder mobilization. The glass beads were collected after mixing, and the binder coating them was recovered and analyzed to compare the carbonyl value between 1666 cm⁻¹ and 1746 cm⁻¹ against the carbonyl of the RAP and virgin binders between those same wavelengths. This difference in carbonyl was used to estimate the degree of RAP binder mobilization. The degree of mobilization depended on the type (i.e., source) of RAP, mixing temperature, the amount of RAP in the mixture, and presence of warm mix additives. When the RAP was more viscous at the mixing temperature, the mobility reduced. This observation was further confirmed via SARA fraction analysis (i.e., asphaltenes and saturates content) and microscopic assessment of the “bee structures” of the RAP binders.

Stimilli, A., Virgili, A., & Canestrari, F. (2015). New method to estimate the “re-activated” binder amount in recycled hot-mix asphalt. *Road Materials and Pavement Design*, 16(sup1), 442–459.

The authors proposed a method to estimate the reactivated RAP binder amount based on the surface area of the RAP aggregates. The main characteristics of the RAP, including gradation and binder content, need to be known beforehand. They used recycled asphalt mixtures with 40 percent RAP content and a coarser and finer gradation, and a reference or control mixture with 25 percent RAP, which is commonly used for maintenance and rehabilitation in Italy and achieves equivalent performance to that of a virgin mixture. In addition, the total binder content was varied in the recycled mixtures with 40 percent RAP content. The mixtures were evaluated based on compactability, IDT strength, and a SCB test at low temperature. The proposed method is based on estimating the reactivated RAP binder film thickness by taking into account the surface area of the RAP aggregates and the binder content in the RAP. Based on their estimate, about 70 percent of the RAP binder is active or available to blend with the virgin binder, while 30 percent acts as black rock. Using this value to obtain the optimum binder content in the recycled mixtures, the authors achieved the best mechanical mixture performance (i.e., comparable to the control mixture). Deviations from the optimum—either more or less binder added—resulted in worse mixture performance.

Vassaux, S., Gaudefroy, V., Boulangé, L., Soro, L. J., Pévère, A., Michelet, A., . . . Mouillet, V. (2018). Study of remobilization phenomena at reclaimed asphalt binder/virgin binder interphases for recycled asphalt mixtures using novel microscopic methodologies. *Construction and Building Materials*, 165, 846–858.

The authors investigated the degree of RAP binder mobilization using binder markers (i.e., calcareous fillers) at the interface between virgin and RAP binders based on the temperature difference between materials. The methods employed included X-ray micro-fluorescence, infrared microscopy in attenuated total reflectance (ATR), and imaging ATR mode. One virgin and two laboratory-produced (i.e., artificially aged) RAP binders were employed. Double-layered specimens that included the virgin binder on one side and the RAP binder on the other were prepared. The virgin binder was always kept at an elevated temperature of 160°C, while the temperature of the RAP binders varied between 0°C and 40°C to simulate a hot and warm conditioning temperature of the RAP binder, respectively. The samples were allowed to cool at room temperature for 2 minutes to allow heat transfer and then cooled in a freezer for 10 minutes. The results indicated that infrared microscopy in imaging ATR mode using the carbonyl function was the best indicator of the RAP binder remobilization. At higher conditioning temperatures (i.e., same temperature for both virgin and RAP binders), the blending zone between the virgin and RAP binder increased. In addition, when a rejuvenator was added to the RAP binder, its mobilization increased even at warm conditioning temperature. The authors recommended the use of a carbonyl distribution profile and profile slope to assess the remobilization of the virgin binder into the RAP aggregate. When using the type of measurements employed by the authors, a carbonyl distribution profile slope less than $6.10 \times 10^{-6} \mu\text{m}^{-1}$ would be considered total remobilization.

Wen, H., & Zhang, K. (2016). Investigation of blending mechanisms for reclaimed asphalt pavement binder and virgin binder in laboratory-produced reclaimed asphalt pavement mixtures. *Transportation Research Record*, 2575(1), 187–195.

The authors investigated blending between RAP and virgin binder by considering three stages: transfer of RAP binder to virgin aggregate when the two materials are heated and in contact before mixing; mechanical blending of the RAP, virgin aggregate, and virgin binder during mixing; and diffusion between RAP and virgin binder after mixing. They studied the effects of blending at each stage on the rheological and fracture properties of asphalt mixtures with 26 percent RAP. The asphalt mixture performance tests the authors considered included dynamic modulus and creep compliance in IDT mode and IDT fracture at intermediate and low temperatures. The authors found that diffusion was the dominant factor affecting the rheological and fracture properties of the recycled mixtures. Therefore, the authors recommended allowing enough time during storage at the silo, transportation, and paving to ensure proper blending between the virgin and RAP binders.

Xu, J., Hao, P., Zhang, D., & Yuan, G. (2018). Investigation of reclaimed asphalt pavement blending efficiency based on micro-mechanical properties of layered asphalt binders. *Construction and Building Materials*, 163, 390–401.

The authors employed a three-layer, staged RAP binder extraction method and AFM to investigate the interaction and extent of blending between RAP and virgin binders under two mixing temperatures (i.e., 150°C and 130°C) and residence times (i.e., up to 7 days). RAP from an 8-year-old field project and artificial (i.e., laboratory aged) RAP were employed. A three-layer, staged extraction was used to obtain binder from the outermost, middle, and innermost layers of the RAP aggregates. The properties obtained from the AFM peak force quantitative nonmechanical property mapping included the Derjaguin-Muller-Toporov (DMT) modulus, adhesion, and energy loss. The results showed that the DMT modulus increased and the adhesion force decreased from the outermost to the innermost layers around the virgin and RAP aggregates. This result confirmed the non-homogeneous blending between the two binders. In addition, with the decrease in mixing temperature, the diffusion of the virgin binder into the RAP binder decreased, leading to more concentration of virgin binder in the outer layers of the RAP aggregate. In addition, the blending between the RAP binder and the virgin binder continued for a long period until a homogeneous blending was achieved.

Xu, Y., Xu, S., & Ji, J. (2014). Measurement method of blending status between virgin and aged binder in recycled asphalt mixtures—A literature review. *Challenges and Advances in Sustainable Transportation Systems* (pp. 311–318).

The authors summarized four types of virgin/RAP binder blending measurement methods: binder-marked, difference-identified, staged extraction, and indirect performance measurements. The binder-marked method consists of adding chemicals such as titanium or iron oxide pigments to the asphalt binder to identify blending with specific tests, such as Fourier transform infrared spectroscopy with attenuated total reflectance (FTIR-ATR) or X-ray spectroscopy (EDS). This method is mostly used to evaluate diffusion between RAP and virgin binder wafer specimens or change at the interface between RAP aggregates coated with virgin binder. The difference-identified method is similar to the binder-marked except that no foreign chemicals or pigments are added to the RAP binder; instead, special types of rejuvenators or mineral powders that can be easily identified under ultraviolet radiation are incorporated. The difference-identified method is less common than the binder-marked method, given the difficulty in finding appropriate markers for the experiments. The staged-extraction method consists in obtaining binder from different layers (usually between two and four) of the RAP aggregates and measuring its properties; the difference in performance is then attributed to the blending between the RAP and virgin binders. This method is commonly used to assess the blending process with time as diffusion between the virgin and RAP binders continue. Finally, the indirect performance measurements method compares the change in binder or mixture mechanical properties between complete blending and actual blending.

Yang, S. H., Susanto, H. A., & Muthia, G. V. (2019). *Reclaimed Asphalt Pavement Binder Contribution to the Asphalt Emulsion Slurry System Using X-Ray Microcomputed Tomography* (No. 19-01217).

When RAP is incorporated in emulsion slurry systems, the assumption is that the material acts as a black rock due to the process being carried out at ambient temperature. However, during its service life, the lighter asphalt fractions in the emulsion can act as a rejuvenator and diffuse in the RAP binder. The authors studied the diffusion mechanism using X-ray microcomputed tomography (CT) and DSR. X-ray micro-CT was used in specimens of three distinct sizes: mastic, RAP aggregate retained on sieves No. 4 and No. 8, and RAP aggregate. Using titanium dioxide (TiO₂) as a tracer, the authors measured the diffusion of the RAP binder and correlated to the G* obtained with the DSR. Wafer binder specimens with various emulsion residue and RAP binder concentrations were prepared for the DSR. The authors confirmed via X-ray CT images that diffusion occurred between the emulsion residue and the RAP binder and calculated the effective rheological properties of the blended binder.

Yu, S., Shen, S., Zhang, C., Zhang, W., & Jia, X. (2017). *Evaluation of the blending effectiveness of reclaimed asphalt pavement binder. Journal of Materials in Civil Engineering*, 29(12), 04017230.

The authors employed a gap-graded blending method consisting of mixing fine RAP, coarse virgin aggregate, and virgin asphalt to prepare asphalt mixtures. Then, after the asphalt mixture cooled down, the coarse aggregates were separated from the fine aggregates via sieving and manual inspection. Next, the binder coating the coarse and fine material was extracted and recovered, characterized, and compared against the properties of extracted and recovered binder from the RAP fine materials and from a control virgin asphalt mixture. There was a linear relationship between the RAP binder content and various rheological properties of the extracted and recovered binder from the recycled asphalt mixture. The authors verified that partial blending occurs in the recycled mixture and that the degree of blending was dependent on the RAP content; the blending ratios of 20 percent, 40 percent, and 60 percent RAP ranged between 21 percent and 83 percent depending on the test parameter. In addition, the authors incorporated a recycling agent to the recycled mixture with 60 percent RAP and noted improved blending between the RAP and virgin binders based on extracted and recovered binder rheological properties. The authors proposed a correction factor (i.e., modified blending chart) for recycled asphalt mixtures with more than 30 percent RAP content to account for partial blending between the RAP and virgin binder in the recycled mixture.

STUDIES ON BINDER AVAILABILITY FOR MIXTURES WITH RAP AND RAS

Ashtiani, M. Z., Mogawer, W. S., & Austerman, A. J. (2018). A mechanical approach to quantify blending of aged binder from recycled materials in new hot mix asphalt mixtures. *Transportation Research Record*, 2672(28), 107–118.

The authors proposed a method to quantify the binder amount in RAS and RAP that blends with virgin binder. The proposed method was based on performing local calibration of the Hirsch model considering a control mixture with only virgin materials. Asphalt binder master curves were constructed and were substituted in the model to estimate corresponding asphalt mixture master curves. Two types of RAS binders were used: tear-off scrap shingles (TOSS) and manufacturer waste scrap shingles (MWSS). The amount of RAP and RAS binders used in the mixtures were limited to 15 percent and 5 percent, respectively. The proposed method was validated through the performance of mixture tests, including four-point flexural beam fatigue, SCB, and DCT. Consistent trends between asphalt mixture tests and proposed degrees of blending for binders were found. The results of the study indicated that the percentage of binder activation was the highest in RAP (40–60 percent), followed by MWSS (20–40 percent) and TOSS (< 20 percent), respectively.

Mogawer, W. S., Booshehrian, A., Vahidi, S., & Austerman, A. J. (2013). Evaluating the effect of rejuvenators on the degree of blending and performance of high RAP, RAS, and RAP/RAS mixtures. *Road Materials and Pavement Design*, 14(sup2), 193–213.

The authors conducted a study to evaluate the impact of rejuvenators on the degree of blending between virgin and recycled binders by comparing measured and predicted dynamic moduli and using the Hirsch model. Confidence intervals with a significance level of $\alpha = 0.05$ were used to evaluate whether or not a good degree of blending occurred. Degree of blending was evaluated for several frequencies ranging from 1 Hz to 10 Hz and at three different temperatures 4°C, 20°C, and 35°C. Results indicated that at 4°C, blending occurred between rejuvenated binder and virgin binder in the 35 percent RAP + 5 percent RAS mixture. However, at temperatures higher than 4°C, predicted values became significantly higher than measured values, and as a result, no conclusion regarding degree of blending was made. The use of rejuvenators improved blending between virgin and recycled materials by mitigating the increase in air voids.

Nazzal, M. D., Kim, S. S., Abbas, A. R., Qtaish, L. A., Holcombe, E., & Hassan, Y. A. (2017). *Fundamental Evaluation of the Interaction between RAS/RAP and Virgin Asphalt Binders* (No. FHWA/OH-2017-24). Ohio Dept. of Transportation.

The authors conducted a study to evaluate blending between RAP and RAS and virgin materials. Two types of RAS were used in this study: tear-off and manufacturing waste. Three virgin asphalt binder's performance grades were considered: PG 58-28, PG 64-28, and PG 64-22. AFM experiments were conducted to characterize the micromechanical properties of the interfacial

zone that develops between the recycled and virgin binders. In addition, mixture tests including an asphalt concrete cracking device, SCB, and IDT were performed, and results were compared to AFM results. AFM results indicated that almost no blending was observed between RAS and virgin binders. However, blending between RAP and virgin binders occurred to a varying degree. Mixture tests demonstrated that the use of RAS negatively impacted the resistance of mixtures to low-temperature cracking and fatigue cracking, which can be attributed to the limited blending between the RAS binder and virgin binder observed in the AFM.

Orešković, M., Pires, G. M., Bressi, S., Vasconcelos, K., & Presti, D. L. (2020). Quantitative assessment of the parameters linked to the blending between reclaimed asphalt binder and recycling agent: A literature review. *Construction and Building Materials*, 234, 117323.

The authors provide a summary of the methods adopted in the literature to assess three blending parameters (DoB, DoA, and DoAv) of reclaimed asphalt binder and virgin binder with and without the inclusion of recycling agents. Methods were categorized into four different categories: (a) chemical approach, (b) mechanical approach, (c) mechanistic approach, and (d) visualization approach. The chemical approach included chromatography and spectroscopy. The mechanical approach included nanoindentation, binder testing, mechanical blends, and mixture testing. The mechanistic approach was composed of modeling and numerical simulation techniques. The visualization approach included microscopy and computed tomography methods. Based on the available literature review, a summary of the advantages and disadvantages of each one of these methods is provided. In addition, recommendations on the appropriate methods to estimate each one of the three blending parameters are provided. A summary of these recommendations is provided in Table A-1.

Table A-1. Recommended methods to estimate blending parameters.

Method	DoA	DoAv	DoB
Mechanical blending	✓	✓	X
Binder testing	X	✓	✓
Asphalt mixture testing	X	X	✓
Nanoindentation	X	X	✓
Chemical approach	X	✓	✓
Microscopy	X	X	✓
Computed tomography	X	X	✓
Modeling techniques	X	X	✓
Numerical simulation techniques	✓	✓	✓

✓ = recommended.

X = not recommended.

Stroup-Gardiner, M. (2016). *Use of Reclaimed Asphalt Pavement and Recycled Asphalt Shingles in Asphalt Mixtures* (No. Project 20-05, Topic 46-05).

This report provides information on the use of high RAP, RAS, or a combination of RAP and RAS materials in asphalt mixtures. Surveys of state agencies were conducted on the current practices adopted for determining recycled material properties, developing mix designs and assessing pavement performance. The literature review and surveys conducted in this study showed that BAFs for RAP and RAS depend on state agency experience. For example:

- Georgia uses the availability factor of 0.75 for RAP.
- A Louisiana laboratory study measured the availability factor for tear-off RAS asphalt based on volumetric method and concluded that binder availability ranges from 0.35 to 0.5.
- An FHWA memorandum recommended using BAFs of 0.70 to 0.85 when there are concerns about premature cracking when using RAS.
- AASHTO PP78-14 uses an availability factor between 0.70 and 0.85 for RAS and 1.0 for RAP.
- State material engineer survey results indicated the following regarding RAP/RAS availability:
 - 18 agencies use an availability factor of 1.0 for RAP and RAS.
 - 11 agencies use asphalt availability factors of less than 1.0. However, these values differ.
 - Examples of specific values reported by eight agencies are:
 - 0.85 for RAS asphalt (four agencies).
 - 0.75 for RAS asphalt (two agencies).
 - 0.70 for RAS asphalt (one agency).
 - 0.75 for RAP *and* RAS (one agency).

Zhao, S., Huang, B., Shu, X., & Woods, M. E. (2015). Quantitative characterization of binder blending: How much recycled binder is mobilized during mixing? *Transportation Research Record*, 2506(1), 72–80.

The authors conducted a study to quantify the amount of recycled binder that could be mobilized and become available to coat aggregates. The amount of RAP and RAS binders used in the mixtures was limited to 40 percent and 10 percent, respectively. GPC tests were performed, and a new parameter was identified: large molecular size percentage (LMSP). This parameter is based on binder molecular weight distribution and was used to differentiate between RAP or RAS and virgin binders as well as their blends. Blending charts were developed to correlate the LMSP parameter with binders that include RAP or RAS. The relationship between LMSP and RAP or RAS binder content was found to be linear. The mobilization rate of RAP/ RAS proved to be a function of the percentage of RAP/RAS in the total mixture. Mixtures with 10 percent to

20 percent RAP showed a mobilization rate of approximately 100 percent. Increasing the RAP content to 80 percent resulted in a mobilization rate of only 24 percent. Similarly, when RAS content was limited to 5 percent, the mobilization rate was found to be 61 percent. Increasing RAS content to 10 percent reduced mobilization rate to 36 percent.

STUDIES ON BINDER AVAILABILITY FOR MIXTURES WITH RAS

Sharifi, N. P., McKay, Z., Blankenship, P., Mahboub, K. C., & Anderson, R. M. (2019). Assessing binder blending level in asphalt mixtures containing recycled asphalt shingles. *Journal of Materials in Civil Engineering*, 31(8), 04019144.

The authors evaluated the degree of blending between RAS and virgin binder. Asphalt mixture specimens were prepared considering three blending scenarios: black rock (BR), actual practice (AP), and total blending (TB). For each one of these scenarios, two RAS contents were considered: 2.5 percent and 5 percent by weight of mixtures. Two mixture tests were performed: flexural beam fatigue and SCB tests. The results demonstrated that fatigue life, dissipated energy, and flexibility index of AP and TB scenarios were lower than those calculated for the BR scenario. No significant difference in fracture energy was observed between the three blending scenarios. The results of the study demonstrated that specimens prepared under the AP scenario performed close to the TB scenario. Based on the study results, the authors concluded that the RAS binder blended (or acted as it blended) with the virgin binder; however, the degree of blending between the two binders was not quantified.

Zhao, S., Huang, B., Shu, X., & Woods, M. E. (2015). Quantitative characterization of binder blending: How much recycled binder is mobilized during mixing? *Transportation Research Record*, 2506(1), 72–80.

The authors employed the AFM to characterize blending between virgin and RAS binders (tear-off and post-manufactured) using two-layer specimens. The effect of temperature on the microstructural properties of a tear-off RAS binder was also evaluated. AFM showed the ability to differentiate between virgin and RAS binders. The blending study indicated that both types of virgin binders (PG 64-22 and PG 52-28) did not blend with the tear-off RAS binder (300 μm thickness) at a maximum temperature 180°C and treating time of 30 minutes. The authors concluded that the interaction between virgin and RAS binders can be described as “mixing” rather than “blending” since the two materials did not blend into one. This mixing zone was found to be in the 25–30 μm range.

Zhao, S., Bowers, B., Huang, B., & Shu, X. (2014). Characterizing rheological properties of binder and blending efficiency of asphalt paving mixtures containing RAS through GPC. *Journal of Materials in Civil Engineering*, 26(5), 941–946.

The authors used different blends of RAS and virgin binders to characterize blending efficiency of RAS binders using GPC and DSR. The effects of RAS content, mixing time, and size of aggregate on blending efficiency were also investigated. In addition, correlations between rheological properties obtained from DSR and the percentage of large molecules (LMS) obtained from GPC were explored. Four different RAS contents were considered: 2.5, 5, 7.5, and 10 percent. The results demonstrated that mixing time influenced the blending between virgin and RAS binders; as mixing time increased, blending also increased. In contrast, the size of virgin aggregate had no effect on blending efficiency. Small RAS aggregates showed higher LMS compared to medium and large aggregates, which indicates the occurrence of partial blending. The percentage of LMS for small, medium, and large aggregates indicated that the most efficient blending occurs at 5 percent RAS content.

Zhou, F., Li, H., Lee, R., Scullion, T., & Claros, G. (2013). Recycled asphalt shingle binder characterization and blending with virgin binders. *Transportation Research Record*, 2370(1), 33–43.

The authors investigated the blending between virgin, RAP, and RAS binders. RAS binders were characterized using BBR and DSR tests. Two types of RAS binders were used in their study: tear-off asphalt shingles and manufacture waste asphalt shingles. Blending between virgin and RAS binders was found to be nonlinear, unlike blending of virgin and RAP binders, which exhibits a linear relationship. However, by limiting the RAS binder to 30 percent, linear charts can be used to estimate blending for blends of virgin and RAS binders and blends of virgin, RAP, and RAS binders. Limiting the RAS binder to 30 percent will also allow application of DSR and BBR tests with no issues.

