Project No. 20-44(24)

PILOT TEST OF PROPOSED STANDARD PRACTICE FOR USE OF RECYCLING AGENTS IN ASPHALT MIXTURES WITH RECYCLED ASPHALT MATERIALS

FINAL REPORT

Prepared for
National Cooperative Highway Research Program
Transportation Research Board
of
The National Academies of Sciences, Engineering, and Medicine

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AASHTO	American Association of State Highway and Transportation Officials
ABCD	Asphalt Binder Cracking Device
AC	Asphalt Concrete
AV	Air Void
BAF	Binder Availability Factor
BBR	Bending Beam Rheometer
Caltrans	California Department of Transportation
CRI_{Env}	Cracking Resistance Index–Environmental
DCT	Disc-Shaped Compact Tension
DelDOT	Delaware Department of Transportation
DOT	Department of Transportation
DSR	Dynamic Shear Rheometer
FAA	Federal Aviation Administration
FI	Flexibility Index
G_f	Fracture Energy
G-R	Glover-Rowe Parameter
HMA	Hot-Mix Asphalt
HWTT	Hamburg Wheel-Tracking Test
IDEAL-CT	Indirect Tension Asphalt Cracking Test
I-FIT	Illinois Flexibility Index Test
ITOA	Intermediate-Term Oven Aging
LMLC	Laboratory-Mixed Laboratory-Compacted
LTOA	Long-Term Oven Aging
NAPA	National Asphalt Pavement Association
NCHRP	National Cooperative Highway Research Program
NMAS	Nominal Maximum Aggregate Size
NRRI	Normalized Rutting Resistance Index
OB	Original Binder
PAV	Pressure Aging Vessel
PG	Performance Grade
PGH	High-Temperature Performance Grade

PGL	Low-Temperature Performance Grade
QA	Quality Assurance
QC	Quality Control
RAM	Recycled Asphalt Material
RAP	Reclaimed Asphalt Pavement
RAS	Recycled Asphalt Shingles
RBR	Recycled Binder Ratio
RPMLC	Reheated Plant-Mixed Laboratory-Compacted
RTFO	Rolling Thin-Film Oven
SCB	Semicircular Bend
SIP	Stripping Inflection Point
SN	Stripping Number
STOA	Short-Term Oven Aging
TTI	Texas A&M Transportation Institute
Tukey’s HSD	Tukey-Kramer Honestly Significant Difference
UTSST	Uniaxial Thermal Stress and Strain Test
WMA	Warm Mix Asphalt

ABSTRACT

Recycled asphalt materials (RAM) such as reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS) are routinely used in the construction of new asphalt concrete (AC) pavements. This practice yields economic and environmental benefits by reducing the amount of virgin materials used in the pavement. RAM is typically stiffer in nature and more prone to cracking than virgin asphalt concrete. For this reason, the amount of RAM in new pavements is generally limited. Mitigation strategies can be employed to increase the amount of RAM while maintaining adequate performance. Such strategies include the use of recycling agents and the substitution of the virgin binder for a softer binder. However, there is currently no standard method for incorporating these strategies in new AC pavements. This research focused on applying and verifying a draft American Association of State Highway and Transportation Officials (AASHTO) standard practice proposed in National Cooperative Highway Research Program (NCHRP) Report 927 from NCHRP Project 09-58 that aims to provide guidelines and tools to standardize the use of recycling agents in asphalt mixtures with high RAM content.

Major findings from this research include the following: recycling agent dose selection method revisions, binder availability factor (BAF) recommendations, previously suggested material selection guideline revisions, and mixture test aging sensitivity results. Researchers found that an adequate and more economical recycling agent dose could be estimated using both the low- and high-performance grades (PG) of binder blends. The BAF was confirmed to be of importance when designing a high RAM mixture. To improve reliability, it is recommended that only one variable be adjusted in a mixture to mitigate the increased stiffness from recycled binders. Some test parameters were found to be sensitive to aging, including the flexibility index from the semicircular bend test and the cracking test index from the ideal cracking test, while others were not observed to be sensitive to aging, including the fracture energy measured by the low-temperature disc-shaped compact tension test. These findings were used to revise the draft AASHTO standard practice proposed in NCHRP Report 927.

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EXECUTIVE SUMMARY

The use of recycling agents in asphalt mixtures with high recycled materials content has been successfully implemented in many projects. Significant cost savings and environmental benefits can be achieved when using these types of asphalt mixtures that commonly contain reclaimed asphalt pavement (RAP) and sometimes include recycled asphalt shingles (RAS). However, due to lack of experience and guidance for mix design and specification limits on recycled asphalt materials (RAM) contents, these mixture types have not been widely utilized. Standard guidance and implementation recommendations are needed to enable wider adoption of these mixtures.

National Cooperative Highway Research Program (NCHRP) Project 20–44(24), "Pilot Test of Proposed Standard Practice for Recycling Agents in Asphalt Mixtures Incorporating RAP and RAS" focused on two pilot field projects on which to apply the draft American Association of State Highway and Transportation Officials (AASHTO) standard practice developed in NCHRP Project 09–58. The effectiveness of this draft standard practice was independently assessed for two climates with one field project in Delaware and one in California. The use of this draft standard practice enables the use of higher RAM while maintaining the desired performance.

Multiple different material combinations and proportions were tested to determine the most effective strategies for increasing the proportion of recycled materials or RAM content. Materials included 4 base virgin binders, 2 RAP sources, 1 RAS source, and 2 recycling agents. Testing was done to investigate both stability and durability in terms of cracking resistance at representative temperatures and with aging. A variety of cracking and rutting performance tests were run to identify deficient mixtures and ensure balanced performance.

Using a relative cost analysis, recommendations were made. Estimated mixture cost savings of 10% on average and up to 32% were possible when engineering a mixture according to the draft AASHTO standard practice. These mixtures maintained or exceeded cracking and rutting performance thresholds and performed comparably to their respective control mixtures with a history of good performance.

Revisions were made to the draft AASHTO standard practice based on experience gained in this study. Most notably, the method for determining an appropriate recycling agent dose was adjusted to determine a more economical/standard dose while maintaining important performance properties. Material selection guidelines were also developed to reduce compatibility issues. Reducing the binder availability factor (BAF) of recycled binders was highlighted as important for mixture performance, especially when using RAS. Additional minor revisions and recommendations were made to help improve workflow and test result consistency.

CHAPTER 1—INTRODUCTION

Construction of new asphalt concrete (AC) roads in the United States commonly includes reclaimed asphalt pavement (RAP). Recycled asphalt shingles (RAS), though less common, are also used in the construction of new roads. Based on an annual survey by the National Asphalt Pavement Association (NAPA), the use of RAP in new AC pavements has grown 59 percent over the past 10 years, from 56 million tons to 89 million tons [1]. Economics are the primary driving force behind the growth in the use of RAP/RAS or recycled asphalt materials (RAM). When RAM is used in an asphalt mixture, less virgin material is required. The asphalt binder is the highest cost material per ton of AC, and its cost and uncertainty in market conditions increase as the price of petroleum oil increases and fluctuates. Reducing the amount of virgin binder in a mixture can significantly reduce the cost of a project. A growing industry push toward sustainability has also increased the drive toward the use of higher RAM contents, which lowers the carbon footprint of new AC pavements.

Despite the growing use of RAP in AC, there is more RAP available than what is being used. RAP stockpiles have continued to grow, from an estimated 110 million tons stockpiled in 2018 to 138 million tons stockpiled in 2019 [1]. In 2019, some states averaged as low as 9 percent RAP in new asphalt mixtures, whereas other states averaged as high as 32 percent RAP. The overall average RAP and RAS used in AC in 2019 was 21.2 percent and 0.218 percent, respectively [1]. The average amount of RAP used in new asphalt mixtures has remained relatively constant over the past 5 years, with the use of RAS falling significantly. The slowed growth and possible decline in the use of RAM in AC is likely due to poor performance, such as premature cracking.

Although there are earlier reports of the use of RAP, its use in asphalt pavements began in earnest in 1974 in test projects in Texas and Nevada [2]. Over 40 states completed RAP implementation projects over the next 10 years (1974–1984) to better understand the potential of RAP in AC. These implementation efforts were due to sponsorships from the Federal Highway Administration [3].

Many recycling techniques have been used over the years to incorporate RAP in asphalt mixtures. In 1987, a method that utilized 90–100 percent RAP in new AC was developed [4]. This method saw limited implementation due to emissions and the significant cost of heating the RAP. Recycling agents and softer virgin binders have become more popular in recent years to increase the amount of RAP in AC to approximately double the national average of 21.2 percent without increasing heating requirements, causing performance issues, or requiring hot-mix plant modifications.

Long-term performance is the biggest unknown when using stiff, brittle, and aged RAM in AC, especially in large quantities. Thus, transportation agencies in most states have set limits on the maximum percentage of RAM that can be used in new AC projects. These limits are set to achieve the desired performance and ensure the durability of the asphalt pavement. Without the addition of a recycling agent or the use of a softer virgin binder, adding large amounts of RAM commonly results in premature cracking of the asphalt pavement. Recycled binder is stiffer than virgin binder because of aging. To mitigate AC cracking from stiff recycled binders, a softer virgin binder grade can be used, or a recycling agent can be added. In 2019, 18 percent of RAP mixtures used a softer binder, and 4 percent used a recycling agent. Of the mixtures using 20 percent or more RAP, 79 percent were reported to use a softer binder or recycling agent [1].

Although recycling agents have been used in AC for many years, there is no standard method for determining a sufficient dose or evaluating their use. Most often, the amount of recycling agent used for a project will be determined by the contractor in coordination with the recycling agent supplier. This decision often leads to inconsistent performance results and conflicts of interest depending on how recycling agent doses are selected. NCHRP Project 09-58 was completed to understand the effect of various recycling agents on AC with high RAM content. Within this project, a draft American Association of State Highway and Transportation Officials (AASHTO) standard practice was developed to standardize how recycling agents are dosed and how the associated binder blends and mixtures are evaluated [5]. The project panel approved a further implementation project to evaluate and revise the use of this standard practice, which formed the basis for this study. The project included laboratory and field data from two additional field projects across the United States.

This report is organized into four chapters. Chapter 1 gives an overview of the project, including the rationale behind the study, the test methods used, and the draft AASHTO standard practice that was the basis of this study. Chapter 2 shows the test results and analysis conclusions of a field project in Delaware. Similarly, Chapter 3 describes the test results and conclusions from a field project in California. Finally, Chapter 4 combines the analysis and conclusions from both field projects and explains how these data were used to revise the draft AASHTO standard practice.

LITERATURE REVIEW

As part of NCHRP Project 09-58 (the precursor to this study), a literature review was published on the use of recycling agents in asphalt mixtures with high recycled material contents [6]. This literature review builds on the findings of that report by adding recent research.

An asphalt binder is a colloid of asphaltenes dispersed in maltenes. The asphalt binder ages as it is produced and exposed to the elements. Aging causes the asphalt binder to become less strain tolerant and thus more susceptible to cracking [6, 7]. This process is commonly described as occurring in two stages, short-term and long-term aging. Short-term aging happens during production and construction and is primarily due to volatilization and the oily components of the maltenes being absorbed by the aggregates as the mixture is heated and mixed at very high temperatures [7]. Long-term aging occurs in the field as the asphalt binder is subjected to ultraviolet radiation, moisture, temperature fluctuations, and freeze-thaw cycles. Long-term aging is primarily due to oxidation of the asphalt binder. Chemical reactions occur between the asphalt binder and atmospheric oxygen and between components within the asphalt binder [8].

Recycling agents can be added to an aged asphalt binder to help partially restore rheological and chemical properties. Recycling agents often contain a large amount of maltene constituents that help to replenish the maltenes lost during aging [7]. This process helps to restore desired properties such as ductility and elastic response in the asphalt binder. The type, dose, binder compatibility, and incorporation method of the recycling agent all impact its effectiveness in restoring asphalt binder properties. On a molecular level, recycling agents can combine differently with the asphalt binder, causing variable performance. Higher aromatic content can help recycling agents diffuse into the asphalt binder, and long-chain saturated hydrocarbons or large functional groups will inhibit their ability to blend with the recycled binder in RAM and mobilize its availability [9].

Many recycling agents have been developed and commercialized, including vegetable oils, tall oils, aromatic extracts, and reacted bio-based oils [5]. Products perform differently depending on their proprietary chemical composition. Modified vegetable oils, reacted bio-oils, and tall oils have been shown to be the most effective in several studies [10, 11]. However, the performance is also temperature dependent; a recycling agent that works well in one climate may not work well in another [12–14]. Performance of a recycling agent has also been shown to be highly correlated with the proportion of total fatty acids [15]. Properly classifying and selecting a recycling agent is important since its ability to diffuse into and soften and partially restore the ductility of aged binders is highly correlated to its chemical composition [6, 15]. To mitigate this risk of inadequate mixture performance, recycling agent type and dose should be carefully selected for each material combination [10, 11, 14].

Moisture susceptibility, rutting, and stripping are primary concerns when using a recycling agent [6, 15–17]. The stripping inflection point (SIP) can be determined using the Hamburg wheel-tracking test (HWTT). SIP may be misleading as a measure of stripping due to the high correlation between 12.5-mm rut depth ($N_{12.5}$) and SIP [16]. A novel method for analyzing HWTT data was developed by Yin et al. and introduced a new stripping number (SN) parameter [16]. Using this novel method, Zhang et al. showed a significant increase in moisture susceptibility with rejuvenated AC, although the severity was dependent on the recycling agent type [17]. Caution is recommended with the use of a recycling agent due to moisture susceptibility concerns. However, other studies indicate that there may be moisture susceptibility benefits from using a recycling agent that is part of a chemical package with a liquid anti-stripping agent.

An Australian case study investigated the effect of a recycling agent on reducing moisture and freeze/thaw damage on mixtures containing RAP [18]. The study noted that there is no Australian standard for the use of recycling agents, thereby validating the need for guidance. The study found that the rejuvenated mixture was up to 20 percent more resistant to stiffness loss after moisture and freeze/thaw damage. This improvement was based on the ratio of the damaged versus undamaged stiffness values. The study noted that the initial stiffness of the rejuvenated specimens was lower than that of the unrejuvenated mixture. However, it did indicate that the long-term performance of mixtures with a recycling agent was improved. The recycling agent dose selection method was not discussed in the Australian case study, but the conclusions help indicate the importance of understanding how recycling agents should be used with caution in AC pavements.

Tran et al. studied the effect of recycling agents on high RAM mixtures in the field and under laboratory conditions [7]. All mixtures in the study used similar gradations, volumetric properties, and asphalt binder content while varying the use of a recycling agent and the amount of RAM. The study concluded that with the use of a recycling agent, higher RAM contents could be used without significantly impacting early field performance. Furthermore, the recycling agent did not have any significant negative impacts on early field performance. However, the mixture that included RAS did show higher amounts of reflection cracking in the field after about one year of traffic. When properly selected, the use of a recycling agent can effectively allow more RAM to be used in AC pavements.

Many studies show that high RAM mixtures can be implemented with similar or better performance than traditional mixtures [13, 14, 18, 20, 21]. Veeraragavan et al. showed that the use of a recycling agent restored the properties of a 50 percent RAP mixture to a state equivalent or better than a standard 20 percent RAP mixture [19]. They further determined that the 50 percent RAP mixture with a recycling agent could result in 17 percent to 25 percent cost savings compared to the 20 percent RAP mixture. While these mixtures provide economic benefits, most state agencies require extensive testing to verify high RAM mixtures or do not allow them at all. This is likely due to the uncertainty in their long-term performance. As the use of recycling agents becomes more standardized, contractors and public agencies will be able to gain more confidence in high RAM mixtures. In turn, this confidence will lead to wider adoption of these practices and significant environmental and economic benefits.

As of 2019, most departments of transportation (DOTs) did not allow the use of recycling agents in hot-mix asphalt (HMA) [6]. While that has started to change in the last 3 years, most new AC mixtures do not include high RAM content or a recycling agent [1]. For the use of recycling agents to become more widespread in high RAM mixtures, several challenges need to be addressed. These challenges include standardizing how to select the type and dose of recycling agent, developing testing criteria for mixtures with high RAM and a recycling agent, and collecting more data regarding long-term performance of these mixtures [6]. Test parameters should focus on binder blend and mixture testing since the testing of recycling agents alone may not indicate how they will perform in a mixture [11]. Long-term aging parameters or aging rate parameters may also be needed for mixtures with high RAM and a recycling agent due to differences in aging for mixtures with a recycling agent [12]. Several of these challenges are directly addressed in this study.

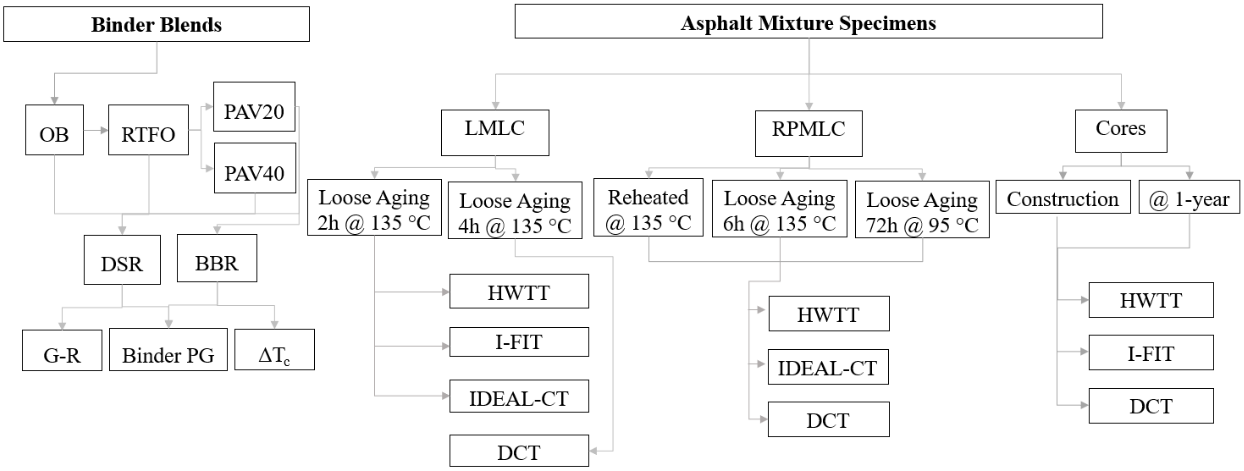
OBJECTIVES

The objectives of this study were as follows:

- Identify field projects in at least one warmer and one colder climate and coordinate with state DOTs to sample materials, gather any available laboratory testing results, and monitor field performance.
- Test laboratory-mixed laboratory-compacted (LMLC) specimens and asphalt binder blends for each field project as described by the draft AASHTO standard practice summarized.
- Analyze and evaluate data to determine the effectiveness of the draft AASHTO standard practice proposed in NCHRP Project 09-58. The effectiveness of the draft practice was evaluated based on its ability to determine an appropriate recycling agent dose to achieve adequate balanced cracking and rutting performance in AC mixtures.
- Based on laboratory findings, propose any needed revisions or additions to the draft AASHTO standard practice.
- Use information gained from the construction of the field projects to develop a guide to aid transportation agencies in the implementation of the revised draft AASHTO standard practice.

TESTING PLAN

Verification of the draft AASHTO standard practice for using recycling agents was completed using laboratory and field data. Laboratory testing was conducted on mixtures and binders to evaluate performance, as shown in Figure 1. Field cores were tested, and available field performance was gathered. Two field projects were used in this study. One field project was in Delaware (colder climate), and one was in California (warmer climate). Field projects included a recycling agent in several of their mixtures and a RAM component. Recycling agent doses for the Delaware project were selected based on a similar methodology to that contained in the draft AASHTO standard practice [5]. Information on how doses were selected for the California mixtures was not available, but the doses were evaluated using the draft AASHTO standard practice tools. For recycling agent doses that were not in agreement with the draft standard method, additional laboratory tests were conducted to understand the performance differences.



Note: OB = original binder, RTFO = rolling thin-film oven, PAV20/40 = pressure aging vessel aging for 20 and 40 h, DSR = dynamic shear rheometer, BBR = bending beam rheometer, G-R = Glover-Rowe parameter, PG = performance grade, ΔT_c = difference between BBR S and m results, LMLC = laboratory-mixed laboratory-compacted, RPMLC = reheated plant-mixed laboratory-compacted, HWTT = Hamburg wheel-tracking test, I-FIT = Illinois flexibility index test, IDEAL-CT = indirect tension asphalt cracking test, DCT = disc-shaped compact tension.

Figure 1. Testing Plan Overview.

A brief description of each test and testing conditions used in this study are provided below:

Dynamic Shear Rheometer (DSR)

The Dynamic Shear Rheometer (DSR) was used to determine the high-temperature performance grade (PGH) and the Glover-Rowe (G-R) parameter according to AASHTO T 315 and AASHTO M 320. Two replicates were tested for all binders and binder blends.

Bending Beam Rheometer (BBR)

The Bending Beam Rheometer (BBR) was used to determine the low-temperature performance grade (PGL) and the ΔTc parameter according to AASHTO PP 78, AASHTO T 313, and AASHTO M 320. One replicate was tested per temperature. All binders and binder blends were tested when possible, some recycled binders were not able to be tested due to binder stiffness.

Hamburg Wheel-Tracking Test (HWTT)

The HWTT was used to determine the rutting resistance and the moisture susceptibility of each mixture according to AASHTO T 324. Rutting resistance was evaluated by the number of cycles to 12.5-mm rut depth ($N_{12.5}$), and the moisture susceptibility was determined using the SN and the SIP. Two replicates were performed per mixture. The HWTT was used to test all specimen types; however, one year old field core specimens were not tested.

Semicircular Bend (SCB) Test

The Semicircular Bend (SCB) test was used to test the intermediate-temperature cracking performance for LMLC specimens and field cores. The SCB test was used to measure the FI according to AASHTO TP 124. Testing was performed at a temperature of 25°C with a 15-mm notch depth. Four replicates were tested for each mixture.

Indirect Tension Asphalt Cracking Test (IDEAL-CT)

The Indirect Tension Asphalt Cracking Test (IDEAL-CT) was used to measure the CT_{Index} according to ASTM D8225. The IDEAL-CT was used to test the intermediate-temperature cracking performance for LMLC and RPMLC specimens. Four replicates were tested for each mixture.

Disc-Shaped Compact Tension (DCT) Test

The Disc-Shaped Compact Tension (DCT) test was used to measure the low-temperature fracture energy (G_f) as specified in ASTM D7313. This test was used to determine the low-temperature cracking performance of the mixture. Specimens were tested at −12°C after intermediate oven aging (ITOA) of 4 hr at 135°C. Two replicates were tested per mixture for all specimen types.

Table 1 shows the Delaware field project details, and Table 2 shows the details for the California field project. Note that both field projects included the use of a recycling agent and have a control/standard mixture that is commonly used in each state.

Table 1. Delaware Field Project Details.

Description	Virgin Binder Grade	RAP	Additive	Optimum Asphalt Content
Mixture 1 Control RAP	PG 64-22	25%	—	5.5%
Mixture 2 RAP w/ Recycling Agent	PG 64-22	25%	2.7% V*	5.5%
Mixture 3 High RAP w/ Soft Binder	PG 58-28	40%	—	5.5%
Mixture 4 High RAP w/ Soft Binder & Recycling Agent	PG 58-28	40%	1.2% V*	5.5%

* Modified vegetable oil recycling agent.
Note: A dash (—) = not applicable.

Table 2. California Field Project Details.

Description	Virgin Binder Grade	RAP	RAS	Additive	Optimum Asphalt Content
Mix A—Control	PG 64-16	0%	0%	—	5.3%
Mix B—Conventional	PG 64-16	12%	0%	—	5.3%
Mix C—RAS Only	PG 58-22	0%	3%	0.75% T*	5.3%
Mix D—RAP/RAS	PG 58-22	10%	3%	1.25% T*	5.6%

* Tall oil recycling agent.

DRAFT AASHTO STANDARD PRACTICE

Laboratory tests were conducted on the field project binder blends and their corresponding LMLC specimens. Testing was also done on field cores and RPMLC specimens if the materials were available. Their performance was assessed based on available thresholds, aging conditions, and tools specified in the draft AASHTO standard practice [5]. The draft standard practice includes guidelines and tools for preparing and evaluating asphalt mixtures and binder blends. Recycling agent dose selection guidelines are given to help standardize how recycling agents are used. This section gives an overview of the draft AASHTO standard practice. Proposed revisions to this draft standard are given in Chapter 4.

Material Preparation Guidelines

For test repeatability and to limit cross-laboratory variability, asphalt binder blends and asphalt mixtures must be prepared in a consistent manner. The draft AASHTO standard practice gives guidelines to standardize these processes and references existing standards when applicable.

Binder blending guidelines specifying blending temperatures and times and the order of blending are given. Binders are heated until they are adequately fluid—between 160°C and 200°C depending on the binder. Recycled binders and additives are then blended with the base binder in the following order: first, the recycling agent or other additive is added; then, the RAP is added, if included; and finally, the RAS is added, if included. After each addition, the blend is hand-stirred for 30 sec and reheated for 1 min between each step. Binders are then directly tested or aged to avoid reheating.

Asphalt mixture guidelines include preheating, recycled material addition, recycling agent addition, aging, and cooling guidelines. Aggregates are preheated overnight at mixing temperatures, and recycled materials and virgin binders are preheated 2 hr prior to aging. Mixtures are mixed and then loose-aged prior to compaction depending on the test being run.

Recycling Agent Dose Selection Methods

The proposed recycling agent dose selection guidelines are summarized in the following three steps:

1. Determine high-temperature performance grade (PGH) of the base binder and RAP/RAS binders per AASHTO M 320.
2. Select the virgin binder, recycled binder ratio (RBR), and RAP/RAS combination, and calculate PGH of the recycled binder blend using Equation 1.1:

$$PGH_{Blend} = (RAP_{BR} \times PGH_{RAP}) + (RAS_{BR} \times PGH_{RAS}) + (B_{BR} \times PGH_{Base}) \qquad (1.1)$$

where:

PGH_{Blend} = continuous PGH of the recycled binder blend (°C);
RAP_{BR} = RAP binder ratio;
PGH_{RAP} = continuous PGH of the RAP binder (°C);
RAS_{BR} = RAS binder ratio;
PGH_{RAS} = continuous PGH of the RAS binder (°C);
B_{BR} = base binder ratio = 1 – RBR; and
PGH_{Base} = continuous PGH of the base binder (°C).

3. Estimate recycling agent dose using Equation 1.2:

$$\text{Recycling Agent } (\%) = \frac{PGH_{Blend} - PGH_{Target}}{\text{Slope Rate}} \qquad (1.2)$$

where:

PGH_{Blend} = continuous PGH of the recycled binder blend (°C) calculated from Equation 1.1; and
PGH_{Target} = continuous PGH of target climate.
Slope Rate = change in PG per % recycling agent determined from blending charts with multiple recycling agent doses or requested from materials supplier. When unknown, use 1.38 for petroleum-based aromatic extracts and 1.82 for all other recycling agent types.

Based on recycling agent dose and recycled material type, add the recycling agent to the HMA mixture following one of these guidelines: For HMA mixtures with only RAP and for all binder blends, the recycling agent is added as 100 percent replacement for the base binder. For HMA mixtures with RAP and RAS and recycling agent doses greater than 5.0 percent, the recycling agent is added as 100 percent addition with a mandatory requirement to ensure adequate mixture rutting resistance.

Component Material Guidelines

Material selection and proportioning guidelines are shown in Table 3. The table provides information on the materials and the amount of materials that should be considered for use in asphalt mixtures.

Table 3. Component Material Selection and Proportioning Guidelines.

Test	**Parameter**	**Component Material**			
		Base Binder	**RAP**	**RAS**	**Recycling Agent**
High-Temperature, Short-Term Aging[a]					
DSR	PGH	≤ 64°C	≤ 100°C	≤ 150°C	—
Low-Temperature, Short- and Long-Term Aging[b]					
BBR	ΔT_c	≥ −3.5°C	≥ −7.5°C	—	—
Proportioning					
	RBR	—	≤ 0.5 RBR (RAP_{BR}+RAS_{BR})	≤ 0.15 RAS_{BR}	—
	Dose	—	—	—	≤ 8–10%[c]

[a] Original binder and rolling thin-film oven aged by AASHTO T 240.

[b] 20-h pressure aging vessel aging @ 100°C by AASHTO R 28.

[c] Percent of total binder in the blend/mixture.

Performance Evaluation Tools

The rheological properties of the binder blends were characterized by performing DSR and BBR tests. Four different aging states were considered: unaged (original), short-term aging in the rolling thin-film oven (RTFO) to simulate aging during production and construction, and long-term aging in the pressure aging vessel (PAV) at 20 h and 40 h to simulate field aging. DSR results were used to evaluate cracking and rutting resistance based on the G-R parameter at 15°C and 0.005 rad/sec (with PAV aging in Black space) and continuous PGH, respectively. BBR results were used to evaluate brittleness and cracking resistance characteristics of the binder blends. Brittleness was evaluated based on ΔT_c, or the difference in critical low temperatures for S and m-value by BBR testing after 20-hr PAV and 40-hr PAV, for comparison with G-R results, although a threshold after 40-hr PAV is not currently available. Cracking resistance was assessed based on continuous low-temperature performance grade (PGL) and ΔT_f, defined as the difference between critical low temperature for BBR stiffness and binder cracking temperature measured in the asphalt binder cracking device (ABCD). Table 4 gives an overview of the proposed binder evaluation tools and thresholds.

Table 4. Proposed Binder Blend Evaluation.

Type of Property	Test	Parameter(s)	Standard(s)	Proposed Threshold & Aging Condition*
High-Temperature, Original, and RTFO Short-Term Aging				
Rutting Resistance	DSR	PGH	AASHTO T 315 AASHTO M 320	Target Climate after RTFO
Intermediate-Temperature, Track with Aging (RTFO, RTFO plus 20-hr PAV, RTFO plus 40-hr PAV)				
Cracking Resistance	DSR	G-R = $\frac{\lvert G^{*}\rvert(cos\delta)^{2}}{sin\delta}$	AASHTO T 315	≤180 kPa after 20-hr PAV ≤600 kPa after 40-hr PAV [5, 20, 21]
Low-Temperature, Short- plus Long-Term Aging (RTFO plus 20-hr PAV)				
Brittleness	BBR	Δ T_c	AASHTO PP 78	≥ −5.0 for virgin after 20-hr PAV [5]
Cracking Resistance		Continuous PGL	AASHTO T 313 AASHTO M 320	Target climate after 20-hr PAV
Cracking Resistance	BBR and ABCD*	Δ T_f	AASHTO PP 78 AASHTO TP 92	≥ 7.0 at Δ Tc = −2.0 ≥ 10.0 at Δ Tc = −6.0 for −2.0 ≤ Δ Tc ≤ −6.0 after 20-hr PAV [22]

* This report includes a limited evaluation of the ABCD, more work is needed before the ABCD is implemented.

Mixtures were evaluated for rutting resistance, moisture susceptibility, and cracking resistance. Rutting resistance and moisture susceptibility were measured in the HWTT after short-term oven aging (STOA) at high temperatures to determine the number of cycles to 12.5-mm rut depth ($N_{12.5}$) and SN. Cracking resistance was evaluated at both intermediate and low temperatures. Selected aging conditions are tied to the existing thresholds. The intermediate-temperature cracking resistance was assessed by measuring the flexibility index (FI) using the semicircular bend (SCB) test and the cracking test index (CT_{Index}) from the IDEAL-CT after ITOA and long-term oven aging (LTOA) protocols, as defined in Table 5. Low-temperature mixture cracking resistance was measured by the fracture energy (G_f) in the DCT test after the ITOA protocol outlined in Table 5. The cracking resistance index–environmental (CRI_{Env}) in the uniaxial thermal stress and strain test (UTSST) was also tested after LTOA on selected mixtures.

Table 5. Proposed Mixture Evaluation.

Type of Property	Test	Parameter(s)	Standard(s)	Proposed Threshold & Aging Condition*
High-Temperature, Short-Term Aging				
Rutting Resistance	HWTT	$N_{12.5}$	AASHTO T 324	≥ 5,000 for PG 58-XX ≥ 7,500 for PG 64-XX (cold) ≥ 10,000 for PG 64-XX (warm) ≥ 15,000 for PG 70-XX ≥ 20,000 for PG 76-XX after STOA (2 hr @ 135°C) [5]
Moisture Susceptibility	HWTT	SN	AASHTO T 324 [10]	≥ 2,000 after STOA (2 hr @ 135°C) [23]
Intermediate-Temperature, Short-Term, and Short- plus Long-Term Aging				
Cracking Resistance	SCB	FI	AASHTO TP 124	≥ 7 after STOA (2 hr @ 135ºC) [20]
	IDEAL-CT	CT_{Index}	ASTM D8225	≥ 80 after STOA (2 hr @ 135ºC) [24]
Low-Temperature, Short- plus Long-Term Aging				
Cracking Resistance	UTSST	CRI_{Env}	ASTM WK60626	≥ 17 after LTOA compacted (5 d @ 85°C) [5]
	DCT	G_f	ASTM D7313	≥ 400 J/m^2 after ITOA loose (4 hr @ 135ºC) [25]

For the Delaware field project, plant mix was collected at the time of construction and used to study aging with a recycling agent. Mixtures were tested using the HWTT, the IDEAL-CT, and the DCT to look at rutting resistance, intermediate-temperature cracking, and low-temperature cracking with aging, respectively. Mixtures were reheated and loose oven aged before compacting and testing. Mixtures were tested at the original reheated state after aging for 6 hr at 135℃ and after aging for 72 hr at 95℃. The asphalt mixture was spread on a pan at a thickness of about 1.5 inches for aging. The mixtures were stirred and rotated occasionally during aging to ensure uniformity.

Field cores for both field projects were evaluated for a subset of the proposed laboratory tests. Field cores were procured at construction for both field projects and about 1 year after construction for the Delaware field project. A set of California field cores were aged for 5 days at 85℃ (AASHTO R 30) in lieu of using field-aged cores. Cores taken at construction were tested for rutting resistance using the HWTT. All cores were tested for intermediate- and low-temperature cracking performance using the SCB and DCT tests, respectively. In addition, trial batch, mix design, and quality control/quality assurance (QC/QA) data collected from the contractor were considered in the analysis.

CHAPTER 2— GUIDELINES FOR HIGH RECYCLED ASPHALT MATERIAL MITIGATION STRATEGIES: DELAWARE FIELD PROJECT

This chapter presents information on a case study of a mill-and-overlay project in Milford, Delaware, constructed in early 2021. The project overlayed two lanes of traffic approximately 1.5 mi long with 11.5-ft lane widths. The project was divided into four sections and used four different asphalt mixtures. Each mixture was approximately 4,000 ft long and 11.5 ft wide (shoulder was not included). Binder blends, field cores, and LMLC specimens were prepared for all four field mixtures. Additional laboratory mixtures were developed and tested to aid in the data analysis.

MATERIALS

The Delaware field project included the following four mixtures, with additional tests performed on a laboratory only (L) version of Mixture 4:

- Mixture 1—25 percent RAP using an unmodified PG 64-22 binder (control).
- Mixture 2—25 percent RAP using an unmodified PG 64-22 binder and a recycling agent.
- Mixture 3—40 percent RAP using an unmodified PG 58-28 binder.
- Mixture 4—40 percent RAP using an unmodified PG 58-28 binder and a recycling agent.
- Mixture 4(L)—40 percent RAP using an unmodified PG 64-22 binder and a recycling agent.

Mix designs were provided by the contractor, Diamond Materials, and approved by the Delaware Department of Transportation (DelDOT). A standard Type C (9.5-mm) Superpave mix design with 75 gyrations was used. A PG 64S-22 binder was used in mixtures containing 25 percent RAP. A PG 58S-28 binder was used in mixtures containing 40 percent RAP.

The recycling agent used in this study was a vegetable oil derivative and is referred to as “V” throughout the report. A warm mix asphalt (WMA) additive was added at a dose of 0.6% to all mixtures. For laboratory fabricated specimens, the WMA additive was omitted from the blend to help isolate the effect of the recycling agent. Binder and recycling agent details are shown in Table 6, with the WMA additive omitted from the design as it was not used in laboratory mixed specimens or binder blends.

Aggregates used in mix designs were all locally sourced and processed by Tri-County Materials in Dover, Delaware. RAP was obtained from various sources before being crushed and stockpiled. The RAP was crushed to ½ inch nominal maximum aggregate size (NMAS) with an average asphalt binder content of 4.5 percent. Mix design gradations and quality control limits are shown in Figure 2.

Table 6. Delaware Mixture Details.

Mixture No.	Mixture Description	Virgin Binder	RAP Content (%)	Total/Virgin Asphalt Binder Content (% by weight of mixture)	Recycling Agent Dosage (% by weight of total binder)
1	Control RAP	PG 64-22	25	5.4/4.3	None
2	RAP w/ Recycling Agent				2.7 V
3	High RAP	PG 58-28	40	5.5/3.7	None
4	High RAP w/ Recycling Agent				1.2 V
4(L)	High RAP w/ Recycling Agent (Additional Laboratory Test)	PG 64-22	40	5.5/3.7	2.7 V

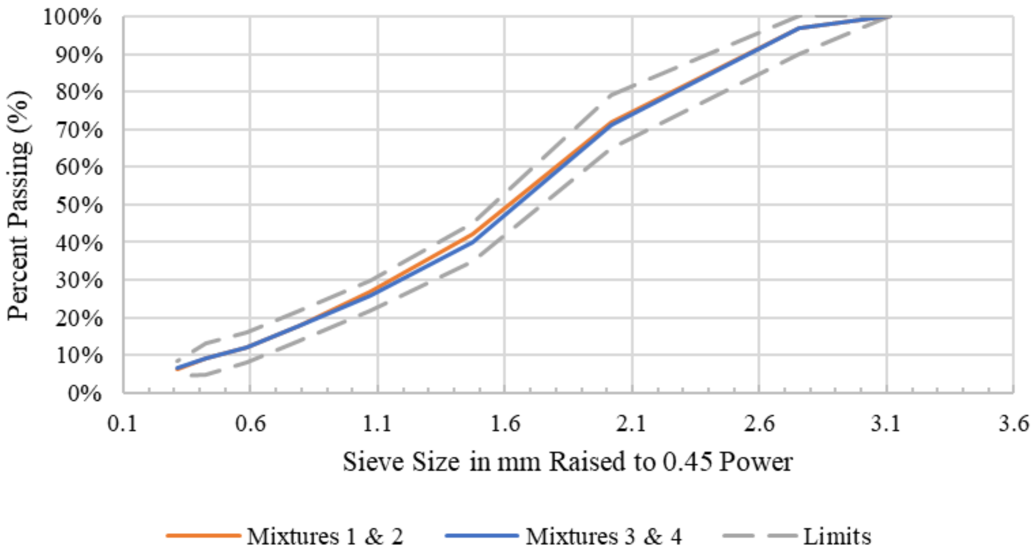


Figure 2. Delaware Mix Design Gradations.

TESTING PLAN

Testing Tools

All the evaluation tools used in this study are specified in the NCHRP Report 927 draft AASHTO standard practice [5]. Both binder and mixture testing were performed. Mixture testing included LMLC specimens, RPMLC specimens and field cores. Table 7 shows the test types and parameters used in this study. Tests were selected to evaluate the rutting resistance and the cracking resistance of each mixture to help determine which mixtures are expected to last the longest in the field. Binder tests were selected to correlate with mixture tests to determine which binder tests could be good indicators of mixture performance. Mixture cracking resistance was tested using intermediate-temperature and low-temperature cracking performance tests. These tests were selected based on the tests used in NCHRP Project 9-58.

Table 7. Delaware Test Details.

	Test Type	**Test**	**Parameter**	**Replicates**	**Aging Protocol***	**Threshold Used, [Reference]**
Binders and Binder Blends	Rutting Resistance	DSR	PGH	2	RTFO	Target Climate
	Cracking Resistance	DSR	G-R	2	RTFO, PAV	≤ 180 kPa after 20-hr PAV, ≤ 600 kPa after 40-hr PAV [5]
	Brittleness	BBR	ΔT_c	2	RTFO, PAV	≥ −5.0 after RTFO + 20-hr PAV
Mixture	Rutting Resistance	HWTT	$N_{12.5}$	2	STOA	≥ 7,500 [5]
	Moisture Susceptibility	HWTT	SN	2	STOA	≥ 2,000 [18]
		HWTT	SIP	2	STOA	≥ 9,000 [5]
	Cracking Resistance	SCB	FI	4	STOA	≥ 7 [5]
		IDEAL-CT	CT_{Index}	4	STOA	≥ 80 [19]
		DCT	G_f	2	ITOA	≥ 400 J/m^2 [26]

* RTFO = rolling thin-film oven, PAV = pressure aging vessel, STOA = short-term oven aging for 2 hr at 135°C, ITOA = intermediate-term oven aging for 4 hr at 135°C.

Binder and Binder Blend Testing

The PGH was determined using the DSR according to AASHTO T 315 and AASHTO M 320. This process helped demonstrate the rutting resistance of the binder blends. The DSR was also used to determine the G-R parameter at 15°C and 0.005 rad/s and to show aging in Black space to highlight cracking susceptibility of the binder blend as it aged. The BBR was used to determine the PGL and ΔT_c of each binder and binder blend according to AASHTO T 313 and AASHTO PP 78. This information helped to reveal the low-temperature cracking resistance, brittleness, and recycling capacity of each binder.

Binders and binder blends were tested at four aging conditions: unaged (original), short-term aging in the RTFO to simulate aging during production and construction, and long-term aging in the PAV at 20 hr and at 40 hr to simulate field aging.

DelDOT required a PG 64-22 binder or equivalent binder blend for the field project location and traffic conditions. In Mixture 2, a recycling agent was added to target 64°C as the true continuous PGH. The recycling agent dose in Mixture 4 was calculated to lower the PGH as close to 64°C as possible without decreasing the PGL lower than −28°C. This deviated from the recommendations in the draft AASHTO standard practice which recommends the PGH be lowered to the true climate PGH without considering PGL. Equation 2.1 and Equation 2.2 were used to help determine the recycling agent dose used in Mixture 2 and Mixture 4 as well as in the adjusted Mixture 4(L). These equations are repeated from Chapter 1 for reference purposes.

$$PGH_{Blend} = (RAP_{BR} \times PGH_{RAP}) + (RAS_{BR} \times PGH_{RAS}) + (B_{BR} \times PGH_{Base}) \quad (2.1)$$

$$Recycling\ Agent\ (\%) = \frac{PGH_{Blend} - PGH_{Target}}{Slope\ Rate} \quad (2.2)$$

where:

PGH_{Blend} = Continuous PGH of the recycled binder blend (°C).
RAP_{BR} = RAP binder ratio.
PGH_{RAP} = Continuous PGH of the RAP binder (°C).
RAS_{BR} = RAS binder ratio.
PGH_{RAS} = Continuous PGH of the RAS binder (°C).
B_{BR} = Base binder ratio = 1 –RBR.
PGH_{Base} = Continuous PGH of the base binder (°C).
PGH_{Target} = Continuous PGH of target climate (°C).
Slope Rate = change in PG per % recycling agent determined from blending charts with multiple recycling agent doses or requested from materials supplier. When unknown, use 1.38 for petroleum-based aromatic extracts and 1.82 for all other recycling agent types.

Mixture Testing

Laboratory-mixed specimens were prepared using mix design data provided by DelDOT. Additional testing was done on Mixture 4(L) by substituting the PG 58-28 binder for the PG 64-22 binder and adjusting the recycling agent dose to 2.7 percent, as shown in Table 6. The specimens were mixed at 145°C and compacted at 135°C. Loose mix for DCT specimens was conditioned at 135°C for 4 hr prior to compaction. For all other tests, the loose mix was conditioned at 135°C for 2 hr prior to compaction. Air voids were targeted at 7 percent ± 0.5 percent for all specimens.

Plant mix was reheated in an oven set to 135°C. After about 30 min of heating, the mix was divided into pans at a uniform thickness of about 1.5 inches. Plant mix was tested at three loose-aged conditions: reheated, reheated plus 6 hr at 135°C, and reheated plus 72 hr at 95°C. These aging protocols were selected based on aging protocols used in NCHRP Report 927 [5]. All mixtures were compacted after aging and after being reheated to 135°C.

Field cores were trimmed as thick as possible and ranged in thickness from about 39 mm to 52 mm. A double-bladed saw was used to ensure parallel faces. Field core test results were corrected for thickness with DCT specimens and for air voids and thickness for SCB specimens. This improved the interpretability of the test results. For both specimen types, the results were corrected for thickness using the simple linear correlation shown in Equation 2.3. For the SCB specimens, the results were also corrected for air voids to a reference of 7 percent air voids. This was done using empirical data from a study done by Batioja-Alvarez et al. [27].

$$R_{50} = R_t \times {}^{t}/_{50} \quad (2.3)$$

where:

R_{50} = the test result corrected to a 50-mm reference thickness;
R_t = the calculated test result using the average thickness; and
t = the average thickness of the specimen (mm).

TEST RESULTS AND DISCUSSION

Binder and Binder Blend Testing

Table 8 summarizes the true performance grade, ΔT_c, and the G-R parameter with aging. The continuous PGH for Mixture 1 measured marginally higher than the PG 64-22 climate range, and the PGL measured marginally lower than specified for Mixture 4. Mixture 1 also showed the highest PGL, and Mixture 4 exhibited the lowest PGH. This finding could indicate cracking concerns for Mixture 1 and rutting concerns for Mixture 4. A higher G-R number indicates a stiffer and more brittle binder. The recommended threshold is $\leq$ 180 kPa after 20 hr PAV aging and $\leq$ 600 after 40 hr PAV aging. All original binders and binder blends performed well below these thresholds, indicating the binders have adequate resistance to embrittlement as they age. The recycling agent in Mixture 2 significantly lowered the G-R parameter after 40 hr PAV, while the effect in Mixture 4 was insignificant. This finding indicates that the Mixture 1 binder will be more brittle with aging, which could lead to higher cracking susceptibility of the AC pavement over time. Mixture 2 showed the lowest stiffness after 40 hr PAV, which could indicate lower cracking susceptibility of the AC pavement over time. The difference in the effect of the recycling agent in Mixtures 2 and 4 could be due to the lower recycling agent dose in Mixture 4, the higher RAP content, or the interaction with the different virgin binders. ABCD results correlate very well with PGL measured by the BBR. In both cases, adding a recycling agent improved the low temperature cracking resistance.

Table 8. Delaware Binder Mixture Properties.

Description	Continuous PG	ΔTc	PGL by ABCD	G-R after RTFO (kPa)	G-R 20-hr PAV (kPa)	G-R 40-hr PAV (kPa)
PG 64-22 Unmodified Virgin Binder	67.5–27.1	1.0	-27.4	3	10	92
PG 58-28 Unmodified Virgin Binder	59.8–27.8	−0.1	-28.1	1	5	39
Recovered RAP Binder	89.3–15.6	−6.5	-22.7	731	2,168	17,565
Mixture 1 Blend, 0.208 RBR, PG 64-22	70.5–23.7	0.0	-24.3	20	58	168
Mixture 2 Blend, 0.208 RBR, PG 64-22, 2.7% V	65.3–28.0	0.3	-28.6	5	54	74
Mixture 3 Blend, 0.327 RBR, PG 58-28	68.4–26.5	−1.3	-26.0	10	63	100
Mixture 4 Blend, 0.327 RBR, PG 58-28, 1.2% V	66.1–28.7	−0.1	-28.2	6	42	95

Aging in Black space is shown in Figure 3. The asphalt binder or binder blends get more brittle as the point moves up and to the left on the chart. Each binder blend is shown after RTFO, 20-hr PAV and 40-hr PAV aging. All four binder blends performed very similar to each other.

Blend 1 was measured to be the least ductile with aging but still performed well below the performance thresholds.

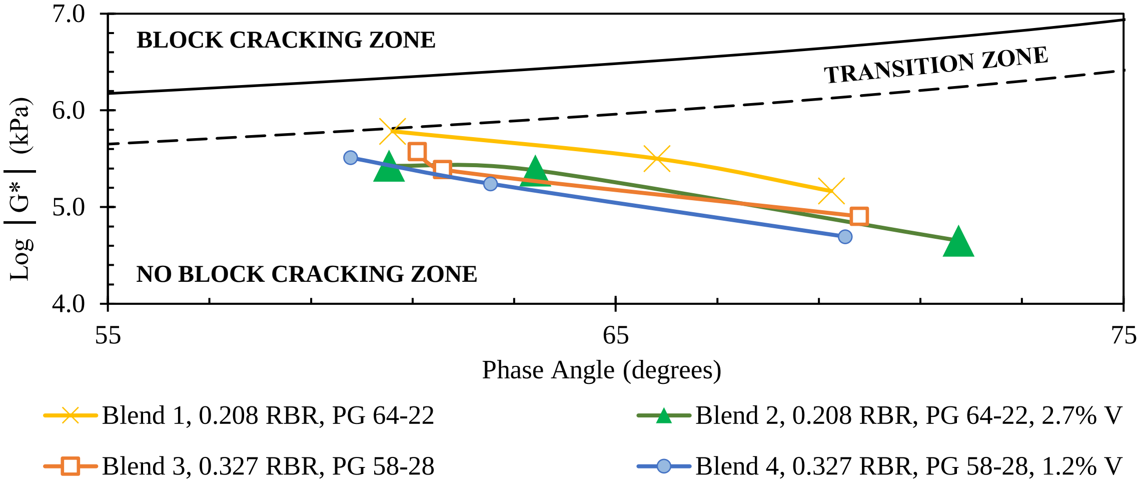


Figure 3. Delaware Binder Aging in Black Space.

Mixture Testing

Laboratory test results are summarized below for LMLC, RPMLC, and field core specimens. Test performance thresholds are indicated with a dashed line. A statistical analysis was conducted on all test results using the Tukey-Kramer honestly significant differences (Tukey's HSD) mean comparison test at a 90 percent confidence interval. The results are shown with a letter to indicate statistical similarity (i.e., if two results are both labeled "A," then they are statistically the same).

Laboratory-Mixed Laboratory-Compacted Specimens

The HWTT was used to determine mixture rutting performance of the LMLC specimens. NCHRP Report 927 [5] proposes a cold climate threshold of the number of passes to a 12.5-mm ($N_{12.5}$) rut depth of ≥ 7,500 passes for mixtures with PG 64-XX binders. Figure 4 shows the HWTT rutting curves. Mixtures 1–3 performed within these thresholds, with Mixture 4 performing marginally below this value. Mixture 4(L) performed above this threshold. As designed, Mixture 4 may not have adequate high-temperature resistance to rutting or moisture damage. This indicates that using a softer binder grade in combination with a recycling agent, as was done for Mixture 4, makes the mixture too soft and may result in premature pavement damage.

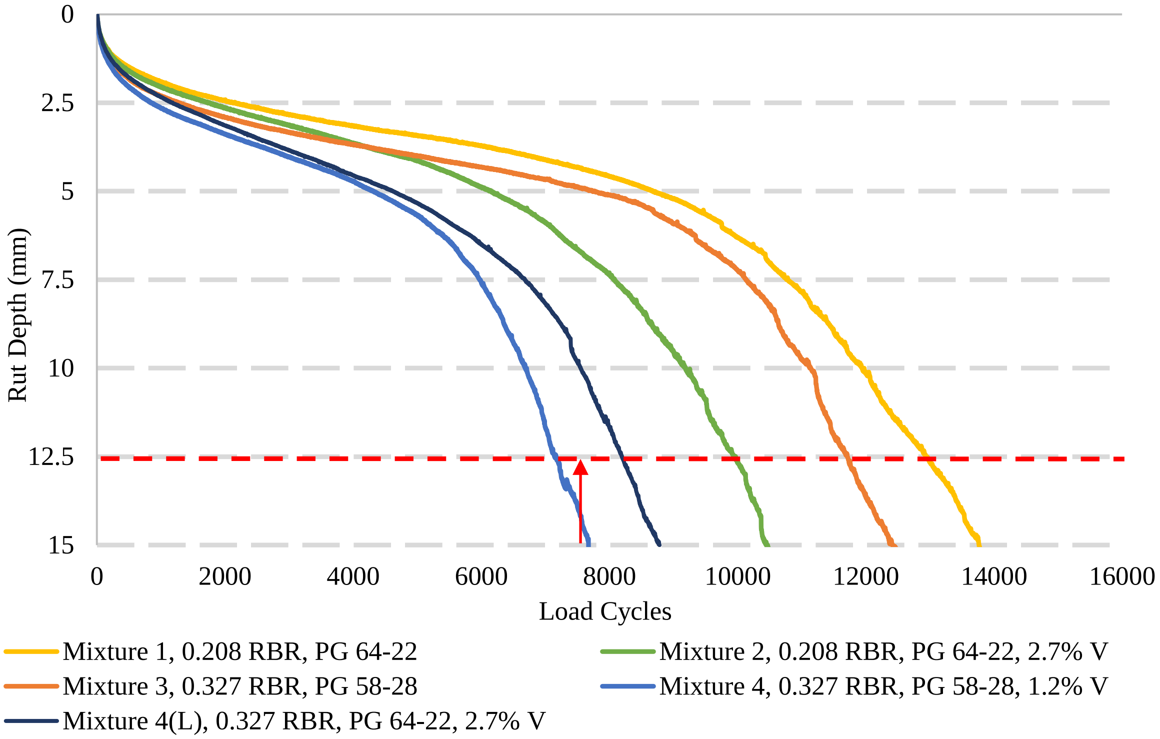


Figure 4. Delaware HWTT Rut Depth.

The SN and SIP are shown in Figure 5. The SN is found by plotting the rut depth versus load cycle curve and reading the load cycle value at the point where the curvature switches from negative to positive. The SIP is determined by fitting two straight lines to the negative and positive curves on the rut depth versus load cycle graph and reading the point where they intersect. For adequate resistance to moisture susceptibility, an SN ≥ 2,000 and an SIP ≥ 9,000 are used. Mixtures 1 and 4 marginally fail the SN threshold, and Mixtures 2 and 4 fall below the SIP threshold. Moisture susceptibility may be an issue for Mixture 4 since it failed both thresholds. This again indicates that using a softer binder grade in combination with a recycling agent, as was done for Mixture 4, may promote premature pavement failure. However, in Mixture 4(L) with a PG 64-22 binder, the mixture increased about 60 percent on the SN parameter and 16 percent on the SIP parameter, indicating a higher resistance to moisture susceptibility.

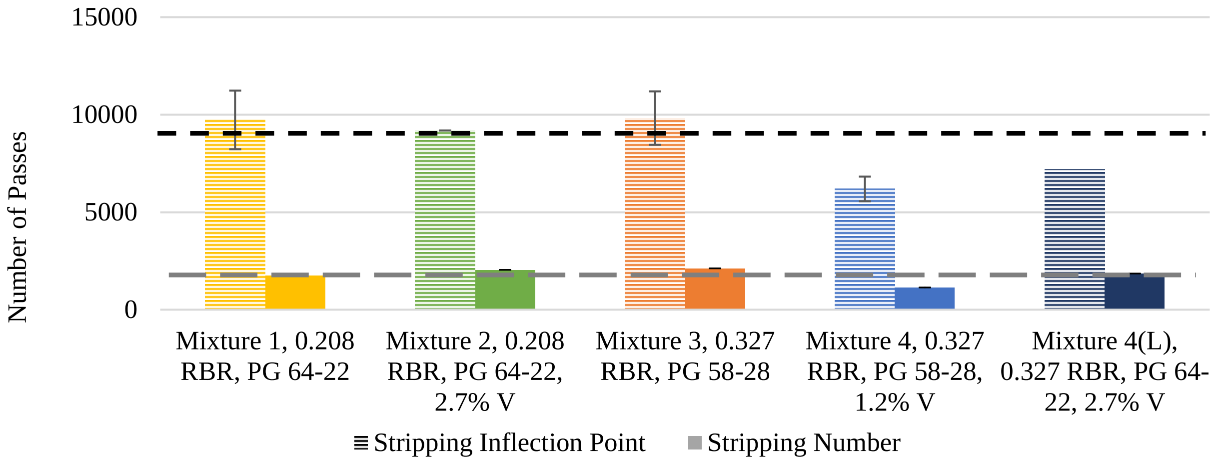


Figure 5. Delaware SIP and SN Results.

The IDEAL-CT was also conducted on LMLC specimens. The results are shown in Figure 6. A proposed CT_{Index} threshold of > 80 was used, and all mixtures exceeded this threshold. This finding indicates that adequate intermediate-temperature cracking performance is expected. Mixture 3 and Mixture 4(L) performed the best, indicating that similar adequate performance is expected when using a softer PG 58-28 binder or when using a PG 64-22 binder plus a recycling agent.

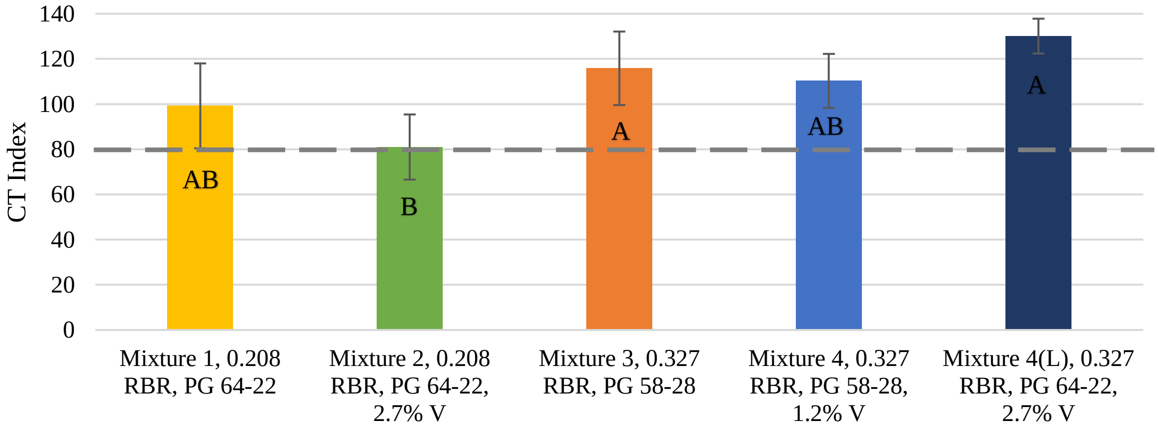


Figure 6. Delaware LMLC CT_{Index} Results.

The Illinois flexibility index test (I-FIT) results are summarized in Figure 7. The proposed threshold for adequate performance is an FI ≥ 7. All mixtures exceeded this threshold, which also indicates that adequate intermediate-temperature cracking performance is expected based on this test. All mixtures were statistically similar.

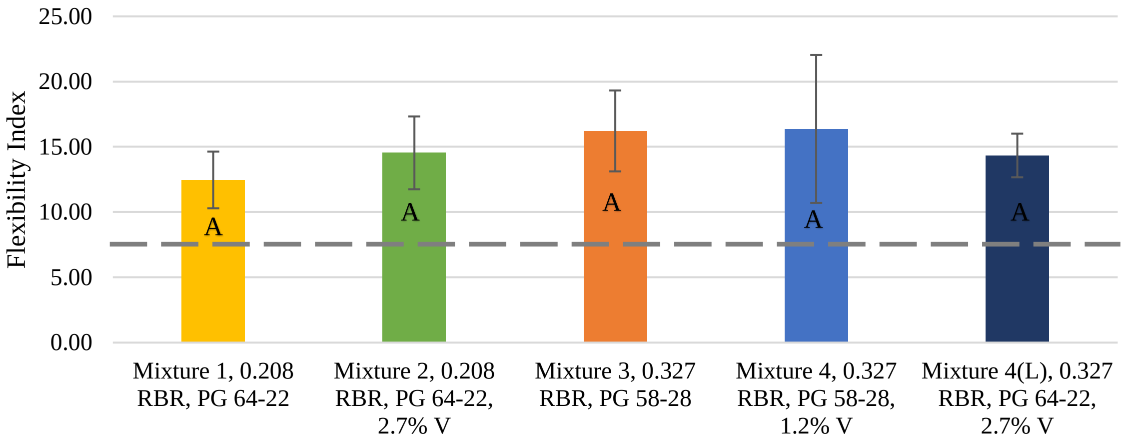


Figure 7. Delaware LMLC FI Results.

DCT results are summarized in Figure 8. The proposed threshold for adequate performance is a G_f > 400 J/m after 4-hr loose mix oven aging at 135°C. All mixtures exceeded this threshold, which indicates that adequate low-temperature cracking performance is expected. Though not statistically significant, the observed differences between mixtures correlate well with PGL binder testing that shows Mixture 1 with the highest PGL value (lowest resistance to low-temperature cracking) and Mixture 4 with the lowest PGL value and therefore the highest resistance to low-temperature cracking.

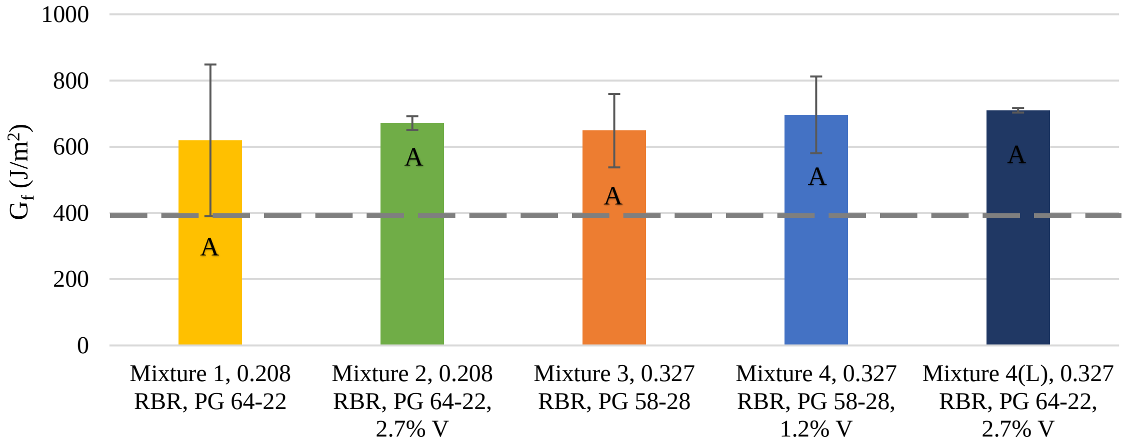


Figure 8. Delaware LMLC DCT Results.

Reheated Plant-Mixed Laboratory-Compacted Specimens

To investigate the long-term effect of adding a recycling agent to Mixture 4, researchers studied RPMLC specimens. HWTT, IDEAL-CT, and DCT tests were performed at three different aging conditions, as detailed in the testing plan. Note that the plant mix ford both mixtures included 0.6% WMA additive.

HWTT results were used to determine if stripping and rut depth remained a concern after aging. Rutting results are shown in Figure 9. Mixture 4 consistently showed higher rutting than Mixture 3, while the difference between the two mixtures decreased with aging.

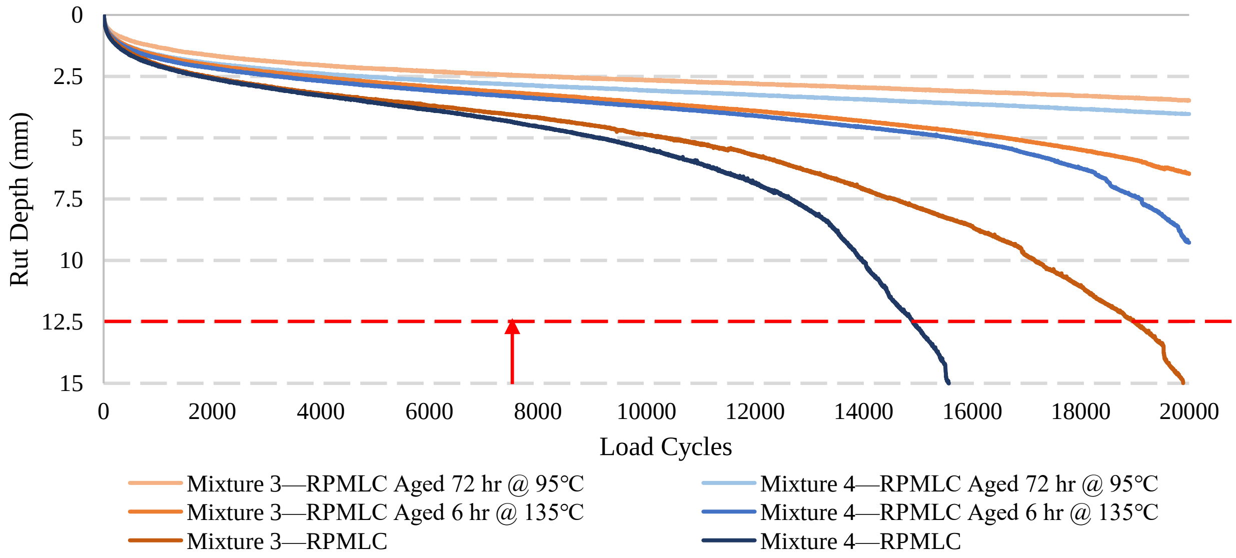


Figure 9. Delaware RPMLC Rut Depth with Aging.

Stripping was only detected in the reheated RPMLC specimens (i.e., without additional aging), and the results are shown in Figure 10. Both the SN and the SIP show that Mixture 3 has a slightly higher resistance to stripping, but these differences are not statistically significant. RPMLC specimens aged for 6 hr at 135°C and 72 hr at 95°C did not exhibit stripping, which indicates that moisture susceptibility becomes less of a concern after aging. Statistical significance is differentiated by adding a subscript SN or SIP to the corresponding test result.

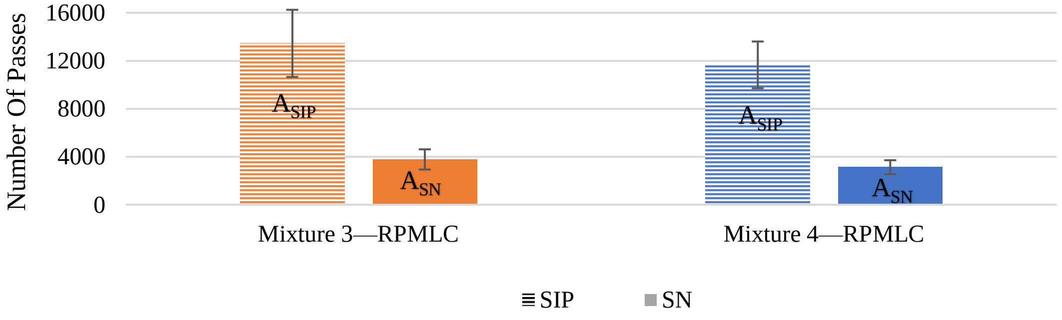


Figure 10. Delaware RPMLC SN and SIP Results.

The IDEAL-CT results are shown in Figure 11 and indicate the intermediate-temperature cracking performance with aging. The CT_{Index} value decreased with aging and was statistically similar between mixtures. This finding indicates that adding a recycling agent in Mixture 4 did not significantly improve intermediate cracking performance. These results agree with the binder G-R testing, which indicated little difference in binder stiffness over time between Mixtures 3 and 4. Statistical significance is differentiated by adding a subscript 1 and 2 to letters corresponding to the two aged states.

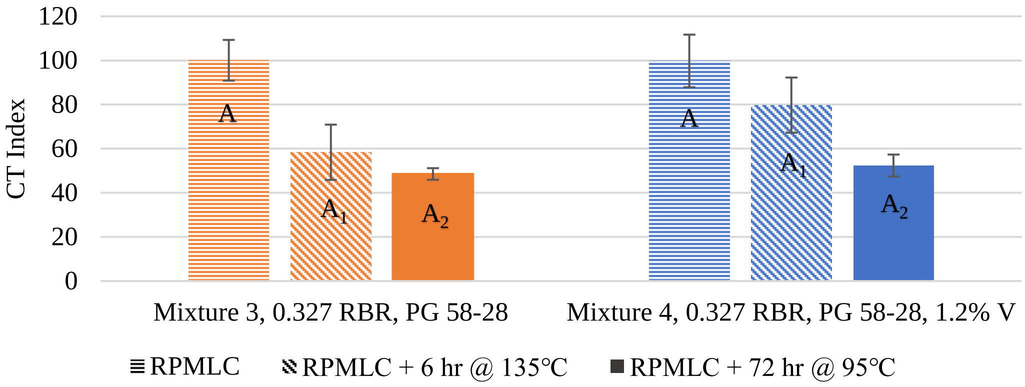


Figure 11. Delaware CT_{Index} with Aging.

An alternative method for analyzing the IDEAL-CT results was recently proposed by Yin et al. [28]. This method creates an interaction diagram by separating the fracture energy (G_f) from the 75 percent of maximum load deformation divided by the 75 percent of maximum load slope (l_{75}/m_{75}). This is shown for the Delaware aging data in Figure 12, with lines of constant CT_{Index} shown in gray and the corresponding CT_{Index} value noted to the bottom right of the line. The large markers are the average G_f versus l_{75}/m_{75} values, with the individual test results shown by the smaller markers.

The l_{75}/m_{75} parameter is thought to be an indication of the ductility of the specimen, and G_f is the energy required to fracture the specimen. Both are important for balanced performance, but mixtures with an equivalent CT_{Index} may not perform the same depending on their location on the interaction diagram. Mixtures 3 and 4 have statistically similar CT_{Index} values before aging but statistically different G_f values (Figure 12). This information could potentially give more insight into mixture performance. Also interesting is that the G_f appears to be less variable than the l_{75}/m_{75} parameter. This information could be useful in discriminating between mixtures. The mixtures both follow a similar trend with aging as they move across the interaction diagram generally from the lower right to the upper left with a relatively constant decrease in l_{75}/m_{75} and an initial increase followed by a sharp decrease in G_f.

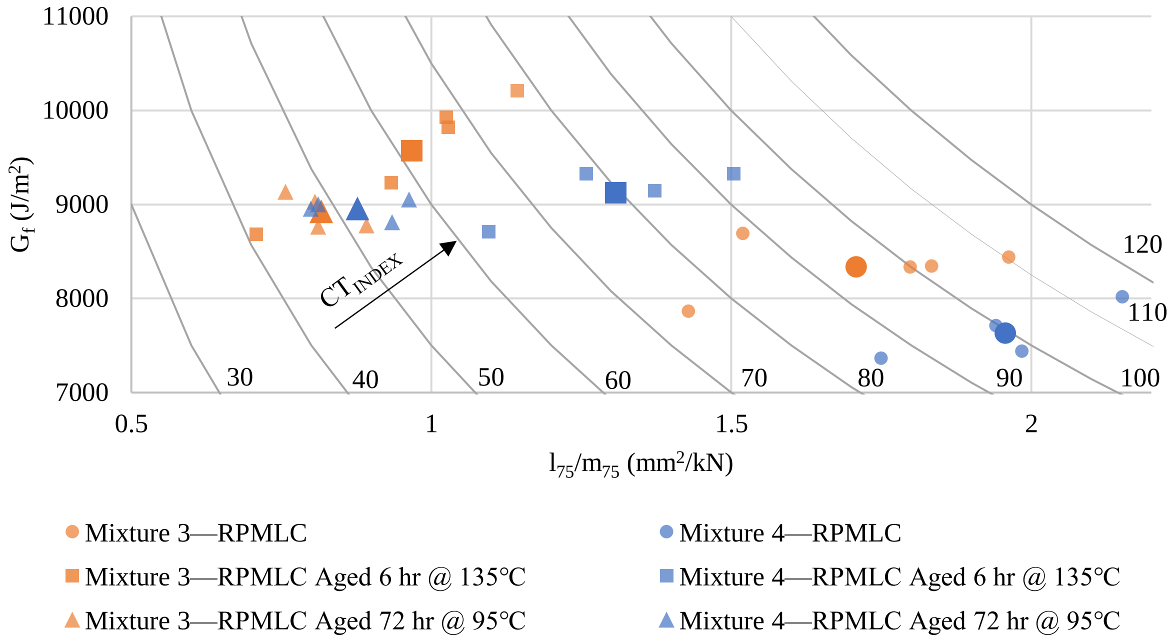


Figure 12. Alternative IDEAL-CT Analysis for Delaware Mixtures.

The DCT results are shown in Figure 13 for RPMLC specimens at the specified laboratory aging conditions. There is no statistical difference between the mixture types or between aged conditions. This finding indicates that DCT is less sensitive to short- and intermediate-term aging than IDEAL-CT and that the recycling agent in Mixture 4 did not significantly improve low-temperature cracking performance.

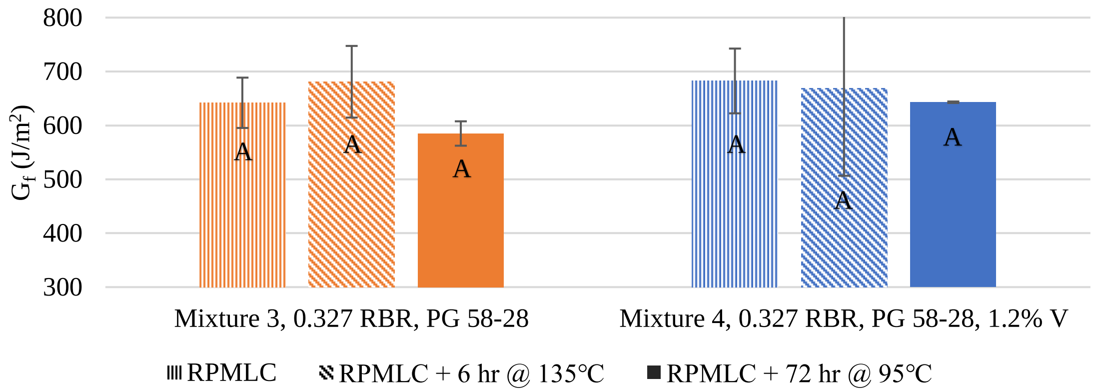


Figure 13. Delaware DCT with Aging.

Field Cores

Field cores acquired soon after pavement construction showed no difference in FI between mixtures, as shown in Figure 14. Cores acquired about 1 year after construction showed noticeably lower FI values and differences between the mixtures. Mixture 1 showed the lowest average FI value, while Mixture 2 had the highest (Figure 14). This finding indicates that the addition of a recycling agent in Mixture 2 significantly improved the intermediate-temperature cracking resistance after aging compared to Mixture 1. Mixture 3 performed better than Mixtures

1 and 4. This result indicates that using the softer PG 58-28 binder was enough to accommodate 40 percent RAP without the need to incorporate a recycling agent, and that adding a recycling agent in Mixture 4 could lower the cracking resistance of the AC pavement after about 1 year of field aging. These results also agree with the binder G-R results that showed Mixture 1 having the highest stiffness and Mixture 2 having the lowest stiffness after 40-hr PAV aging. Statistical significance is differentiated by adding a subscript 1 to letters corresponding to cores tested after 1 year. The field cores also include 0.6% WMA additive for all mixtures and cannot be directly compared to LMLC results. It is also important to note that the field core FI results were generally higher as compared to the corresponding LMLC FI results.

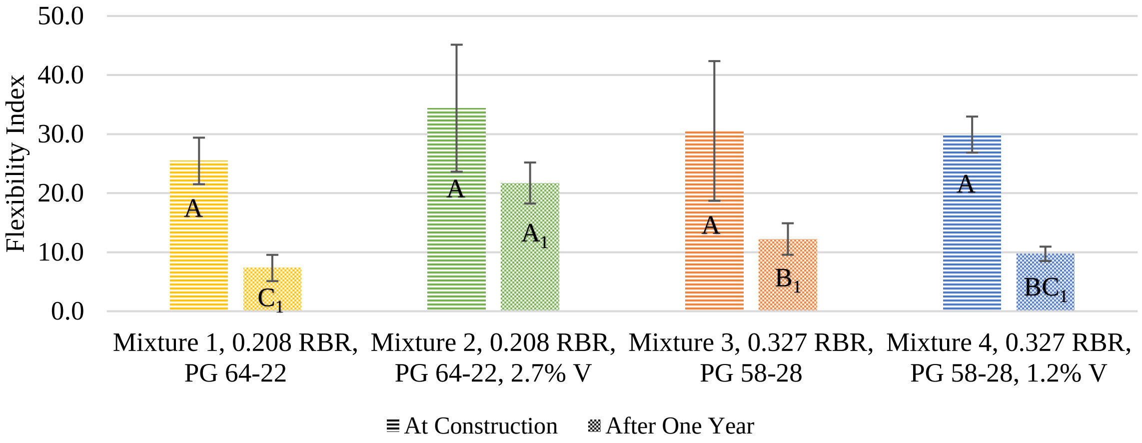


Figure 14. Delaware Field Cores FI over Time (corrected for thickness and %AV).

The low-temperature cracking performance of the field cores was evaluated using the DCT test at −12℃. From a statistical standpoint, the low-temperature performance shows no difference between mixtures or over time (Figure 15). This reinforces the observation that DCT seems to be less sensitive to aging, as seen with the laboratory aged specimens. However, similar trends to the I-FIT results can be seen, with Mixture 2 performing the best, Mixture 1 performing the poorest, and Mixtures 3 and 4 performing between the other two mixtures. These results also agree with the binder results that showed Mixture 1 having the highest PGL value after 20-hr PAV aging. This finding again helps confirm that adding a recycling agent to Mixture 2 was beneficial, while adding a recycling agent to Mixture 4 was not needed.

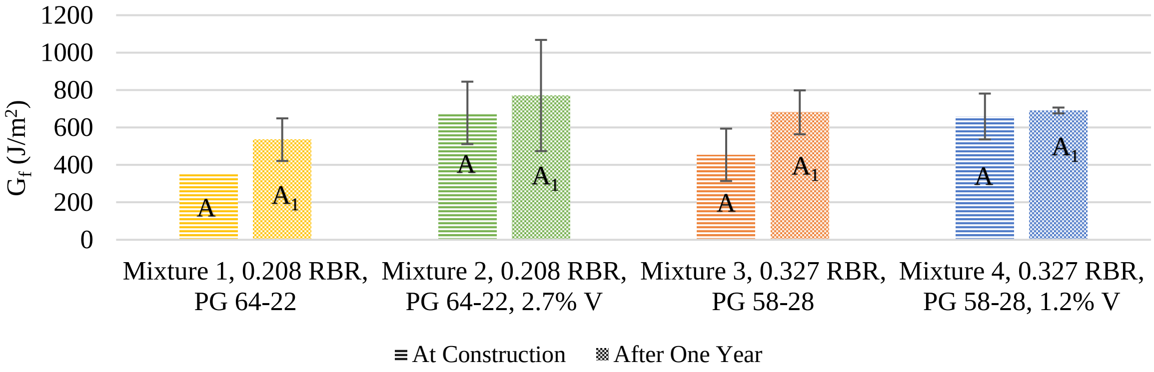


Figure 15. Delaware Low-Temperature Fracture Energy over Time.

COST COMPARISON

An approximate relative cost of each mixture compared to the control Mixture 1 is shown in Figure 16. These approximate values were calculated using economics data found in NCHRP Report 927, Appendix H [5]. The approximate cost per ton of an asphalt mixture was calculated using published cost estimates for the binder, aggregate, RAP, and recycling agent. Transportation and production costs were assumed to be the same for all mixtures in this analysis. It was assumed that both unmodified binders used in this study cost the same because the binder cost data were not available.

Mixture 2 was estimated to cost about 3 percent more than the control mixture due to having the same amount of RAP as the control Mixture 1 but incorporating the recycling agent, making it less attractive unless improvements can be expected in the durability of the mixture. Mixtures 3, 4, and 4(L) had estimated cost savings between about 10 percent and 13 percent. This is a significant savings if the pavement durability is not diminished by the increased amount of RAP. This factor can be assessed by measuring cracking resistance of specimens with laboratory aging.

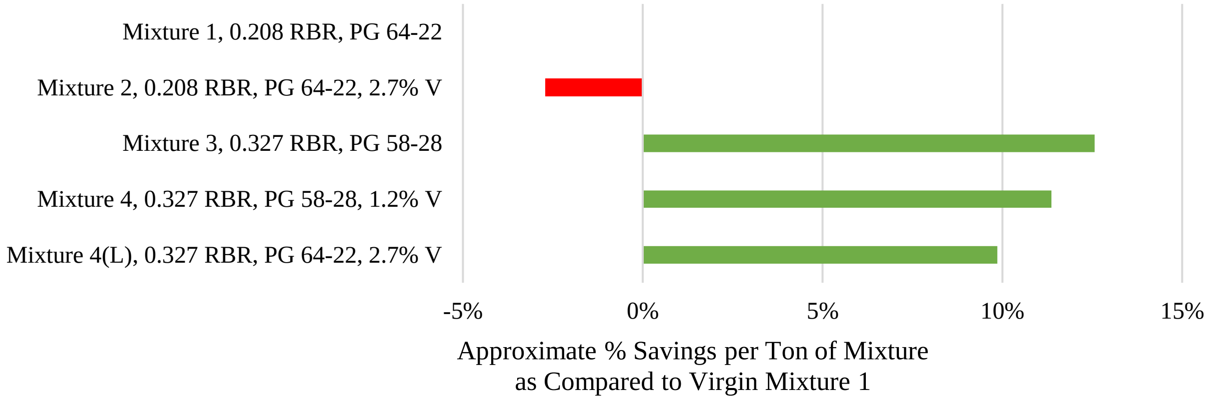


Figure 16. Delaware Mixture Relative Cost Comparison.

DELAWARE CASE STUDY CONCLUSIONS AND RECOMMENDATIONS

This study examined the binder and mixture performance of mixtures with 25 percent and 40 percent RAP and evaluated mitigation strategies to accommodate the increased RAP content, including adding a softer binder, incorporating a recycling agent, and using both a softer binder and a recycling agent. Trends were observed across tests on LMLC specimens, RPMLC specimens, and field cores. These trends were compared to binder test results for further confirmation. The following key findings were drawn from the test results:

- Binder test results agreed with mixture performance results. The stiffness measured by the G-R parameter after 40 hr in the PAV correlated well with the CT_{Index} and the FI measured after laboratory and field aging. The PGL value correlated well with the DCT results measured after 4 hr of aging at 135℃ for the LMLC and RPMLC specimens. This finding indicates that binder testing may be able to help eliminate problematic blends with minimal testing. PG grading and G-R testing is a good way to determine binder stiffness over time. Comparing several blends allows for the optimal blend to be selected. However, binder testing did not appear to identify potential rutting concerns that were found during mixture testing.

- When including 25 percent RAP, the mixture with a recycling agent performed adequately in initial performance tests and significantly higher in cracking performance tests after 1 year of field aging versus the mixture without a recycling agent. In this case, adding a recycling agent is expected to improve long-term cracking performance without causing rutting or moisture susceptibility issues.
- Mixtures with 40 percent RAP performed adequately in all cracking performance tests; however, when using a recycling agent and a softer PG 58-28 binder, the mixture exhibited moisture susceptibility and rutting resistance issues. This finding indicates that using both a recycling agent and a softer binder may result in premature rutting and moisture damage to the AC pavement.
- Rutting resistance and stripping resistance were improved after laboratory aging, indicating that after some time, the AC pavement could be significantly less susceptible to rutting and stripping.
- Intermediate-temperature cracking performance was statistically similar for mixtures with 40 percent RAP with and without a recycling agent. This trend continued for RPMLC specimens aged for 6 hr at 135°C and 72 hr at 95°C. Field cores showed similar results, with the mixture with a recycling agent performing worse after 1 year than the mixture without a recycling agent. This result strengthens the observation that using both a recycling agent and a softer binder could lead to rutting issues and may even decrease cracking performance.
- In the adjusted laboratory mixture with 40 percent RAP, a PG 64-22 binder, and a recycling agent at a higher dose, rutting resistance was adequate, and the IDEAL-CT intermediate-temperature cracking performance was significantly improved over other mixtures with 40 percent RAP. The stripping parameters were also improved over the 40 percent RAP mixture using a softer binder and a recycling agent; however, they were still below recommended thresholds. This finding further supports the conclusion that either a recycling agent or a softer binder should be used as a softening strategy, but not both.
- In both RPMLC specimens and field cores, DCT test results showed no statistical difference with aging. This result indicates that with the materials in this project, the DCT test parameter was not sensitive to aging. Further testing is needed to explore this observation.
- Based on these findings, researchers recommended that either a softer-grade binder or a recycling agent be used to improve the performance of high RAP mixtures. Furthermore, if the recycled binder and softer base binder blend is sufficiently soft to meet specifications, an additional recycling agent is likely unnecessary and may even prove detrimental to long-term pavement performance.

CHAPTER 3—GUIDELINES FOR HIGH RECYCLED ASPHALT MATERIAL MITIGATION STRATEGIES: CALIFORNIA FIELD PROJECT

This chapter presents information on a case study of a mill-and-overlay project constructed in late 2021 in El Dorado County, California. This project was selected because it is in a relatively warm climate and included RAP, RAS, and a recycling agent. The project overlayed two lanes of traffic approximately 0.8 mi long with 12-ft lane widths. The project was divided into four field mixtures and used four different asphalt mixtures. Each mixture was approximately 1,000 ft long and 24 ft (two lanes) wide. A case study was done on binder blends, field cores, and LMLC specimens for all four field mixtures. Additional laboratory-developed mixtures were tested to aid in the data analysis.

MATERIALS

The California field project included four mixtures labeled A–D. Additional sets of laboratory tests were performed on adjusted versions of Mixtures C and D and on three high RBR laboratory mixtures. Mixture C showed significantly lower cracking resistance than the control (Mixture A). Additional tests were done raising the recycling agent dose or increasing the total binder content to evaluate what mitigation was needed to improve the performance. Alternatively, Mixture D showed significantly higher cracking resistance than the control (Mixture A). Additional tests were performed to determine if Mixture D could be made more economical while maintaining adequate performance by removing the recycling agent. All mixtures used in this study are described in Table 9.

Mix designs for Mixtures A–D were approved by the California Department of Transportation (Caltrans). All four mix designs had an NMAS of ½ inch. The RAP had an ignition oven measured asphalt binder content of 4.37 percent and a specific gravity of 2.554. RAP was crushed on-site to ⅜-inch nominal aggregate size. The RAS had an asphalt binder content of 14.58 percent and a sand equivalent of 92. General mixture components and proportions are also shown in Table 9, and the design aggregate gradations are shown in Figure 17. For Mixture D, the RAP/RAS material was received pre-blended at a 10:3 RAP-to-RAS ratio. The contractor also noted that the virgin binder content in Mixture D was raised 0.35 percent from that shown in the mix design due to the mixture not achieving optimum field compaction. The adjusted binder content was used in all laboratory tests.

Mixtures C and D were constructed using the same tall oil recycling agent. The doses were selected by the contractor in collaboration with the recycling agent supplier. The contractor selected the softer binder and recycling agent doses to match the control PGH. In the development of the additional laboratory mixtures, a recycling agent dose was targeted to restore the continuous PGH as close as possible while maintaining the PGL.

Table 9. California Mixture Details.

Mixture	Mixture Description	Virgin Binder	RAP/RAS Content (%)	Total/Virgin Asphalt Binder Content (%)	Recycling Agent Dose (% by weight of total binder)
A	Control	PG 64-16	0/0	5.3/5.3	0
B	Conventional	PG 64-16	12/0	5.3/4.8	0
C	RAS	PG 58-22	0/3	5.3/4.8	0.75
C(L1)	RAS	PG 58-22	0/3	5.7/5.3	0
C(L2)	RAS	PG 58-22	0/3	5.3/4.8	1.5
D	RAP/RAS	PG 58-22	10/3	5.65/4.8	1.5
D(L)	RAP/RAS	PG 58-22	10/3	5.65/4.8	0
Lab 1	High RAP/RAS	PG 58-22	50/3	5.65/3.0	0
Lab 2	High RAP/RAS	PG 58-22	50/3	5.65/3.0	1.5
Lab 3	High RAP	PG 58-22	50/0	5.68/3.5	0

Mixture aggregate gradation curves are shown in Figure 17. Laboratory mixtures labeled C(L1/L2) or D(L) matched their corresponding Mixture C or D aggregate gradations and varied in binder content, binder type, or recycling agent dose. Laboratory Mixtures 1–3 were developed to closely match the aggregate gradation of test Mixture D.

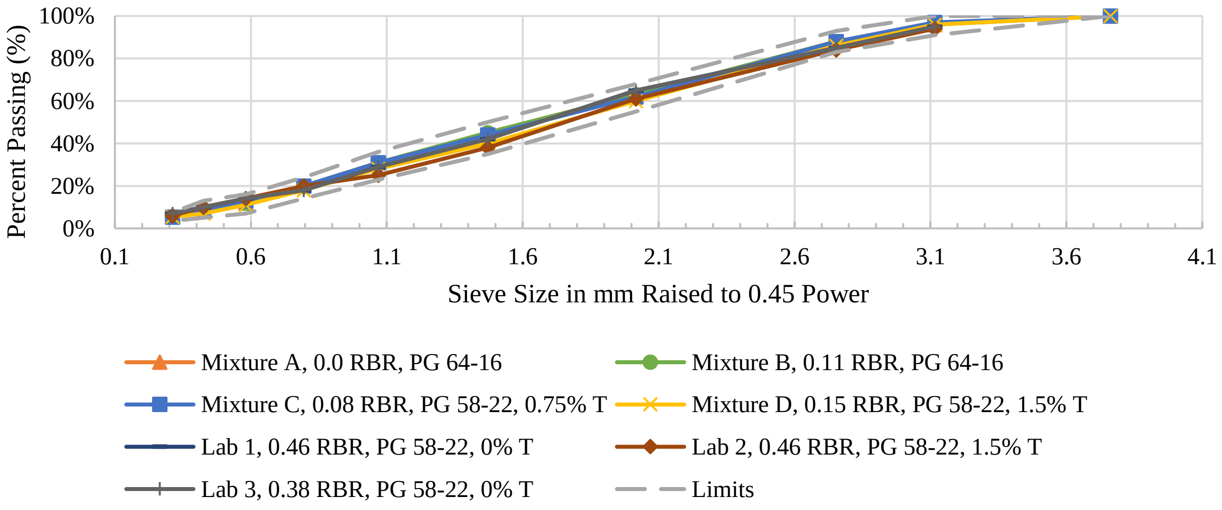


Figure 17. California Mix Design Aggregate Gradations.

TESTING PLAN

Testing Tools

All the evaluation tools used in this study are specified in the NCHRP Report 927 draft AASHTO standard practice [5]. Binder and mixture testing was performed for all mixtures placed in the four field mixtures and the six additional mixtures developed in the laboratory. Mixture testing was conducted on LMLC specimens and field cores for the four field mixtures. Binder and mixture tests were selected to help understand the overall performance and determine the best-performing mixture. Tests and thresholds used in this study are shown in Table 10 along with the references used to select each threshold.

Table 10. California Test Details.

	Test Type	Test	Parameter	Replicates	Aging Protocol*	Threshold Used, [Reference]
Binders and Binder Blends	Rutting Resistance	DSR	PGH	2	RTFO	Target Climate
	Cracking Resistance	DSR	G-R	2	RTFO, PAV	≤ 180 kPa after 20-hr PAV, ≤ 600 kPa after 40-hr PAV [5]
	Brittleness	BBR	ΔT_c	2	RTFO, PAV	≥ −5.0 after RTFO + 20-hr PAV
Mixture	Rutting Resistance	HWTT	$N_{12.5}$	2	STOA	≥ 10,000 [5]
	Moisture Susceptibility	HWTT	SN	2	STOA	≥ 2,000 [18]
		HWTT	SIP	2	STOA	≥ 9,000 [5]
	Cracking Resistance	SCB	FI	4	STOA	≥ 7 [5]
		IDEAL-CT	CT_{Index}	4	STOA	≥ 80 [19]
		DCT	G_f	2	ITOA	≥ 400 J/m^2 [21]

*RTFO = rolling thin-film oven, PAV = pressure aging vessel, STOA = short-term oven aging for 2 hr at 135°C, ITOA = intermediate-term oven aging for 4 hr at 135°C.

Binder and Binder Blend Testing

The PGH was determined using the DSR according to AASHTO T 315 and AASHTO M 320. This process helped demonstrate the rutting resistance of the binder blends. The DSR was also used to determine the G-R parameter at 15°C and 0.005 rad/sec and to show aging in Black space to highlight cracking susceptibility of the binder blend as it aged. The BBR was used to determine the PGL and ΔT_c of each binder and binder blend according to AASHTO T 313 and AASHTO PP 78. This information helped to reveal the low-temperature cracking resistance and brittleness of the binder blends and the recycling capacity of each virgin binder.

Binders and binder blends were tested at four aging conditions: unaged (original), short-term aging in the RTFO to simulate aging during production and construction, and long-term aging in the PAV at 20 hr and at 40 hr to simulate field aging.

The RAS binder in this project was too stiff to test directly. These materials included preblended RAP/RAS, by testing this blend, an approximate PGH of the RAS was calculated. The estimated PGH was determined by using the tested properties of the RAP and the blended RAP/RAS binders and calculated using Equation 3.1 (in most cases it would be more practical to blend the RAS binder with a virgin binder), an adapted version of Equation 3.1 has been added to the draft AASHTO standard practice):

$$PG_{RAS} = \frac{\left(PB_{Blend} - \left(PG_{RAP} \times \%RAP\right)\right)}{\%RAS} \tag{3.1}$$

where:

PG_{Blend} = continuous PGH of the recycled binder blend (°C);
PG_{RAP} = continuous PGH of the RAP (°C);
$\%_{RAP}$ = percent of the binder blend that is RAP expressed as a decimal;
$\%_{RAS}$ = percent of the binder blend that is RAS expressed as a decimal.

Mixture Testing

LMLC specimens for the four field mixtures were prepared using mix design data provided by the University of California-Davis and approved by Caltrans. Additional testing was done on adjusted versions of Mixtures C and D [C(L1), C(L2), and D(L)] and three high RBR mixtures (Lab 1, Lab 2, and Lab 3). For the additional mixture tests, the recycling agent dose was selected using Equations 3.2 and 3.3 [4] but was limited such that the PGL was not lower than −27.9°C to match the performance of the control (Mixture A). PGL can be substituted for PGH in these equations to estimate low-temperature performance. This method was used to adjust the proposed draft AASHTO standard practice recycling agent dosage recommendations. The lower limit of −28°C was selected to keep the binder blends in the same six degree range, −22°C to −28°C, as the control. The specimens were mixed at 160°C and compacted at 145°C for mixtures using a PG 64-16 virgin binder and mixed at 150°C and compacted at 140°C for mixtures using a PG 58-22 virgin binder. Loose mix for DCT specimens was conditioned at 135°C for 4 hr prior to being heated to compaction temperature. For all other tests, the loose mix was conditioned at 135°C for 2 hr prior to being heated to compaction temperature, as specified in NCHRP Report 927. Air voids were targeted at 7 percent ± 0.5 percent for all specimens.

$$PGH_{Blend} = \left(RAP_{BR} \times PGH_{RAP}\right) + \left(RAS_{BR} \times PGH_{RAS}\right) + \left(B_{BR} \times PGH_{Base}\right) \tag{3.2}$$

$$Recycling\ Agent\ (\%) = \frac{PGH_{Blend} - PGH_{Target}}{Slope\ Rate} \tag{3.3}$$

where:

PGH_{Blend} = Continuous PGH of the recycled binder blend (°C).
RAP_{BR} = RAP binder ratio.
PGH_{RAP} = Continuous PGH of the RAP binder (°C).
RAS_{BR} = RAS binder ratio.
PGH_{RAS} = Continuous PGH of the RAS binder (°C).
B_{BR} = Base binder ratio = 1 – RBR.
PGH_{Base} = Continuous PGH of the base binder (°C).
PGH_{Target} = Continuous PGH of Target Climate (°C).

Slope Rate = change in PG per % recycling agent determined from blending charts with multiple recycling agent doses or requested from materials supplier. When unknown, use 1.38 for petroleum-based aromatic extracts and 1.82 for all other recycling agent types.

Field cores were trimmed as thick as possible and ranged in thickness from about 38 mm to 56 mm. Cores were tested initially and after laboratory aging. Aging was done at 85℃ for 5 days after being trimmed to testing size per AASHTO R 30. Notching for DCT and SCB specimens was done after the cores were aged to preserve notch dimensions.

TEST RESULTS AND DISCUSSION

Binder and Binder Blend Testing

Test results for binders and binder blends evaluated in this study are shown in Table 11. The PG 64-16 binder behaved like a PG 64-22 binder, and the PG 58-22 binder behaved like a PG 64-28 binder. Both binders had a $\Delta T_c \geq -1.0$, which indicates that the binders are both expected to have good resistance to low-temperature cracking and have a high capacity for recycling. The recovered RAP binder was a relatively stiff PG 94-10 binder and is expected to be brittle, with a ΔT_c of −6.5. The recovered RAS material was too stiff to test, but using the continuous PGH, it was estimated using a weighted average of the data from the recovered RAP and the recovered blended RAP/RAS. It was estimated to be a very stiff PG 232-XX binder. The blended RAP/RAS binder was measured to be a PG 124-XX binder. It was too stiff to allow for measurement of the PGL.

All the binder blends were PG 70-22 binders except for the virgin binder used in Mixture A. The RAS in Blend C would not melt to blend with the virgin binder. So that it could be added uniformly throughout the blend, the RAS was ground into a fine powder using a mortar and pestle and slowly added to a blend of virgin binder and recycling agent. The RAS was the consistency of a fine sand, as shown in Figure 18. The mixture was then heated to 190ºC and blended to try to activate the RAS binder. The RAS used in this California field project is very stiff in nature and probably has a very low amount of binder activation. Like what was observed with the Delaware blends, the ABCD results correlated very well with the PGL measured by the BBR.

Figure 18. California Ground RAS Binder.

Table 11. California Binder Properties.

Description	Continuous PG	ΔTc	PGL by ABCD	G-R after RTFO (kPa)	G-R 20-hr PAV (kPa)	G-R 40-hr PAV (kPa)
PG 64-16 Virgin Binder	68.7–25.3	−1.0	-25.9	7	71	2,729
PG 58-22 Virgin Binder	65.0–27.9	−0.1	-26.9	3	55	1,253
Recovered RAP Binder	97.7–13.7	−6.5	-7.1	15,497	21,579	35,355
Recovered RAS Binder*	232.9–XX	—	—	—	—	—
Recovered RAP/RAS Binder	128.9–XX	—	—	—	—	—
Blend A, 0.0 RBR, PG 64-16	68.7–25.3	−1.0	-25.9	7	71	2,688
Blend B, 0.11 RBR, PG 64-16	71.9–24.0	0.5	-23.7	23	129	6,144
Blend C, 0.08 RBR, PG 58-22, 0.75% T	70.8–26.2	−2.2	-26.7	54	107	3,357
Blend D, 0.15 RBR, PG 58-22, 1.5% T	73.4–23.5	−3.0	-24.4	35	268	5,203

* Estimated using a weighted average of the RAP and RAP/RAS results.

Aging results in Black space are shown in Figure 19. The chart shows binder blends as stiffer and more brittle as the point moves up and to the left. Each binder blend is shown after RTFO, 20-hr PAV, and 40-hr PAV aging. Blend C showed some unusual behavior, which could be due to the RAS activating during PAV aging. Blends B and C showed the most brittle behavior after 40-hr PAV aging, which may indicate susceptibility to age-related cracking.

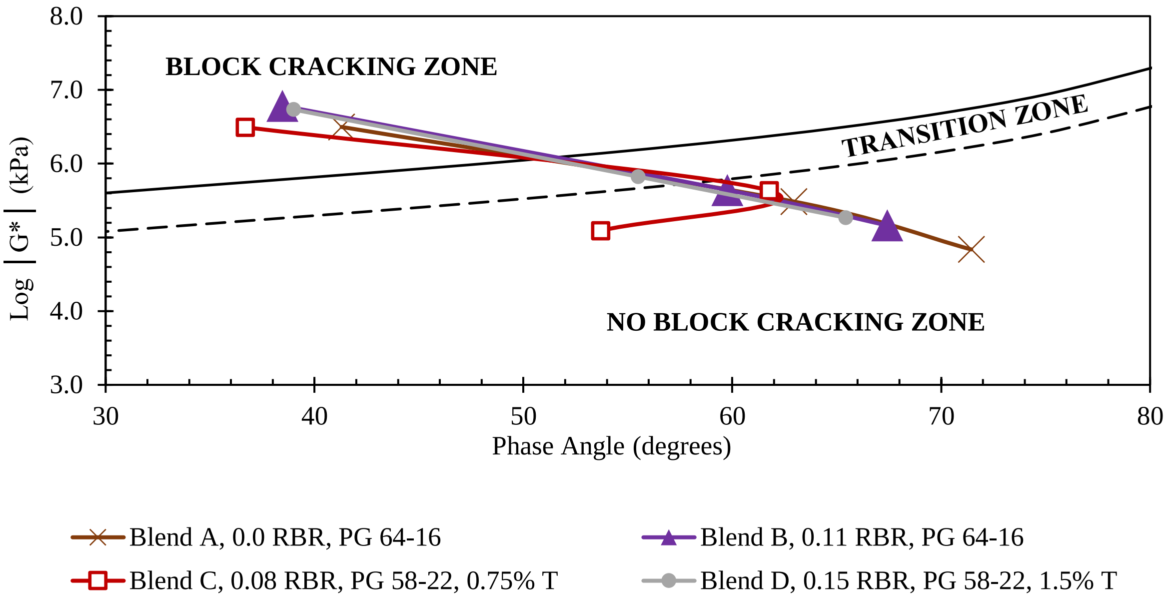


Figure 19. California Binder Aging in Black Space.

Mixture Testing

Mixtures were tested according to the mixture testing plan. When a mixture performed significantly different than Mixture A, additional testing was performed to determine how the mixture could be adjusted.

To help understand potential mix design improvements, several adjusted laboratory mixtures were developed. Mixture C performed below the proposed LMLC threshold. To address this, Mixture C(L1) was developed with a higher virgin binder content that was calculated by assuming 0 percent of the RAS binder activated. Mixture C(L2) was developed with a higher recycling agent dose than was calculated using Equations 3.1 and 3.2. Mixture D performed better than the control Mixture A, indicating that the recycling agent may not be needed to meet performance thresholds. Researchers tested this theory in Mixture D(L1) by removing the recycling agent.

Laboratory-Mixed Laboratory-Compacted Specimens

Rutting results are shown in Figure 20. All mixtures exhibited good rutting resistance, and no mixtures exhibited stripping. All four field mixtures as well as the six additional laboratory mixtures are expected to have adequate rutting resistance. Mixture D(L) was not tested due to material constraints, but it is assumed that it would have adequate rutting resistance since removing the recycling agent from Mixture D should increase its rutting resistance.

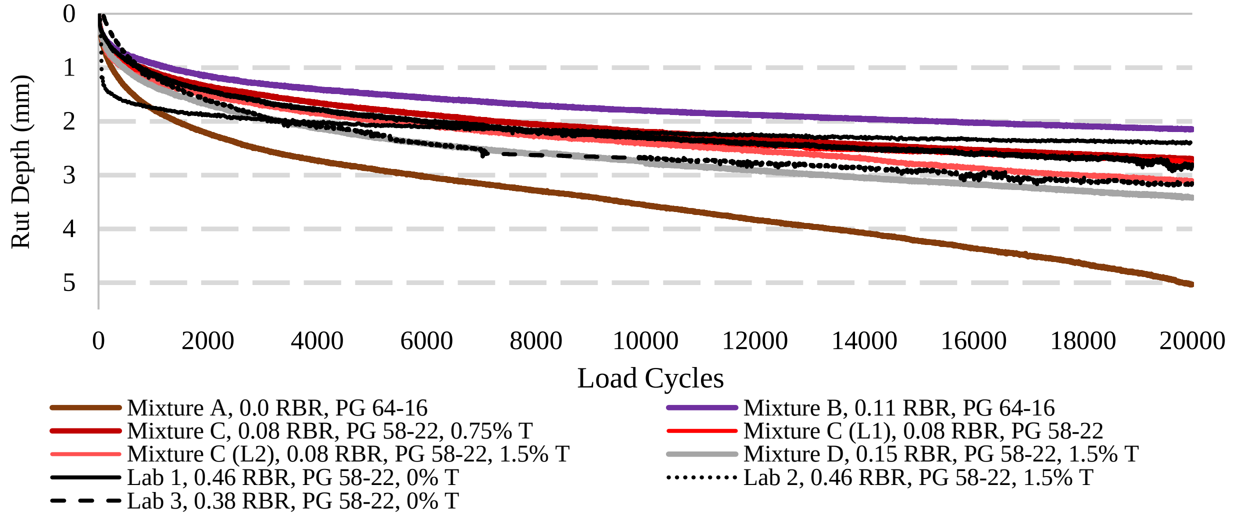


Figure 20. California HWTT Rut Depth.

The IDEAL-CT test results are shown in Figure 21. Mixture A is expected to have the highest and Mixture C is expected to have the lowest intermediate-temperature cracking resistance, as indicated by the Tukey's HSD letters. Mixture C falls below the proposed threshold of 80, which indicates it may not have adequate intermediate-temperature cracking resistance.

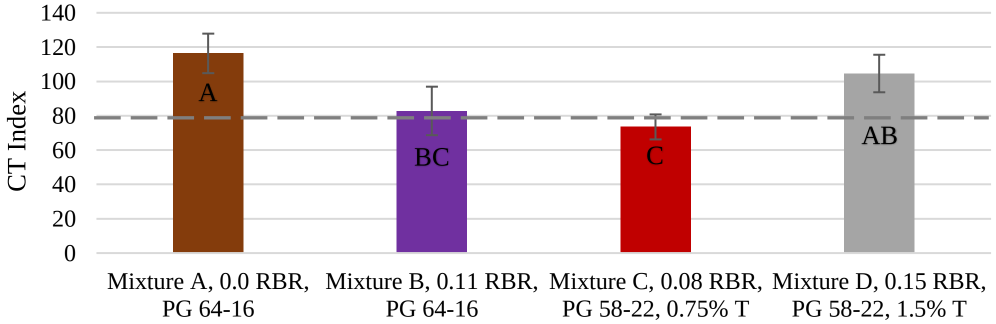


Figure 21. California LMLC CT$_{\text{Index}}$ Results.

The IDEAL-CT results for the adjusted mixture tests are shown in Figure 22 along with their field mixture counterpart (Mixture D). Mixtures C(L1) and C(L2) were not tested due to material constraints. Mixture D(L) had the highest CT$_{\text{Index}}$ value, with Mixture Lab 3 also meeting the threshold of 80. This finding indicates that both these mixtures are expected to have adequate intermediate-temperature cracking resistance. Mixtures Lab 1 and Lab 2 tested significantly below the threshold and are not expected to have adequate intermediate-temperature cracking resistance. This result is likely due to the 50 percent RAP and 3 percent RAS making both Mixture Lab 1 and Lab 2 too stiff. The recycling agent in Mixture Lab 2 was not able to mitigate the RAS binder. However, when comprised of 50 percent RAP with 0 percent RAS, the mixture met cracking requirements without a recycling agent. This finding indicates that the softer binder was able to handle 50 percent RAP while maintaining adequate intermediate-temperature cracking resistance.

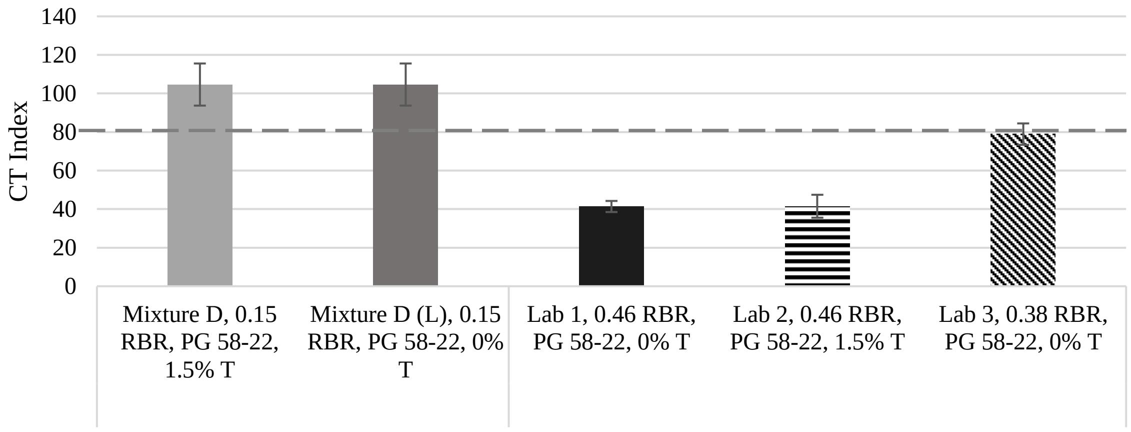


Figure 22. California Adjusted LMLC Specimens CT_{Index} Results.

The FI results for the four field mixtures are shown in Figure 23. Mixtures A and D performed the best, likely due to Mixture A including only a virgin binder and Mixture D including a recycling agent and having the highest total binder content. Mixture C performed below the threshold, likely due to the stiff RAS binder and low recycling agent dose.

Mixture A has only a virgin binder and was used as the control mixture for performance comparisons. Mixture B has no recycling agent to mitigate the stiff RAP binder and exhibited lower cracking resistance than Mixture A. It is likely that adding a recycling agent would have improved the cracking performance of Mixture B. Mixture C has a high RAS content and a low recycling agent dose, resulting in lower cracking performance. Mixture D performed similar to Mixture A.

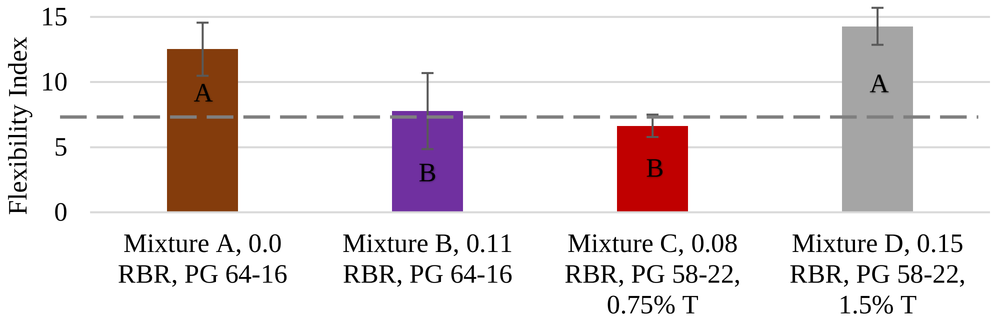


Figure 23. California LMLC FI Results.

The FI results for the adjusted mixture tests are shown in Figure 24. Both Mixture C(L1) and C(L2) performed above the proposed threshold. This result indicates that adding either more virgin binder or a higher recycling agent dose will increase the mixture cracking performance. Mixture D(L1) was still able to perform above the proposed threshold without a recycling agent. Mixture D was designed with a higher binder content that appears to assume 0 percent RAS activation. Although including the recycling agent showed no performance concerns, removing it could be used as a cost-saving measure, as seen in Mixture D(L1). Mixtures Lab 1 and Lab 2 did not pass the cracking threshold either with or without a recycling agent. This result is due to the stiff RAS binder; this binder is stiffer than recommended by the draft AASHTO standard practice. Mixture Lab 3 removed the RAS and was able to meet the performance thresholds.

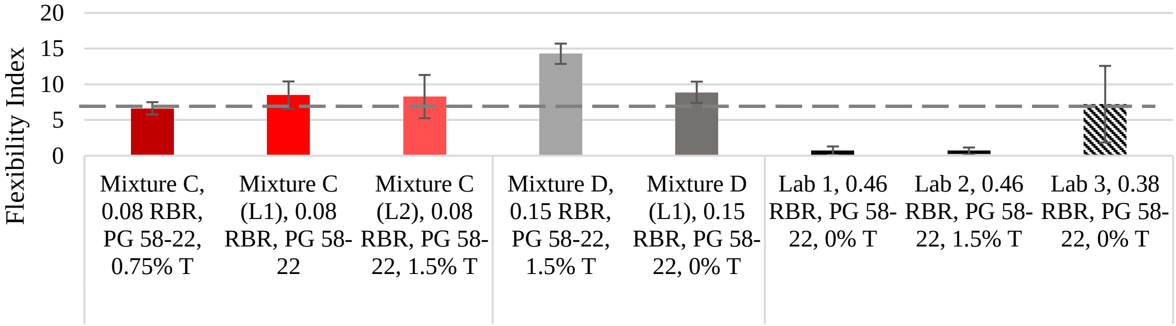


Figure 24. California Adjusted LMLC FI Results.

DCT is a low-temperature cracking resistance test. All four field mixtures exceeded the low-temperature cracking performance threshold of 400 J/m^2, as shown in Figure 25. This finding indicates that all four mixtures are expected to perform adequately in terms of low-temperature thermal cracking based on this testing parameter.

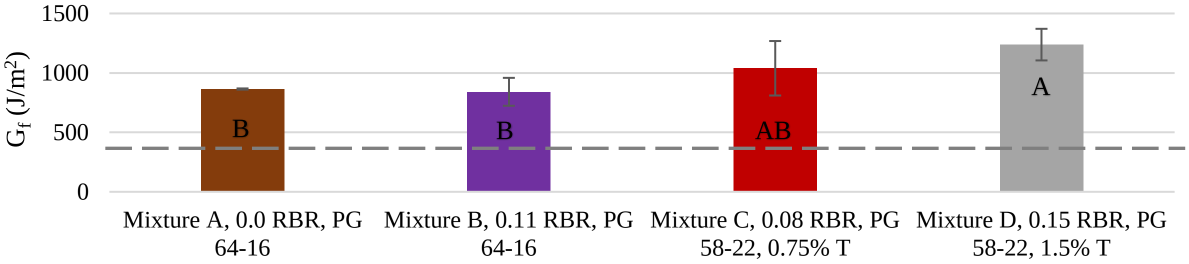


Figure 25. California Low-Temperature LMLC Cracking Performance by G_f.

The DCT fracture energy results for the adjusted laboratory mixtures are shown in Figure 26. All mixtures exceeded the low-temperature cracking performance threshold, indicating that all mixtures are expected to have adequate low-temperature performance based on this testing parameter. Mixture C(L2) performed the best, likely due to the softer binder and recycling agent. Mixture C(L1) performed adequately, indicating that the softer binder is enough to mitigate the RAS binder. Mixture D(L1) performed adequately, which again indicates that a recycling agent was not needed in Mixture D for adequate performance. Mixture Lab 3 was not tested due to material constraints, but it is assumed that it would perform adequately since it has a higher virgin binder content than Mixture Lab 1 and contains no RAS. Both these adjustments are expected to increase the low-temperature performance.

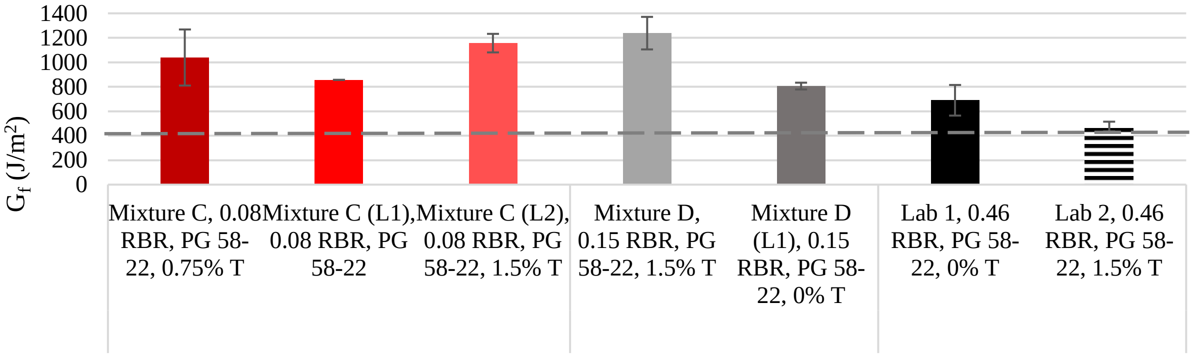


Figure 26. California Low-Temperature Adjusted LMLC Cracking Performance by G_f.

Field Cores

The initial cores showed no statistical difference in cracking performance between mixtures based on FI values, as shown in Figure 27. This finding indicates that the initial intermediate-temperature cracking resistance is expected to be the same between the four field mixtures. After aging of the construction cores for 5 days at 85°C, Mixture D showed the highest FI value, and Mixtures B and C showed the lowest FI values. This result indicates that with aging, Mixture D is expected to have the highest intermediate-temperature cracking resistance and Mixtures B and C the lowest. This expected performance increase is likely due to the higher virgin binder content in Mixture A and the higher total binder content and recycling agent content in Mixture D. The statistical significance is differentiated by adding Tukey's HSD letters and a subscript 1 to letters corresponding to cores tested after aging.

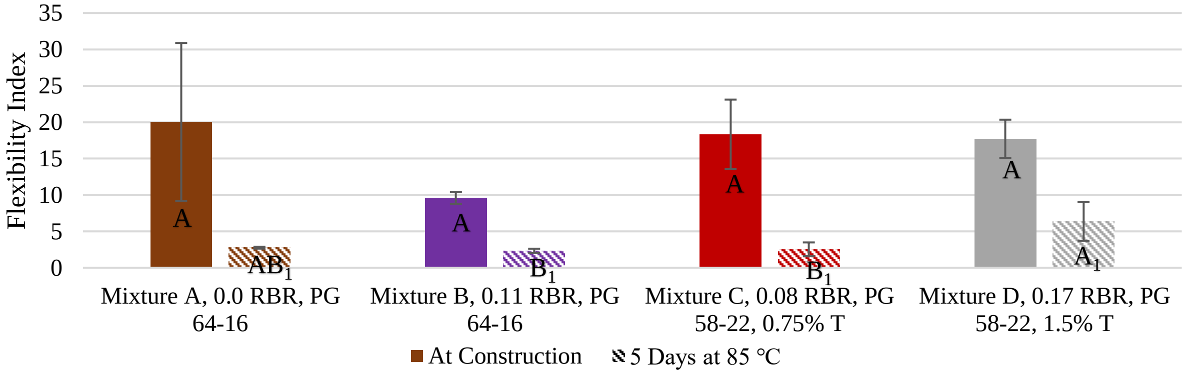


Figure 27. California Field Cores FI (corrected for thickness and %AV).

No statistical difference was seen between mixtures according to the DCT test for the initial cores and the cores after aging, as shown in Figure 28. This result indicates that DCT for these mixtures was not sensitive to aging condition. However, Mixture D does appear to have the best performance. Mixture A was not tested because there were insufficient cores.

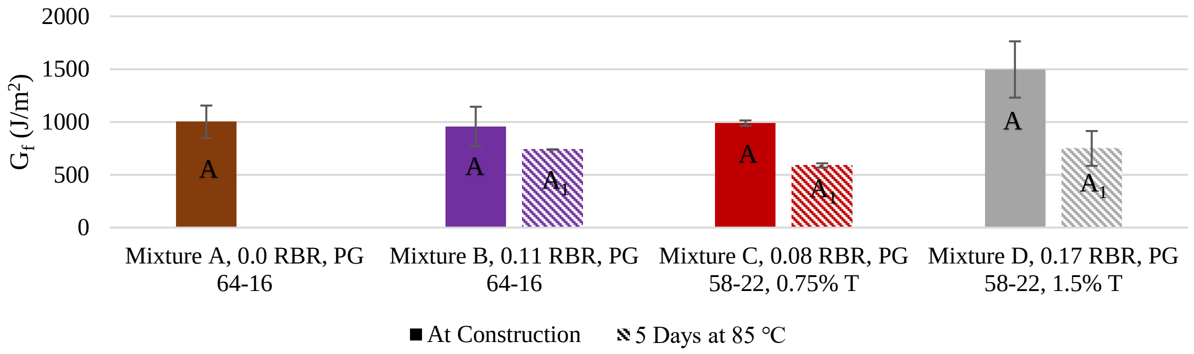


Figure 28. California Low-Temperature Field Cores Cracking Performance by G_f.

COST COMPARISON

An approximate cost-savings analysis is shown in Figure 29. These approximate values were calculated using economics data found in NCHRP Report 927, Appendix H [5]. The approximate cost per ton of an asphalt mixture was calculated using representative cost estimates for the binder, aggregate, RAM, and recycling agent. Transportation and production costs were assumed to be the same for all mixtures in this analysis. It was assumed that both unmodified binders used in this study cost the same since the binder cost data were not available. However, softer binders are generally less expensive, which should increase the economic benefit of all mixtures using a PG 58-22 binder.

The three high RBR laboratory mixtures (Lab 1–3) were the most economical; however, mixtures Lab 1 and Lab 2 performed significantly below FI and CT_{index} performance thresholds. Mixtures B, C, C(L2), D, and D(L) had similar intermediate cost savings; Mixture C(L1) had minimal savings compared to Virgin Mixture A. These cost estimates were used in conjunction with mixture performance data to identify the optimal mixture.

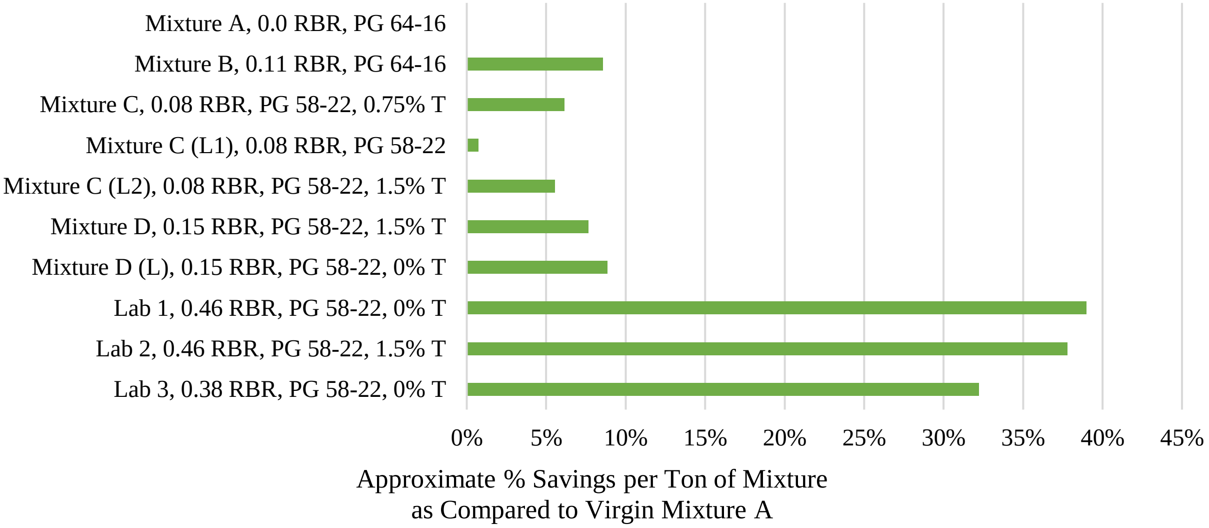


Figure 29. California Mixture Relative Cost Comparison.

CALIFORNIA CASE STUDY CONCLUSIONS AND RECOMMENDATIONS

This study involved one field project, four field mixtures, and six additional laboratory mixtures. The study included the testing of binder blends, LMLC specimens, and field cores. Any conclusions drawn from this study are based on the location and the materials used, and further research may be necessary to verify findings. The researchers drew the following conclusions from this study:

- When using a climate-grade binder and adding a RAP component, a recycling agent should be used to maintain equivalent performance to a virgin mixture. When using a softer-grade binder, a recycling agent is not needed for mixtures containing RAP.
- The addition of RAS significantly increased cracking susceptibility; however, several methods were able to mitigate this issue, as listed below. It is also important to note that a softer-grade virgin binder was used in all RAS mixtures.
    - Adequate cracking performance was restored by increasing the virgin binder content based on the assumption that 0 percent of the RAS binder activates. This method was useful with mixtures containing RAS only and mixtures containing RAP and RAS; however, this method may be less economical.
    - Adequate performance was also restored by using a larger recycling agent dose, and the dose was calculated to restore the continuous PGH without decreasing the continuous PGL below −28. The PGL was the controlling factor in this case.
- Mixtures with 10 percent RAP and 3 percent RAS with or without a recycling agent performed adequately in all tests by increasing the virgin binder content based on the assumption that 0 percent of the RAS binder activates. Without the additional binder, the mixture did not achieve adequate field compaction. As a cost-saving measure, a recycling agent should not be used when cracking performance is adequate without one. However, adding the recycling agent did not impact rutting resistance and is not expected to decrease the pavement life.
- Mixtures with 50 percent RAP and 3 percent RAS did not perform adequately in cracking performance with or without a recycling agent. Further research is necessary to determine if assuming a reduced binder availability factor (BAF) or adding a recycling agent could restore the cracking performance while maintaining cost savings.
- In mixtures with RAS and an RBR < 0.3, adequate mixture performance could be achieved by reducing the BAF or adding a recycling agent. However, when adding a RAS binder in mixtures with an RBR > 0.3, the cracking performance was significantly reduced even with an added recycling agent. Performance testing should be done before including RAS in a high RAM mixture.
- Based on these results, it is recommended that the RAS be used to help with rutting resistance when using a softer binder but that the RAS binder not be considered as contributing significantly to the total effective binder content. It is also recommended that RAS not be used in high RBR mixtures.
- A 50 percent RAP mixture performed adequately without an added recycling agent. The softer-grade binder was adequate to mitigate the RAP binder. This mixture will have higher cost savings if implemented in the field. Further research is necessary to determine how this mixture will perform with aging.

CHAPTER 4—FINAL ANALYSIS AND CONCLUSIONS

Over the course of this study, laboratory testing was completed for 16 different asphalt mixtures based on two field projects. Binder testing was also performed on all virgin binders and the binder blends corresponding to the eight field mixtures. Table 12 gives an overview of the mixture variables, testing conditions, test specimen types, and tests conducted for each mixture. For additional mixture details, refer to Table 6 and Table 9. The selected tests and test thresholds or performance criteria were selected based on material availability and the draft AASHTO standard practice, respectively. All laboratory mixtures (labeled (L#) or Lab #) were developed to test the effect of changing one variable on the mixture performance. The following variables were adjusted in various mixtures: the total binder content, the virgin/base binder grade, the use/amount of recycling agent, and the amount of RAM. These adjustments were selected to test the different guidelines in the draft AASHTO standard practice, including recycling agent dose selection method, BAF, and maximum RBR limits.

Table 12. Overview of Project Mixture Analyses.

Mixture	RAP	RAS	Recycling Agent	Softer Binder	High RBR (over 0.3)	Specimen Types	Mixture Testing
A						LMLC, Field Core	HWTT, IDEAL-CT, SCB, DCT
B	x					LMLC, Field Core	HWTT, IDEAL-CT, SCB, DCT
C		x	x	x		LMLC, Field Core	HWTT, IDEAL-CT, SCB, DCT
C(L1)		x		x		LMLC	HWTT, SCB, DCT
C(L2)		x	x	x		LMLC	HWTT, SCB, DCT
D	x	x	x	x		LMLC, Field Core	HWTT, IDEAL-CT, SCB, DCT
D(L)	x	x		x		LMLC	HWTT, IDEAL-CT, SCB, DCT
Lab 1	x	x		x	x	LMLC	HWTT, IDEAL-CT, SCB, DCT
Lab 2	x	x	x	x	x	LMLC	HWTT, IDEAL-CT, SCB, DCT
Lab 3	x			x	x	LMLC	HWTT, IDEAL-CT, SCB
1	x					LMLC, Field Core	HWTT, IDEAL-CT, SCB, DCT, UTSST
2	x		x			LMLC, Field Core	HWTT, IDEAL-CT, SCB, DCT, UTSST
2(L)	x		x			LMLC	HWTT, IDEAL-CT, SCB, DCT
3	x			x	x	LMLC, RPMLC, Field Core	HWTT, IDEAL-CT, SCB, DCT, UTSST
4	x		x	x	x	LMLC, RPMLC, Field Core	HWTT, IDEAL-CT, SCB, DCT, UTSST
4(L)	x		x		x	LMLC	HWTT, IDEAL-CT, SCB, DCT

COMBINED ANALYSIS OF DELAWARE AND CALIFORNIA FIELD PROJECTS

When using high RAM content, increased RBR is economical but generally decreases cracking performance. An analysis was done to determine if the RBR influenced the cracking performance of LMLC specimens in this study. Figure 30 shows a scatterplot of the FI and CT_{Index} versus the RBR. The red line indicates the proposed cracking threshold for LMLC specimens. The results outlined in black indicate mixtures that were designed using the methodology and tools provided in the draft AASHTO standard practice [5]. The scatterplot shows no linear correlation between the RBR and the cracking indices. Based on the experimental design, this result does not imply that the RBR does not affect intermediate-temperature cracking resistance. If all other variables were held constant, changing the RBR would likely decrease cracking resistance. However, this finding does indicate that if mixtures are designed using the tools and recommendations in the draft AASHTO standard practice, adequate cracking performance can be achieved in mixtures with high RBR. By using the proper mitigation strategies, high RBR mixtures can be designed to improve the sustainability of the mixture. Most mixtures in the study did perform above the minimum cracking threshold. However, the economic viability of many mixtures was improved by following the draft AASHTO standard practice.

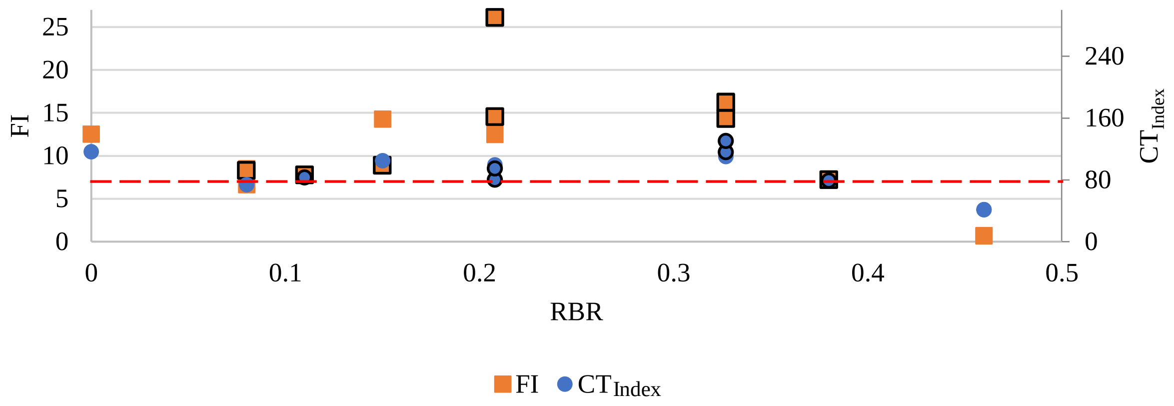


Figure 30. LMLC Cracking Performance versus RBR.

The field projects in this study included one warmer weather climate and one colder weather climate project. Both projects have different rutting resistance thresholds due to the temperature sensitivity of asphalt. To compare the rutting resistance of all mixtures from both field projects, the normalized rutting resistance index (NRRI) was used. The NRRI normalizes the rutting performance based on different thresholds for different binder grades and different methods to conduct the HWTT, and NRRI ≥ 1 indicates that the corresponding mixture meets the rutting resistance requirement. The NRRI is calculated using Equation 4.1:

$$NRRI = \frac{RRI}{Min\ RRI\ for\ Specified\ PG} \tag{4.1}$$

where:

RRI = rut resistance index = N (1-RD);
N = number of wheel passes; and
RD = rut depth (in).

The NRRI of all mixtures used in this project are plotted against their respective RBR values in Figure 31. The red line indicates an NRRI of 1, which is the threshold for meeting the rutting requirements. All mixtures except one met this threshold, and no linear trend was seen with RBR. This finding shows that adequate rutting performance can be achieved regardless of RBR. This may be an expected result since mixtures with high RBR are generally stiffer and more resistant to rutting; however, it is important to note that maintaining rutting resistance with the incorporation of recycling agents and utilizing the appropriate aggregate gradation is vital when adding more recycled materials to a mixture. Using the recommendations in the draft AASHTO standard practice, the researchers adjusted the mixture that fell below the rutting threshold in two different ways to improve rutting resistance. Figure 2 and Figure 17 of this report show the various aggregate gradations for the mixtures in this study.

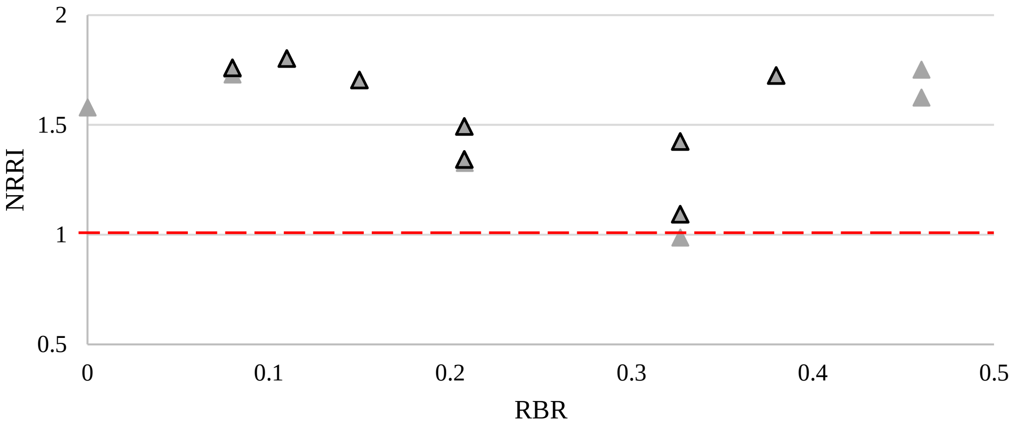


Figure 31. LMLC Rutting Performance versus RBR.

Following the draft AASHTO standard practice to adjust field mixtures, the researchers improved the economics of several mixtures while maintaining adequate rutting and cracking performance. Figure 32 shows a scatterplot of the FI and CT_{Index} versus the estimated relative cost of each mixture compared to the corresponding control mixture. The estimated cost is the estimated cost per ton of the asphalt mixture based on materials only. Production temperatures were held constant in adjusted mixtures, and it was assumed that the cost of production and placement would be equivalent for the various mixtures. Again, the red line indicates the proposed cracking threshold for LMLC specimens, and the results outlined in black indicate mixtures that were designed using the draft AASHTO standard practice. It is interesting to note that the cost of the mixture does not correspond well with its cracking performance. If a mixture is designed and engineered using the proper tools and with cost in mind, it is possible to design a low-cost mixture with good cracking performance. Low-temperature cracking performance was adequate with all mixtures and can been seen in Figure 8 and Figure 22 for the Delaware and California field projects, respectively.

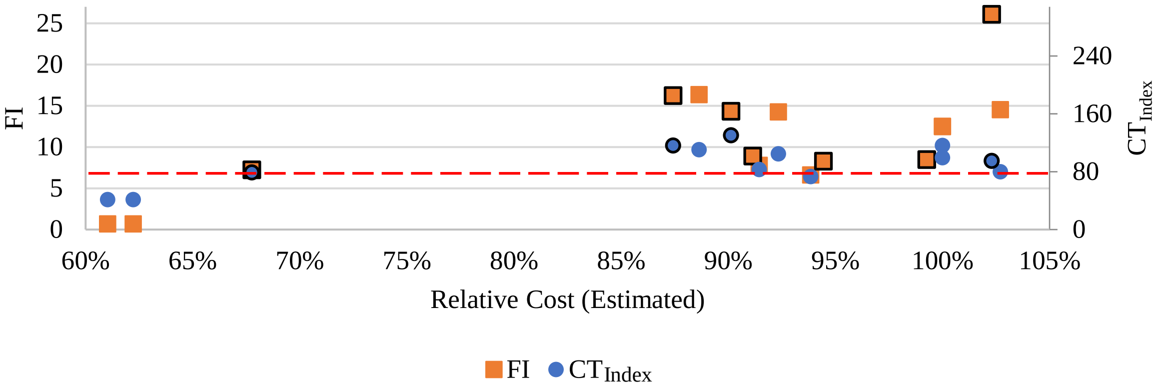


Figure 32. LMLC Cracking Performance versus Relative Cost.

The DCT was used to capture the low-temperature cracking resistance of asphalt mixtures in this study. It was noted in both field projects that the fracture energy (G_f) did not show sensitivity to aging. The field cores for both studies showed no statistical difference between the original and the aged cores (as shown in Figure 14 and Figure 27). A mini study was done on the Delaware reheated plant mix with aging, and it also showed that the DCT G_f parameter was not sensitive to aging. Also noteworthy is that when all specimen types were compared, there was no statistical difference between specimen types or with aging, as shown in Figure 33. The Tukey's HSD letters indicate statistical similarity at a 95 percent confidence interval. Thus, utilizing only G_f of the mixture may not give adequate information on how the mixture will perform at low temperatures. A different testing parameter may be needed to better capture the effect of aging on low-temperature cracking performance.

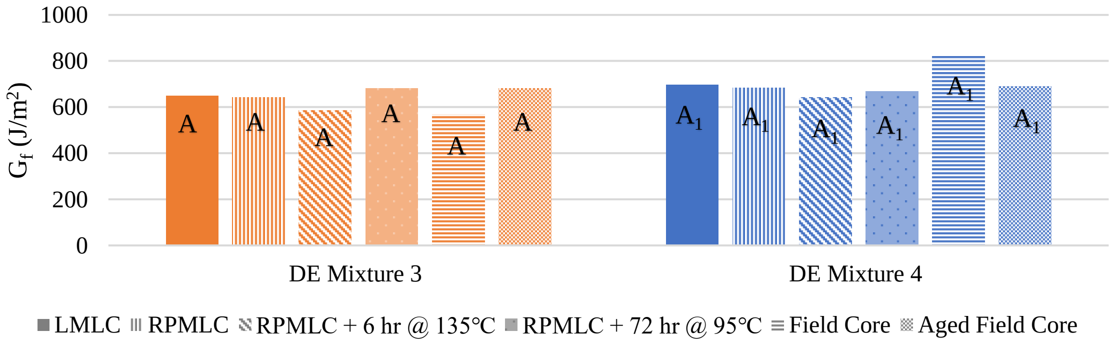


Figure 33. DCT (G_f) with Aging.

Delaware Mixture 4 included both a softer binder and a recycling agent to mitigate high RBR, and this mixture showed lower rutting and stripping resistance without an increase in cracking performance (as shown in Figure 4). Unexpectedly, there was a statistical decrease in cracking performance after 1 year for field aging, as measured by I-FIT on field cores (as shown in Figure 13). This result could be due to compatibility issues between the recycling agent and the virgin binder causing the mixture to be more susceptible to cracking. Mixture 4(L) was identical except that a climate-grade binder was used, and Mixture 3 used the softer binder with no recycling agent (as shown in Table 6). Both of these mixtures performed equivalent or better in rutting and cracking performance tests (as shown in Figure 5 through Figure 8), indicating that using either a softer binder or a recycling agent in high RAP mixtures is better than using both mitigation strategies in the same mixture.

California Mixture D also included a softer binder and a recycling agent to mitigate the RAP and RAS binders. Mixture D showed adequate rutting and cracking resistance in all tests and exhibited statistically higher cracking resistance than the virgin control mixture (as shown in Figure 19 and Figure 22). The recycling agent was removed in Mixture D(L), and it continued to exhibit adequate cracking and rutting resistance while being a more economical mixture (as shown in Figure 21 and Figure 23). This again indicated that only one mitigation strategy is probably needed in mixtures with RAP. The RAS in this mixture appears to have helped maintain rutting resistance when both a recycling agent and softer binder were used; however, removing the recycling agent decreases the cost of the mixture without affecting performance.

DRAFT AASHTO STANDARD PRACTICE REVISIONS

As highlighted in both the Delaware and the California field projects, rutting, stripping, and cracking data showed that using more than one high RAM mitigation strategy (i.e., using a recycling agent and a softer binder) did not improve mixture cracking performance and was detrimental to rutting and stripping performance. A note was added to the draft AASHTO standard practice recommending that mixtures use only one high RAM mitigation or softening strategy. This practice will help improve rutting performance and decrease the cost of the mixture.

In the California field project, cracking performance was improved in several mixtures by assuming a reduced BAF for the stiff RAS binder. Currently, the draft AASHTO standard practice only includes BAF for RAP as a function of PGH. The actual availability of the recycled binder depends on more variables, including how the recycled material was processed, the use/type of recycling agent, the mixing temperature, and the storage time and temperature. Due to the limitations of the current BAF guidelines, this section was removed from the revised draft AASHTO standard practice. It is still recommended in a note that a reduced BAF be considered by assuming something less than 100 percent. More research is needed for better BAF guidelines, and other current studies are addressing this issue.

When testing field cores, the variation in thickness and air voids from that required by the test method standard made the test results difficult to interpret. After a correction factor was applied for both air voids and thickness, the results were more consistent and interpretable. The cores were cut as close to the test thickness as possible, and a linear correction was used to correct for any variation. For the I-FIT results, the air voids were corrected using data from a recent study [26]. A note was added to the revised draft AASHTO standard practice suggesting that field cores be corrected for thickness and air voids to allow for comparison against the performance criteria and with laboratory-compacted specimens.

Delaware and California field mixtures used lower recycling agent doses than the current draft AASHTO standard practice recommends. The recycling agent supplier for the Delaware field project shared the methodology used to determine the recycling agent doses for the Delaware mixtures. No information about the dose selection methodology was available for the California field project. Using the Delaware dose selection methodology, researchers verified and adjusted the California mixture doses as part of the additional laboratory testing. This methodology has proven effective at determining reasonable recycling agent doses, was used to revise the dose selection method outlined in Section 1.5 and was added to the revised draft AASHTO standard practice. The revised dose selection method is summarized in the following six steps:

1. Determine PGH and PGL of the base binder and RAP/RAS binders per AASHTO M 320. If the RAP or RAS binders are too stiff to test directly, the estimated PGH and PGL can be determined by blending the recycled binder with a base binder with known properties. Test the binder blend and then estimate the PGH and PGL using Equation 4.1:

$$PG_{RAP/RAS} = (PG_{Blend} - (PG_{Base} \times \%Base)) / \%RAP/RAS \tag{4.1}$$

where:

PG_{Blend} = continuous PGH or PGL of the recycled binder blend (°C);
PG_{Base} = continuous PGH or PGL of the base binder (°C);
$\%_{Base}$ = percent of the binder blend that is base binder expressed as a decimal; and
$\%_{RAP/RAS}$ = percent of the binder blend that is RAP or RAS expressed as a decimal.

2. Select the base binder, RBR, and RAP/RAS combination, and calculate PGH and PGL of the recycled binder blend using Equation 4.2:

$$PG_{Blend} = (RAP_{BR} \times PG_{RAP}) + (RAS_{BR} \times PG_{RAS}) + (B_{BR} \times PG_{Base}) \tag{4.2}$$

where:

PG_{Blend} = continuous PGH or PGL of the recycled binder blend (°C);
PG_{Base} = continuous PGH or PGL of the base binder (°C);
B_{BR} = base binder ratio = 1 – RBR;
RAP_{BR} = RAP binder ratio; and
RAS_{BR} = RAS binder ratio;

3. Estimate recycling agent dose using Equation 4.3:

$$\text{Recycling Agent (\%)} = (PGL_{Blend} - PGL_{Target}) / \text{Slope Rate} \tag{4.3}$$

where:

PGL_{Blend} = continuous PGL of the recycled binder blend (°C) calculated from Equation 4.2; and
PGL_{Target} = continuous PGL of the target climate − 3ºC.
Slope Rate = change in PG per % recycling agent determined from blending charts with multiple recycling agent doses or requested from materials supplier. When unknown, use 1.38 for petroleum-based aromatic extracts and 1.82 for all other recycling agent types.

4. Check that the estimated PGH meets target climate requirements using Equation 4.4:

$$PGH_{Estimated} = PGH_{Blend} - (\text{Recycling Agent (\%)} \times \text{Slope Rate}) \tag{4.4}$$

where:

PGH_{Blend} = continuous PGH of the recycled binder blend (°C) calculated from Equation 4.2.

5. If the estimated PGH does not meet target climate requirements, adjust PGL_{Target} in Equation 4.3 down to as low as the target climate PGL − 5.9ºC.
6. If the estimated PGH still does not meet target climate requirements, calculate a revised recycling agent dose to target the climate PGH + 5.9ºC using Equation 4.5.

$$\text{Recycling Agent (\%)} = (PGH_{Blend} - PGH_{Target}) / \text{Slope Rate} \tag{4.5}$$

where:

PGH_{Target} = continuous PGH of the target climate + 5.9ºC.

Mix design properties may need to be adjusted if the estimated recycling agent dose is too high or if a suitable dose cannot be calculated to bring both PGH and PGL within acceptable limits. Consider using a BAF less than 100 percent for the recycled RAP and/or RAS binders or adjusting the mix design with respect to component materials or proportions to modify the mixture.

CONCLUSIONS

All conclusions are based on the materials and asphalt mixtures used in this study. This section summarizes the conclusions that were common between mixtures used in both field projects. Chapters 2 and 3 provide the conclusions for the individual Delaware and California field projects, respectively.

- Adequate cracking and rutting performance of asphalt mixtures can be balanced in high RBR mixtures. Tools outlined in the draft AASHTO standard practice help to efficiently design and engineer high RBR mixtures.
- Economics can be improved by adding more RAM in asphalt mixtures while maintaining adequate and balanced performance.
- DCT fracture energy is a good tool to compare low-temperature cracking performance between mixtures; however, it should not be used to evaluate the effects of aging.
- Only one mitigation strategy should be initially used to soften mixtures with high RAP content. Based on the materials and mixtures in this study, the addition of a recycling agent to a mixture with a softer binder did not significantly improve cracking resistance and decreased rutting resistance. Additional mitigation may be necessary when using RAS or with exceptionally stiff RAP binders. Limiting the number of mitigation strategies will also reduce the number of variables during mix design making compatibility issues more apparent.

FUTURE WORK

Several areas of research needing further development were observed during this study:

- Based on recent research, IDEAL-CT results could be reanalyzed to better discriminate between asphalt mixtures, as shown in Figure 12. By using data already collected, a reanalysis could yield useful information on further potential of the IDEAL-CT parameters. The following additional research tasks could be completed using these reanalyzed IDEAL-CT results:

  - Investigate a possible relationship with the binder G-R parameter.
  - Explore a potential relationship with a newly introduced “poker-chip” direct tension binder test [29].
  - Evaluate if alternative multiple thresholds based on G_f and l_{75}/m_{75} parameters can better discriminate between mixtures.
  - Determine the variability of G_f and l_{75}/m_{75} independently to evaluate if a less variable test parameter could be adopted for construction acceptance.
- The DCT FI parameter did not discriminate between aged specimens in this study. Additional work could be done to identify if a different DCT parameter can be utilized to better capture the effects of aging.
- Binder and recycling agent compatibility likely caused mixture performance issues in this study. More research is needed on the compatibility of recycling agents, virgin binders, and recycled binders.
- More research should be done to develop guidance on selection of recycling agent type.
- Using an appropriate BAF was observed to be important to mixture performance in this study. Additional work should be done to develop further guidance on the BAF selection for both RAP and RAS.
- Field core test results need to be corrected for air voids and thickness. A standard method for correcting field core test results should be verified based on a large data set of many different asphalt mixtures.

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APPENDIX A—DELAWARE CONSTRUCTION REPORT

INTRODUCTION

The Delaware Department of Transportation (DelDOT) executed an overlay project on Old Shawnee Rd. in mid-April 2021. The approximately 1.5-mile overlay project was paved on April 13th-14th and located in Milford, Delaware. An overview of the project location is shown in Figure A-1(a), Old Shawnee Rd is highlighted in red in Figure A-1(b). The project overlayed two traffic lanes (one in each direction). The road is undivided and lane widths are 11.5 ft. The project was divided into four sections and used four different asphalt mixtures. Each section was approximately 3,940 ft. long.

(a) **(b)**

Figure A-1. Project Location: (a) Overview, (b) Old Shawnee Rd.

The section of the road prior to construction was in poor condition with a significant amount of cracking. Approximately two inches of pavement was milled off and replaced. Field cores were taken after the new pavement was placed. The average core depth was around four inches. A typical field core obtained after construction is shown in Figure A-2.

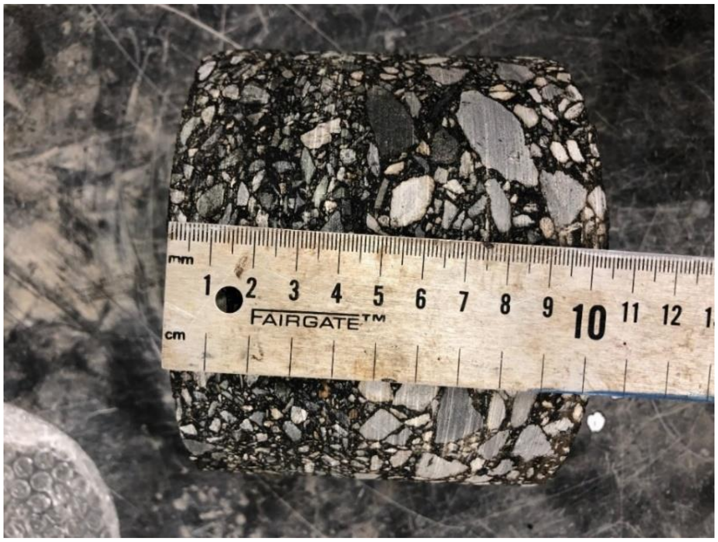


Figure A-2. Typical Field Core.

MATERIALS AND MIXTURES

All four test sections used DelDOT's standard Type C (9.5 mm) Superpave mix designed with 75 gyrations. A PG 64-22/ PG 64S-22 binder was used in mixtures containing 25% recycled asphalt pavement (RAP). A PG 59.2-29.0/ PG 58S-28 binder was used in mixtures containing 40% RAP. Mixture components and proportions are shown in Table A-1.

Materials used in these mix designs are referred to as fine aggregate 1 (FA1), coarse aggregate 2 (CA2), coarse aggregate 3 (CA3), and recycled asphalt pavement (RAP). Materials were all locally sourced and processed by Tri-County Materials in Dover DE. The material properties for each aggregate are shown in Table A-2.

RAP was obtained from various sources before being crushed and stockpiled. The RAP was crushed to ½ inch nominal aggregate size. The RAP had an asphalt binder content of 4.5% and a moisture content of 6.1%.

Table A-1. Test Section/Mixture Descriptions.

Section No.	Mixture Description	Virgin Binder Type and Content	RAP Content (RBR)	Total Asphalt Binder Content	Aggregate Contents	Rejuvenator Dosage
1	Control RAP	4.3% PG 64-22	25%	5.4%	42% FA1, 19% CA2, 14% CA3	None
2	RAP w/ Rejuvenator	4.3% PG 64-22	25%	5.4%	42% FA1, 19% CA2, 14% CA3	2.7% V*
3	High RAP w/ Soft Binder	3.7% PG 58-28	40%	5.5%	27% FA1, 22% CA2, 11% CA3	None
4	High RAP w/ Soft Binder & Rejuvenator	3.7% PG 58-28	40%	5.5%	27% FA1, 22% CA2, 11% CA3	1.2% V*

*V = modified vegetable oil

Table A-2. Component Aggregate Properties.

Material	Moisture Content	Absorption	LA Abrasion	Sodium Sulfate Soundness	Passing #200 Sieve
Fine Aggregate 1	5.4%	1.70	23.0	1.3%	-
Coarse Aggregate 2	2.6%	0.64	-	-	4.7%
Coarse Aggregate 3	3.8%	-	-	-	-

The indirect tension asphalt cracking test (IDEAL-CT), the Texas Overlay (OT) cracking test, and the Asphalt Pavement Analyzer (APA) rutting tests were performed by DelDOT to verify mixture performance. The results are shown in Table A-3. DelDOT currently has no requirement for the APA rutting test since the use of the test is exploratory. DelDOT refers to the Federal Aviation Administration (FAA) specifications to verify APA rutting performance, which requires less than 10 mm rut depth at 4,000 passes following AASHTO T 340 with 250 psi hose pressure and 64°C test temperature (AC 150/5370-10H, 2018). Results for this field project met these criteria and also achieved specified limits used by New Jersey Department of Transportation (NJDOT) and Virginia Department of Transportation (VADOT) requiring rut depths less than 7 mm and 8 mm respectively, for high RAP mixtures (Yin et al. 2021). The IDEAL-CT cracking tolerance limit currently recommended by the Oklahoma Department of Transportation (OKDOT) is a minimum of 80, which all DelDOT mixtures achieved (Yin et al. 2021). With regard to the OT cracking test, DelDOT does not currently specify a limit, but using as reference the threshold recommended by NJDOT of a minimum of 175 cycles, the DelDOT mixtures complied with this value (Bennert, 2015).

Table A-3. Performance Test Results during Mix Design.

Mixture	APA Rut Depth at 20,000 passes, mm	IDEAL-CT cracking tolerance index	OT, Number of Cycles
Control RAP	2.5	117	813
RAP w/ Rejuvenator	3.0	124	1,169
High RAP w/ Soft Binder	3.0	137	2,044
High RAP w/ Soft Binder & Rejuvenator	3.4	167	2,952

*V = modified vegetable oil.

ASPHALT PLANT

All four mixtures were produced at an asphalt mix plant located on the Southeast side of Dover, Delaware. Figure A-3 shows an overview of the plant. The average distance between the plant and the test sections was about 15 miles or approximately 25 minutes away by vehicle. The counter flow drum plant had a capacity of 400 tons per hour. A Pulse Jet baghouse emission system was used. The plant had three silos with a capacity of 300 tons each. The asphalt plant had two binder storage tanks with 30,000 gallons of capacity each.

The modified vegetable oil rejuvenator was injected into the insulated asphalt binder line, and the blend was directly injected to the mixing drum. The temperature of the binder in the storage tanks was maintained at 300°F.

Figure A-3. Overview of the Asphalt Plant at Dover, Delaware.

MIX PRODUCTION AND PAVING

Mixtures were produced and paved in two days. All four mixtures were produced between 300°F and 315°F. Day one (4/13/21) ambient temperature was around 46°F in the early morning and 59°F in the afternoon. Day two (4/14/21) ambient temperature was around 45°F in the early morning and 64°F in the afternoon. Day one was cloudy in the morning and sunny in the afternoon. Day two was mostly sunny in the morning and cloudy in the afternoon. Sample collection began after production of 100 tons of mixture for each test section.

Production of the control RAP (Section 1) began in the morning on April 14, 2021. Mixtures were produced at 250 tons/hour capacity. Approximately 500 tons of each mixture were produced and placed. Table A-4 shows the plant, paving, and ambient temperatures.

Table A-4. Production, Paving, and Ambient Temperatures.

Section	Mixture	Date of Production	Plant Mix Temp., °F	Paving Temp., °F	Ambient Temp., °F
1	Control RAP	04/13/2021	300 – 315	285 – 295	46 – 59
2	RAP w/ Rejuvenator	04/13/2021	300 – 315	285 – 295	52 – 59
3	High RAP w/ Soft Binder	04/14/2021	300 – 315	285 – 295	45 – 64
4	High RAP w/ Soft Binder & Rejuvenator	04/14/2021	300 – 315	285 – 295	45 – 64

There was no TTI staff on site due to the COVID-19 pandemic. The state QA inspector took samples to be sent to TTI. This project was not setup with station numbers or mile markers, so distances from intersections were used to establish test section limits. Each section was approximately 3,940 ft. long and 11.5 ft. wide. Test sections did not include bicycle lanes or shoulders. The control RAP (Section 1) was South West bound starting at the Rt. 113 intersection. The RAP with Rejuvenator (Section 2) was placed in the same lane starting at the end of Section 1 and ending at the Shawnee Rd. intersection. The High RAP with Soft Binder (Section 3) was placed North East bound starting at the Shawnee Rd. intersection. The High RAP w/ Soft Binder & Rejuvenator (Section 4) was placed in the same lane starting from the end of Section 3 and ending at the Rt. 113 intersection. Approximate section limits are shown in Figure A-4, and lane widths are exaggerated. The project layout and sample core locations can be seen in Figure A-5.

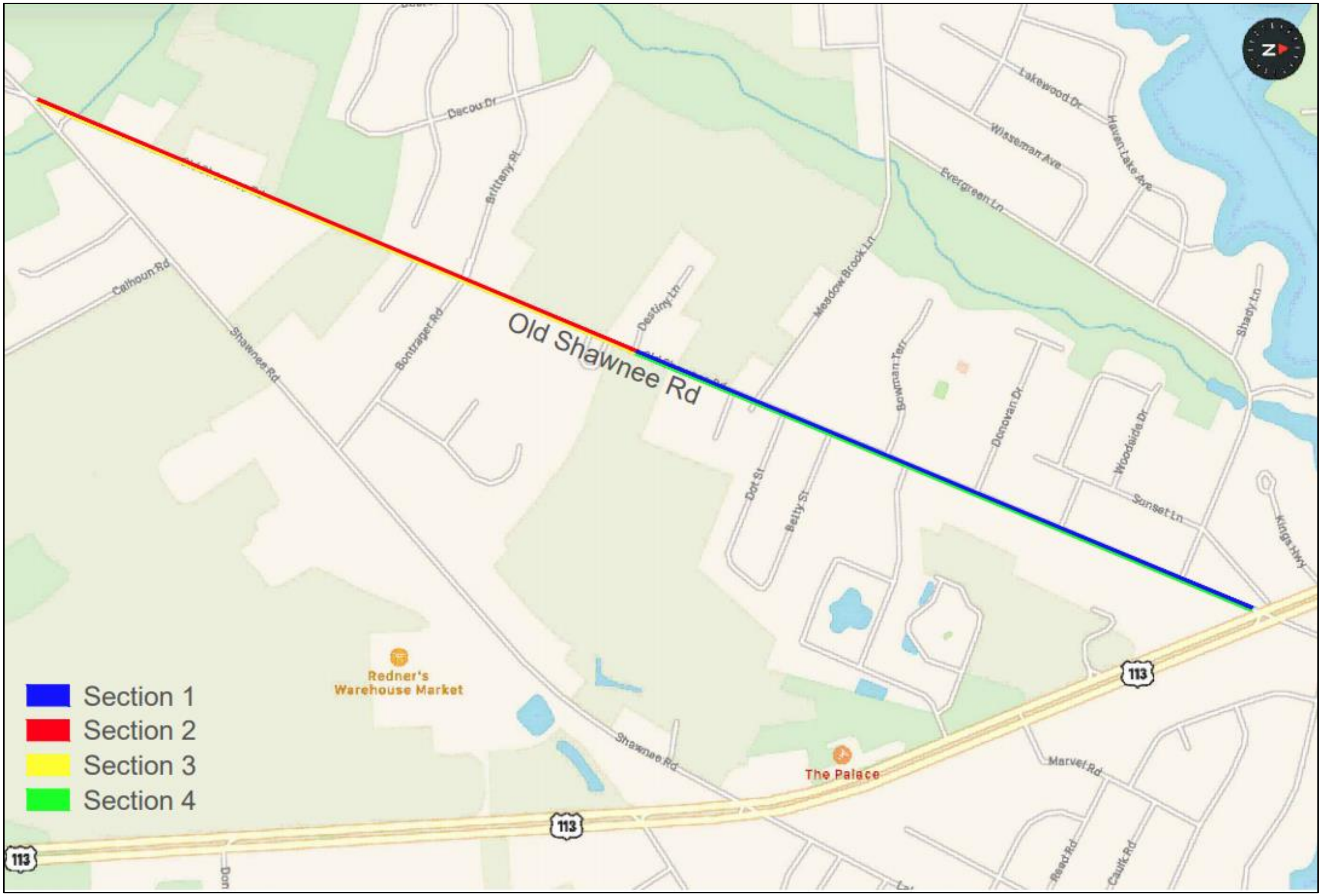


Figure A-4. Approximate Test Section Limits.

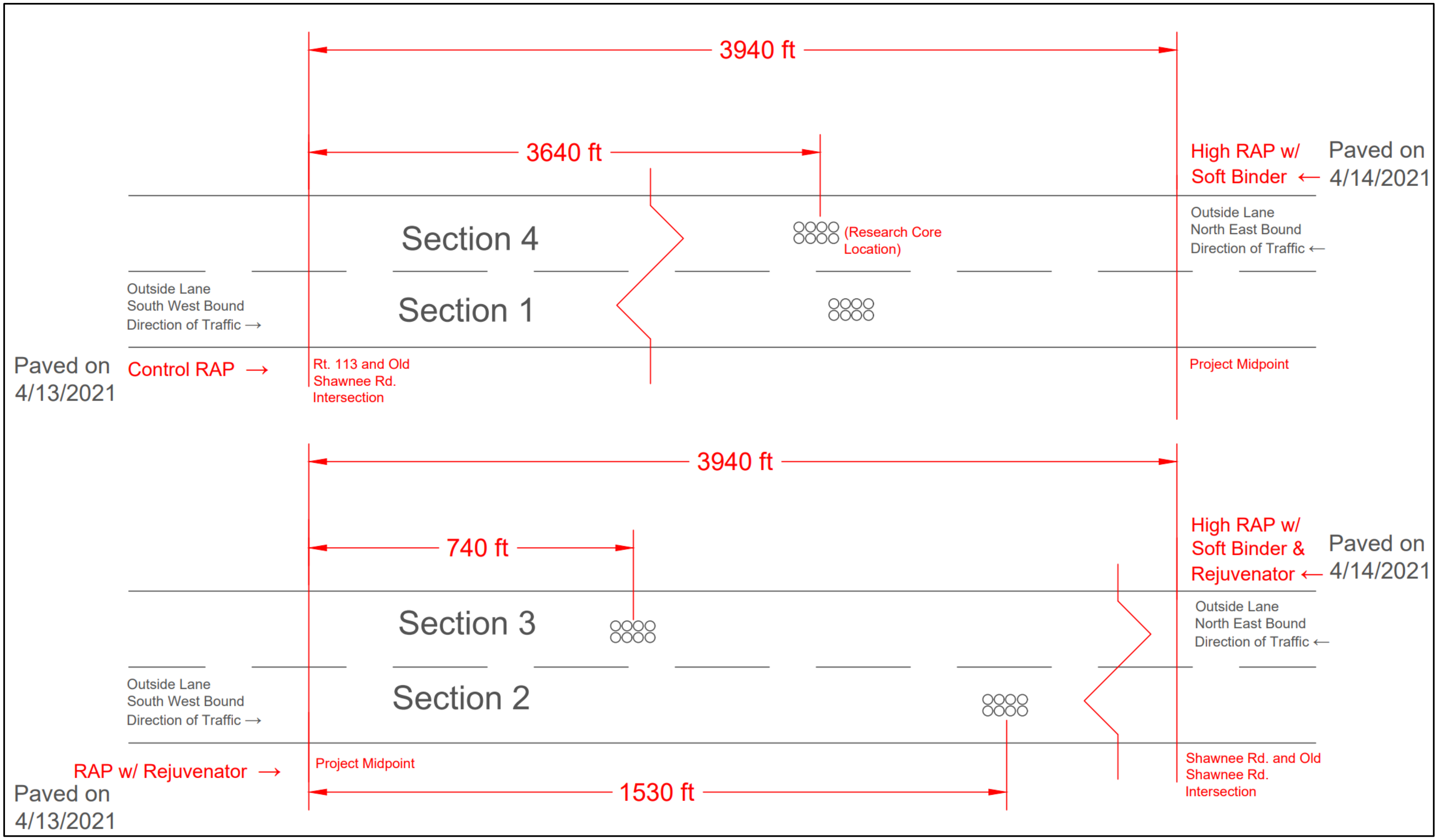


Figure A-5. Project Layout and Core Locations.

Before laydown, the contractor applied a CSS1-H tack coat at rate of 0.09-0.12 gal/sq yd. Dump trucks were used to transport mixtures to the job site. The trucks were tarped according to current DelDOT specifications. The temperature behind the paver was measured using an infrared temperature gun. A 10-ft. CAT paver was used to reheat and spread the asphalt mixture. Two 10-ton rollers were used for the breakdown and compaction of the mixture. A 6-ton roller was used for finishing detailed work. Rollers in vibratory mode were set to 10-12 impacts per foot. Patterns were established for each mixture to achieve 92% compaction. All four test sections were paved in a similar fashion. Parking of equipment was not allowed on the newly paved mat. The dump trucks and paver are shown in Figure A-6, and a 10-ton roller is shown in Figure A-7.

Figure A-6. Dump Trucks and Paver.

Figure A-7. 10-Ton Roller.

Performance testing was completed by DelDOT during construction as part of their QA program. Average test results are summarized in Table A-5. The APA rutting test results complied with the FAA threshold of less than 10 mm rut depth at 4,000 passes, and the IDEAL-CT cracking tolerance index was adequate based on the OKDOT threshold of 80 for the PG 64-xx mixtures. The OT test also met the minimum value of 175 cycles recommended by NJDOT.

Table A-5. Performance Test Results during Construction.

Section	Mixture	APA Rut Depth at 20,000 passes, mm	IDEAL-CT cracking tolerance index	OT, Number of Cycles
1	Control RAP	3.9	99	1,150
2	RAP w/ Rejuvenator	7.2	163	2,767
3	High RAP w/ Soft Binder	3.4	92	1,614
4	High RAP w/ Soft Binder & Rejuvenator	5.0	138	756

DelDOT collected loose mix and cores from each test section to verify the material quality and assure compliance with the current job mix formula (JMF). Using the ignition oven, asphalt binder content (AC) and gradation of residual aggregate were determined and reported. Table A-6 and Table A-7 summarize QA results of AC content and aggregate gradation relative to mix design specifications. Laboratory- molded density and volumetric properties of mixtures including air voids (AV) and voids in the mineral aggregate (VMA) were also determined and reported in Table A-8 and Table A-9. Target values per the JMF are provided, as well as the upper and lower limits (i.e., LL and UL, when applicable) according to DelDOT specifications.

Table A-6. QA Measured AC during Construction.

Section No.	Section Name	Date Sampled	Section Size (tons)	Sample	Asphalt Content (%)	
					JMF	QA
1	Control RAP	4/13/2021	600	1	5.4	5.29
				2		5.34
2	RAP w/ Rejuvenator	4/13/2021	600	1	5.4	5.40
3	High RAP w/ Soft Binder	4/14/2021	600	1	5.5	5.16
				2		5.24
4	High RAP w/ Soft Binder & Rejuvenator	4/14/2021	600	1	5.5	5.25

Table A-7. QA Gradation of Residual Aggregate during Construction.

Section No.	Section Name	Date Sampled	Section Size (tons)	Sieve Size (mm)	Design JMF	Current JMF	LL	UL	Cumulative % Passing	
									Sample # 1	Sample # 2
									QA	QA
1	Control RAP	4/13/2021	600	12.5	100.0	100.0	100.0	100.0	100.0	100.0
				9.50	97.0	97.0	90.0	100.0	97.0	97.0
				4.75	72.0	73.0	66.0	80.0	74.0	74.0
				2.36	42.0	42.0	37.0	47.0	42.0	42.0
				1.16	27.0	27.0	23.0	31.0	26.0	26.0
				0.60	18.0	18.0	14.0	22.0	18.0	18.0
				0.30	12.0	12.0	8.0	16.0	13.0	13.0
				0.15	9.0	9.0	5.0	13.0	9.0	9.0
				0.075	6.4	6.4	4.4	8.0	6.4	6.4
2	RAP w/ Rejuvenator	4/13/2021	600	12.5	100.0	100.0	100.0	100.0	100.0	-
				9.50	97.0	97.0	90.0	100.0	97.0	-
				4.75	72.0	73.0	66.0	80.0	71.0	-
				2.36	42.0	42.0	37.0	47.0	40.0	-
				1.16	27.0	27.0	23.0	31.0	25.0	-
				0.60	18.0	18.0	14.0	22.0	18.0	-
				0.30	12.0	12.0	8.0	16.0	13.0	-
				0.15	9.0	9.0	5.0	13.0	9.0	-
				0.075	6.4	6.4	4.4	8.0	6.5	-
3	High RAP w/ Soft Binder	4/14/2021	600	12.5	100.0	100.0	100.0	100.0	100.0	100.0
				9.50	97.0	97.0	90.0	100.0	96.0	97.0
				4.75	71.0	71.0	64.0	78.0	72.0	71.0
				2.36	40.0	41.0	36.0	46.0	42.0	41.0
				1.16	26.0	27.0	23.0	31.0	28.0	27.0
				0.60	18.0	18.0	14.0	22.0	20.0	18.0
				0.30	12.0	13.0	9.0	17.0	15.0	13.0
				0.15	9.0	10.0	6.0	14.0	10.0	10.0
				0.075	6.6	6.7	4.7	8.2	6.9	6.7
4	High RAP w/ Soft Binder & Rejuvenator	4/14/2021	600	12.5	100.0	100.0	100.0	100.0	100.0	-
				9.50	97.0	97.0	90.0	100.0	98.0	-
				4.75	71.0	71.0	64.0	78.0	70.0	-
				2.36	40.0	41.0	36.0	46.0	41.0	-
				1.16	26.0	27.0	23.0	31.0	27.0	-
				0.60	18.0	18.0	14.0	22.0	19.0	-
				0.30	12.0	13.0	9.0	17.0	14.0	-
				0.15	9.0	10.0	6.0	14.0	9.0	-
				0.075	6.6	6.7	4.7	8.2	6.4	-

Table A-8. QA In-Place Air Voids During Construction.

Section No.	Section Name	Date Sampled	Section Size (tons)	Sample	In-Place Air Voids (%) *			
					JMF	QA	LL	UL
1	Control RAP	4/13/2021	600	1	4.0	4.2	2.0	6.0
				2		4.4	2.0	6.0
2	RAP w/ Rejuvenator	4/13/2021	600	1	4.0	3.7	2.0	6.0
3	High RAP w/ Soft Binder	4/14/2021	600	1	4.0	2.8	2.0	6.0
				2		3.4	2.0	6.0
4	High RAP w/ Soft Binder & Rejuvenator	4/14/2021	600	1	4.0	3.3	2.0	6.0

*Average Value, 3 cores tested per reported result.

Table A-9. QA Voids in the Mineral Aggregate During Construction.

Section No.	Section Name	Date Sampled	Section Size (tons)	Sample	VMA (%) *			
					JMF	QA	LL	UL
1	Control RAP	4/13/2021	600	1	15.5	4.2	14.0	17.5
				2		4.4	14.0	17.5
2	RAP w/ Rejuvenator	4/13/2021	600	1	15.5	3.7	14.0	17.5
3	High RAP w/ Soft Binder	4/14/2021	600	1	15.5	2.8	14.0	17.5
				2		3.4	14.0	17.5
4	High RAP w/ Soft Binder & Rejuvenator	4/14/2021	600	1	15.5	3.3	14.0	17.5

*Average Value, 3 cores tested per reported result.

Pictures taken by the contractor of the finished project are shown in Figure A-8. The travel and bicycle lanes can be seen. Note that the study area only includes the travel lanes.

(a) (b)

(c) (d)

Figure A-8. Finished Project: (a) Old Shawnee Rd. and Bontrager Rd. Intersection, (b) Old Shawnee Rd. North East Bound, (c) Old Shawnee Rd. South West Bound, (d) Old Shawnee Rd. North East Bound.

SAMPLE COLLECTION

Asphalt binders PG 64-22 and PG 58-28 were sampled from storage tanks at the mixing plant as per AASHTO T40. Aggregates were sampled from stockpiles at the plant site as per AASHTO T2. RAP was sampled from a processed stockpile at the plant site according to AASHTO T2. Loose plant mix samples were sampled from trucks at the plant according to AASHTO 168. Cores were sampled from the driving lane once the pavement was sufficiently cooled. There were 32 cores sampled for research and 12 cores procured for DelDOT quality assurance. The materials sampling scheme is listed in Table A-10 with the assumption that 5-gallon buckets weigh approximately 50lbs each.

Table A-10. Materials Sampling Scheme.

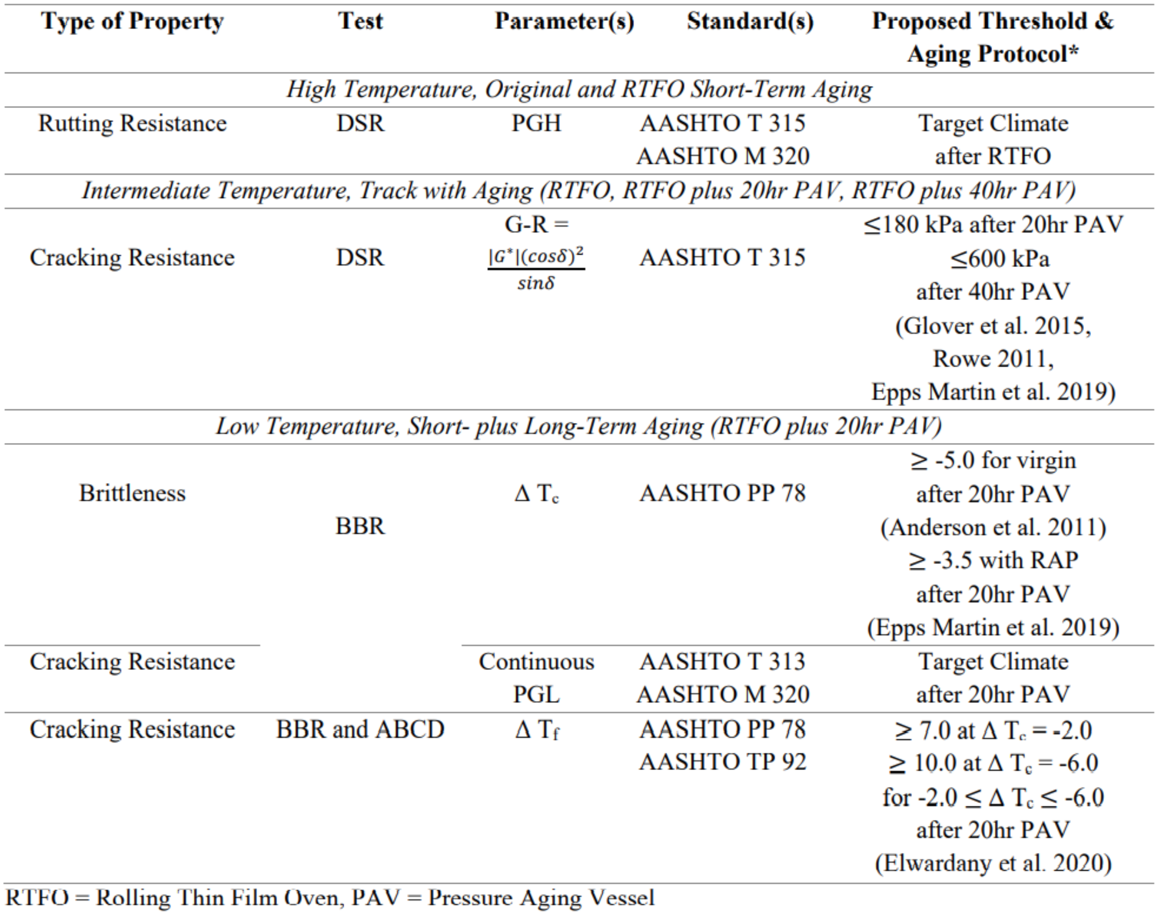
Sample Type	Material	Point of Sampling	Amount
Lab-Mixed, Lab-Compacted	Fine Aggregate 1	Stockpile at Plant	19 (5-gal buckets)
	Coarse Aggregate 2	Stockpile at Plant	11 (5-gal buckets)
	Coarse Aggregate 3	Stockpile at Plant	6 (5-gal buckets)
	RAP	Processed Stockpile at Plant	17 (5-gal buckets)
	PG 64-22 Asphalt	Storage Tank at Plant	4 (5-gal buckets)
	PG 64-22 Asphalt	Storage Tank at Plant	
Plant-Mixed, Lab-Compacted	Loose Mix	Truck at Plant	48 (5-gal buckets)
Plant-Mixed, Lab-Compacted	Lab-Compacted Specimen	Tri-County Lab	16 (Specimens)
Plant-Mixed, Field-Compacted	Road Cores	Travel Lane	32 (Cores)

LABORATORY TEST PLAN

Laboratory tests will be conducted on the selected binder blends and their corresponding laboratory-mixed laboratory-compacted (LMLC) mixtures as shown in Table A-11 and A-12, respectively, and their performance will be assessed based on thresholds when available. These evaluation tools are specified in the AASHTO Draft Standard Practice (NCHRP Report 927) with a few changes/additions based on recent research and/or equipment availability.

As shown in Table A-11, the rheological properties of the binder blends will be characterized by performing dynamic shear rheometer (DSR) and bending beam rheometer (BBR) tests. Four different aging states will be considered: unaged (original), short-term aging in the rolling thin film oven (RTFO) to simulate aging during production and construction, and long-term aging in the Pressure Aging Vessel (PAV) at 20hr and 40hr to simulate field aging. DSR results will be used to evaluate cracking and rutting resistance based on the G-R parameter at 15°C and 0.005 rad/sec (with aging in Black space) and continuous PGH, respectively. BBR results will be used to evaluate brittleness and cracking resistance characteristics of the binder blends. Brittleness will be evaluated based on ΔT_c, or the difference in critical low temperatures for S and m-value by BBR testing, after 20hr PAV and 40hr PAV for comparison with G-R results, although a threshold after 40hr PAV is not currently available. Cracking resistance will also be assessed based on continuous PGL and ΔT_f defined as the difference between critical low temperature for BBR stiffness and binder cracking temperature measured in the Asphalt Binder Cracking Device (ABCD).

Table A-11. Proposed Binder Evaluation.



Type of Property	Test	Parameter(s)	Standard(s)	Proposed Threshold & Aging Protocol*
High Temperature, Original and RTFO Short-Term Aging				
Rutting Resistance	DSR	PGH	AASHTO T 315 AASHTO M 320	Target Climate after RTFO
Intermediate Temperature, Track with Aging (RTFO, RTFO plus 20hr PAV, RTFO plus 40hr PAV)				
Cracking Resistance	DSR	$G\text{-}R = \frac{\lvert G^*\rvert(\cos\delta)^2}{\sin\delta}$	AASHTO T 315	≤180 kPa after 20hr PAV ≤600 kPa after 40hr PAV (Glover et al. 2015, Rowe 2011, Epps Martin et al. 2019)
Low Temperature, Short- plus Long-Term Aging (RTFO plus 20hr PAV)				
Brittleness	BBR	ΔT_c	AASHTO PP 78	≥ -5.0 for virgin after 20hr PAV (Anderson et al. 2011) ≥ -3.5 with RAP after 20hr PAV (Epps Martin et al. 2019)
Cracking Resistance		Continuous PGL	AASHTO T 313 AASHTO M 320	Target Climate after 20hr PAV
Cracking Resistance	BBR and ABCD	ΔT_f	AASHTO PP 78 AASHTO TP 92	$\geq$ 7.0 at $\Delta T_c = -2.0$ $\geq$ 10.0 at $\Delta T_c = -6.0$ for $-2.0 \leq \Delta T_c \leq -6.0$ after 20hr PAV (Elwardany et al. 2020)

RTFO = Rolling Thin Film Oven, PAV = Pressure Aging Vessel

As shown in Table A-12, mixtures will be evaluated for rutting resistance, moisture susceptibility and cracking resistance. Rutting resistance and moisture susceptibility will be measured after short-term oven aging (STOA) at high temperatures to determine the number of cycles to 12.5mm rut depth ($N_{12.5}$) and stripping number (SN), respectively, using the Hamburg Wheel-Tracking Test (HWTT). Cracking resistance will be evaluated at both intermediate and low temperatures. The intermediate- temperature cracking resistance will be assessed by measuring the Flexibility Index (FI) using the semi-circular bend (SCB) test and the cracking test index (CT_{Index}) from the IDEAL-CT after STOA protocols as defined in Table A-12. Low-temperature mixture cracking resistance will be measured by determining the cracking resistance index-environmental (CRI_{Env}) in the uniaxial thermal stress and strain test (UTSST) and the fracture energy (G_f) in the disc-shaped compact tension (DCT) test after different longer-term aging protocols as defined in Table A-10. Alternate thresholds are also available to evaluate mixtures at intermediate temperatures after yet another different longer-term aging protocol (e.g., FI $\geq$ 5 after LTOA compacted 3d at 95ºC (Al-Qadi et al. 2019)). These aging protocols and thresholds are tied to field performance.

Field cores will also be used for a subset of the proposed laboratory tests. The contractor provided eight cores per section for a total of 32 cores. Four cores per section will be used for the HWTT. Two cores will be used for an Illinois FI Test (I-FIT), and stiffness (M_R) will also be determined on the same core prior to determining FI. The final two cores will be used for a low temperature DCT test to determine fracture energy (G_f). Data from all four test sections will be compared in the final evaluation.

Table A-12. Proposed Mixture Evaluation.

Type of Property	Test	Parameter(s)	Standard(s)	Proposed Threshold & Aging Protocol*
		High Temperature, Short-Term Aging		
Rutting Resistance	HWTT	$N_{12.5}$	AASHTO T 324	≥ 5,000 for PG 58-XX ≥ 7,500 for PG 64-XX (cold) ≥ 10,000 for PG 64-XX (warm) ≥ 15,000 for PG 70-XX ≥ 20,000 for PG 76-XX after STOA (2hr @ 135°C) (Epps Martin et al. 2019)
Moisture Susceptibility	HWTT	SN	AASHTO T 324 Yin et al. (2014)	≥ 2,000 after STOA (2hr @ 135°C) (Epps Martin et al. 2014)
		Intermediate-Temperature, Short-Term and Short- plus Long-Term Aging		
Cracking resistance	SCB	FI	AASHTO TP 124	≥ 7 after STOA (2hr @ 135ºC) (Epps Martin et al. 2019)
	IDEAL-CT	CT_{Index}	ASTM D8225	≥ 80 after STOA (2hr @ 135ºC) (Zhou et al. 2017, OK DOT 2020)
		Low-Temperature, Short-plus Long-Term Aging		
Cracking resistance	UTSST	CRI_{Env}	ASTM WK60626	≥ 17 after LTOA-compacted (5d @ 85°C) (Epps Martin et al. 2019)
	DCT	G_f	ASTM D7313	≤ 400 J/m^2 after ITOA-loose (4hr @ 135ºC) (Marasteanu et al. 2012)

*STOA = short-term oven aging, ITOA = intermediate-term oven aging (following STOA), LTOA = long- term oven aging (following STOA)

Analysis will include a comparison of information obtained with current DelDOT control mixtures and that obtained by applying the AASHTO Draft Standard Practice (NCHRP Report 927) for the rejuvenated sections to determine the effectiveness and needed revisions. Comparisons will also be made between the control sections and the rejuvenated sections, and the available performance thresholds will be evaluated if possible, with limited early field performance. Knowledge gained from this field project will be utilized to recommend revisions to the AASHTO Draft Standard Practice (NCHRP Report 927) and prepare a guide for all state DOTs toward nationwide implementation.

APPENDIX B—CALIFORNIA CONSTRUCTION REPORT

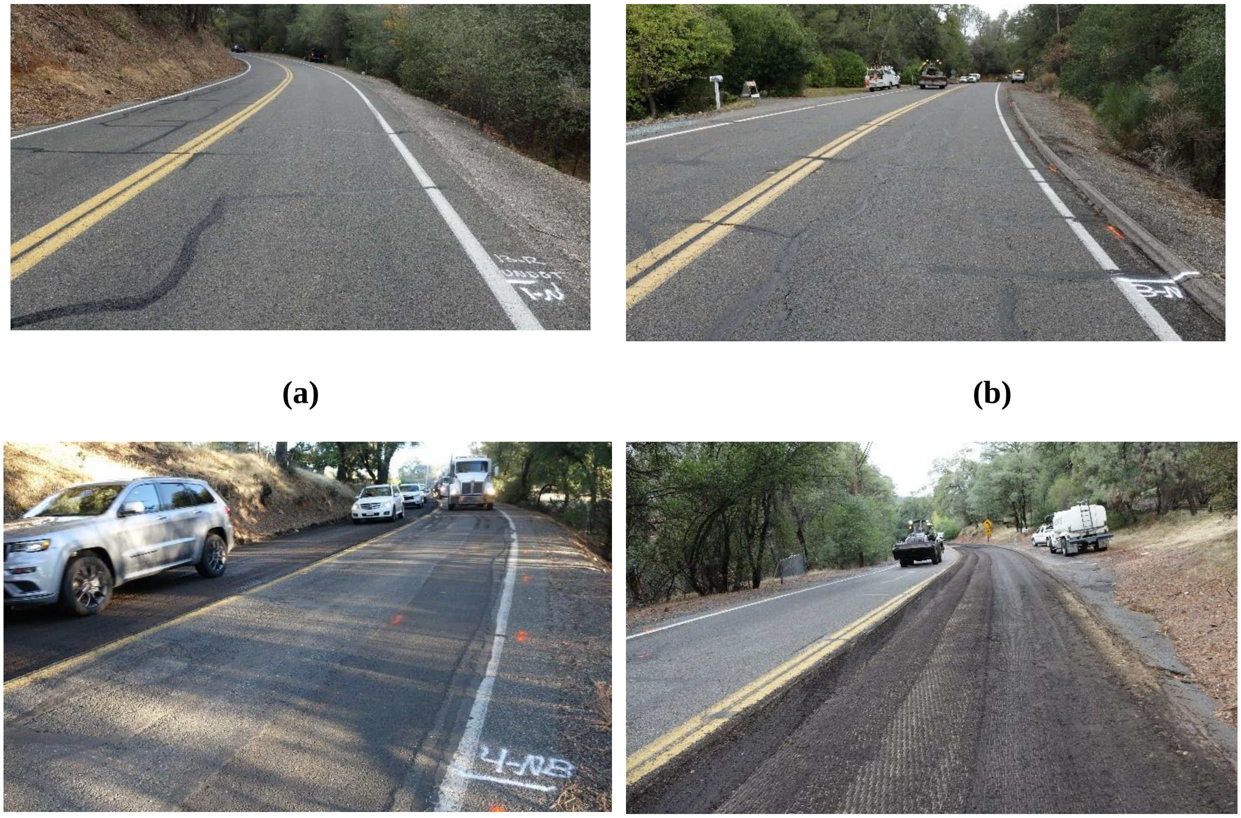
INTRODUCTION

The California Department of Transportation (Caltrans) executed an overlay project on State Highway 49 (SH 49) in El Dorado County beginning November 2, 2021. The project overlayed two lanes of traffic approximately 0.8 miles long. An overview of the project location is shown in Figure B-1(a), and the project limits are shown in Figure B-1(b). The road is undivided and lane widths are 12 feet. The project was divided into four sections and used four different asphalt mixtures. Each section was approximately 1,000 ft. long and 24 feet (two lanes) wide.

(a) **(b)**

Figure B-1. Project Location: (a) Overview, (b) El Dorado SH 49 Project Limits.

Preconstruction the pavement was generally in poor condition with lots of longitudinal, horizontal and alligator cracking. Preconstruction pavement condition and condition after milling are shown in Figure B-2. The pavement was milled before placing the new asphalt layer. After milling there were still visible cracks that appeared to extend the entire depth of the pavement. Approximately 1.8 inches of pavement were milled off and replaced with approximately 2.4 inches of new asphalt pavement.



(a) (b)

(c) (d)

Figure B-2. Overall Condition Preconstruction: (a) Test Section 2, (b) Test Section 3, (c) Test Section 4, (d) Test Section 3 Milled.

MATERIALS AND MIXTURES

Four mixtures were used on the El Dorado 49 overlay project. All four sections used a ½ inch hot mix asphalt Superpave (HMA-SP) type mixture. The control mixture had no recycled material and no rejuvenator. The other three mixtures included a mixture with recycled asphalt pavement (RAP) only, Recycled Asphalt Shingles (RAS) only and a mixture with both RAP and RAS. Both the RAS and the RAP/RAS mixtures included a tall oil rejuvenator.

All aggregate materials used in the mix designs were sourced from a local quarry. The materials include ¼ inch rock dust, 3/8 inch crushed rock, ½ inch crushed rock and mineral filler (MF).

The RAP has an asphalt binder content of 4.37% and a specific gravity of 2.554. RAP was crushed on site to 3/8 inch nominal aggregate size. The RAS has an asphalt binder content of 14.58% and a sand equivalent of 92. Table B-1 shows the mix design properties of each section. Recycling agent doses were selected by the contractor in collaboration with the recycling agent supplier. The recycling agent supplier recommended the rejuvenator dose to restore the high temperature performance grade (PGH) and low temperature performance grade (PGL). The PGH range was targeted and not the continuous grade PGH as recommended by NCHRP Report 927 (Epps-Martin et al. 2019).

Table B-1. Test Section Mixture Descriptions.

Section No.	Mixture Description	Virgin Binder Type and Content (% by weight of mixture)	RAP/RAS Content (% by weight of mixture)	Total Asphalt Binder Content (% by weight of mixture)	Aggregate Contents	Rejuvenator Dosage (% by weight of total binder)
1	Control	4.3% PG 64-16	0/0	5.0	49.5% ¼”, 34% 3/8”, 14% ½”, 2.5% MF	None
2	RAS Only w/ Rejuvenator	3.7% PG 58-22	0/3	5.0	44% ¼”, 38% 3/8”, 13% ½”, 2% MF	0.75 T*
3	Conventional RAP	4.3% PG 64-16	12/0	4.9	42% ¼”, 30% 3/8”, 15% ½”, 1% MF	None
4	RAP/RAS w/ Rejuvenator	3.7% PG 58-22	10/3	5.0	39% ¼”, 32% 3/8”, 15% ½”, 1.0% MF	1.5 T*

*T = Tall oil

Caltrans required several QA (quality assurance) tests for report purposes only, i.e., there is no required performance threshold. Tests will be performed by University of California, Davis. These tests are listed in Table B-2.

Table B-2. Report Only, QA Tests.

Quality Characteristic	Parameter	Test Method	Requirement
Hamburg wheel track	Minimum number of passes at inflection point	California Test 389	Report Only
IDEAL-CT	Cracking Tolerance Index	ASTM D 8225	Report Only*
I-FIT	Flexibility Index	AASHTO TP 124	Report Only
Bending Beam Fatigue	Number of Cycles	AASHTO T 321	Report Only
Repeated Load Triaxial test	Number of Load Repetitions	AASHTO T 378	Report Only

*Must meet or exceed control performance CT value if RAS is used.

The indirect tension asphalt cracking test (IDEAL-CT) was performed during the mix design phase to verify mixture performance. The results are shown in Table B-3. Caltrans specified that all mixtures with RAS must have a cracking tolerance (CT) index value greater than or equal to the control mix value. There is no specified threshold for the indirect tensile strength (ITS) value. The Repeated Load Triaxial test results are also reported with no specified performance threshold.

Table B-3. IDEAL-CT and Repeated Load Triaxial Test Results, during Mix Design.

Section No.	Mixture	IDEAL-CT CT Index	IDEAL-CT ITS	Repeated Load Triaxial test (Cycles to Deformation)			
				Flow #	1%	3%	5%
1	Control	118	157		122	735	1104
2	RAS Only w/ Rejuvenator	122	163		448	2793	3811
3	Conventional RAP	-	-		-	-	-
4	RAP/RAS w/ Rejuvenator	164	147		203	1343	1928

MIX PRODUCTION AND PROJECT LAYOUT

Mixtures were produced by George Reed Inc. at their batch plant located in Clements California. The plant uses a six-ton pugmill with a hot elevator. HMA was batched directly, silos were not used for production. The plant only had one recycled materials feed. Thus, for Section 4 the RAP and RAS were pre-blended in a cold drum prior to being transported to the recycled materials feed.

Mixtures were produced and paved in two days. A TTI representative measured mixture temperatures at the plant with temperatures ranging between 324°F and 340°F. Day one ambient temperature was around 65°F when paving commenced in the late morning and 76°F in the afternoon. Day two ambient temperature was around 56°F in the early morning and 82°F in the afternoon. Day one was cloudy in the morning with some light precipitation and sunny in the afternoon. Day two was sunny in the morning and in the afternoon. Sample collection began after production of 100 tons of mixture for each test section. Measured temperatures at the plant and during construction are shown in Table B-4.

Table B-4. Production, Paving and Ambient Temperatures.

Section	Mixture	Date of Production	Plant Mix Temp., °F	Paving Temp., °F	Ambient Temp., °F
1	Control RAP	11/02/2021	324 - 329	296 - 324	65 – 76
2	RAS Only w/ Rejuvenator	11/02/2021	-	-	65 – 76
3	Conventional RAP	11/03/2021	-	300 – 305	56 – 82
4	RAP/RAS w/ Rejuvenator	11/03/2021	340	307 – 308	56 – 82

Each section was approximately 1000 feet long and 24 feet wide. The target overlay thickness was 0.2 feet or approximately 2.4 inches. Table B-5 lists section limits and section details. Approximate section limits are shown in Figure B-3. The project layout and sample core locations are shown in Figure B-4.

Table B-5. Section Limits and Details.

Section	Type	County	Route	Section Limits		Length (ft)	Width (ft)	Volume (ft^3)	Tonnage
1	0% RAP and RAS	ED	49	13.100	13.289	997.9	24	4790.0	371.2
2	3% RAS	ED	49	13.29	13.478	997.9	24	4790.0	371.2
3	12% RAP	ED	49	13.48	13.668	1003.2	24	4815.4	373.2
4	3% RAS and 10% RAP	ED	49	13.67	13.857	997.9	24	4790.0	371.2

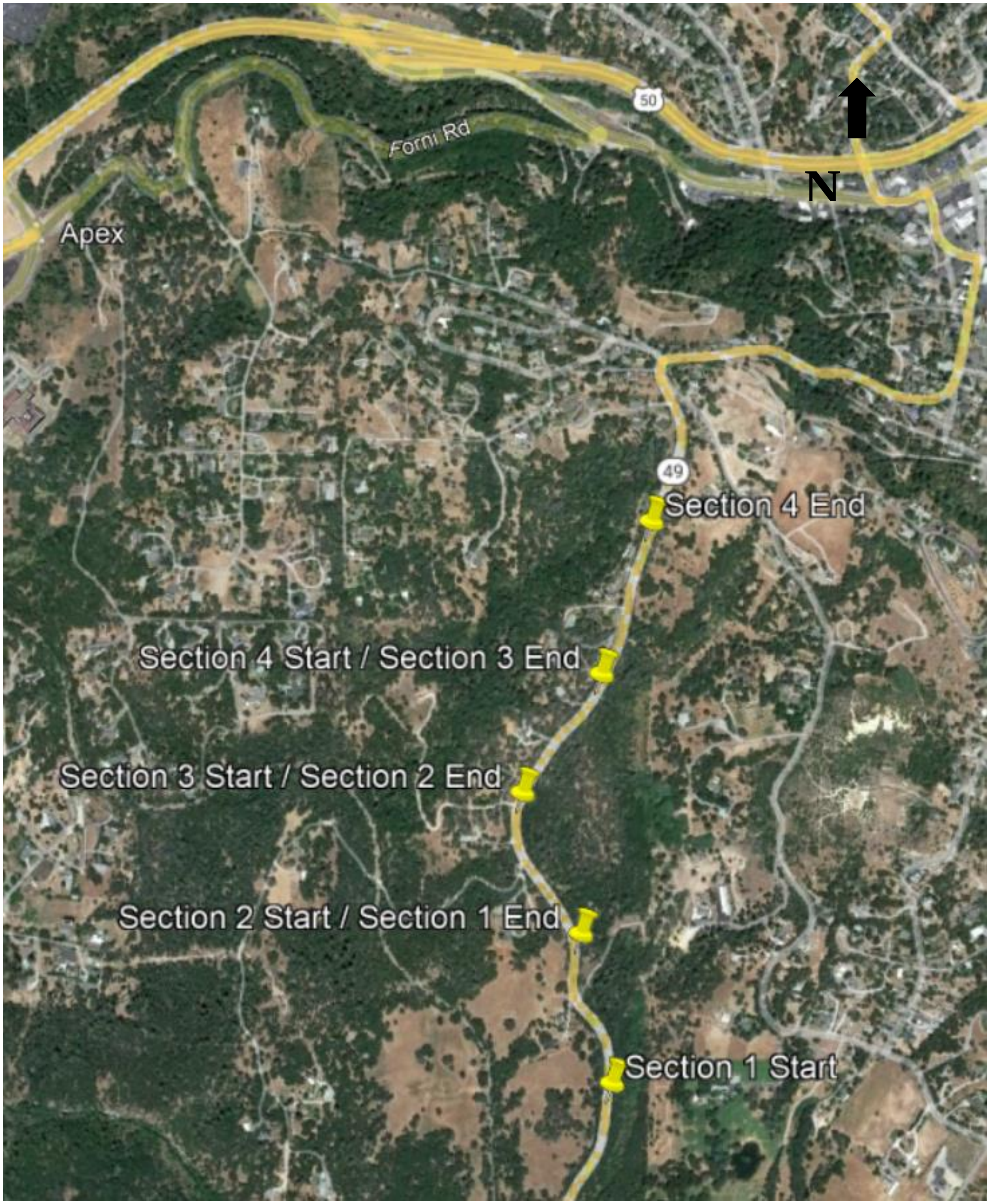


Figure B-3. Project Section Limits.

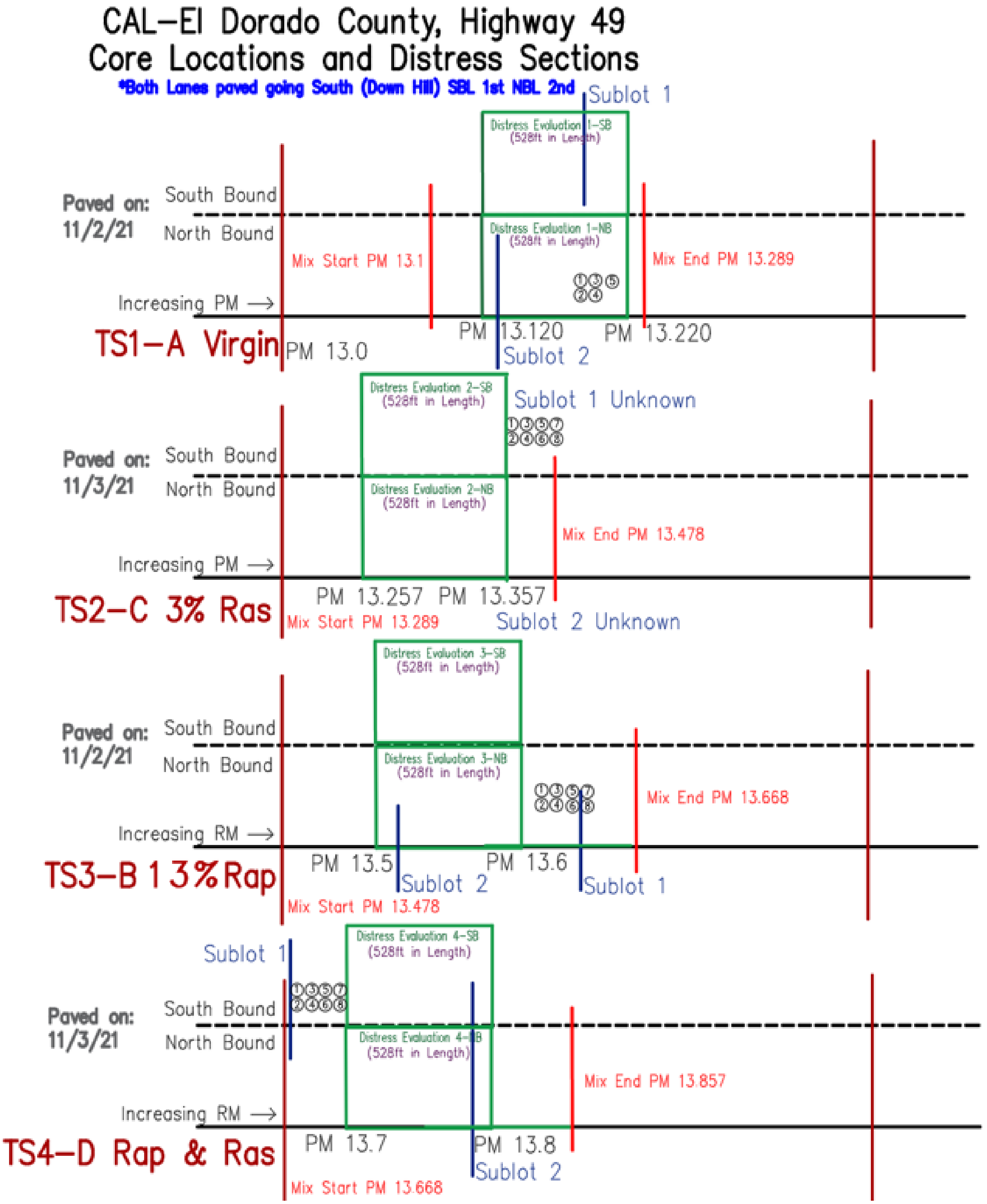


Figure B-4. Core Locations and Distress Sections.

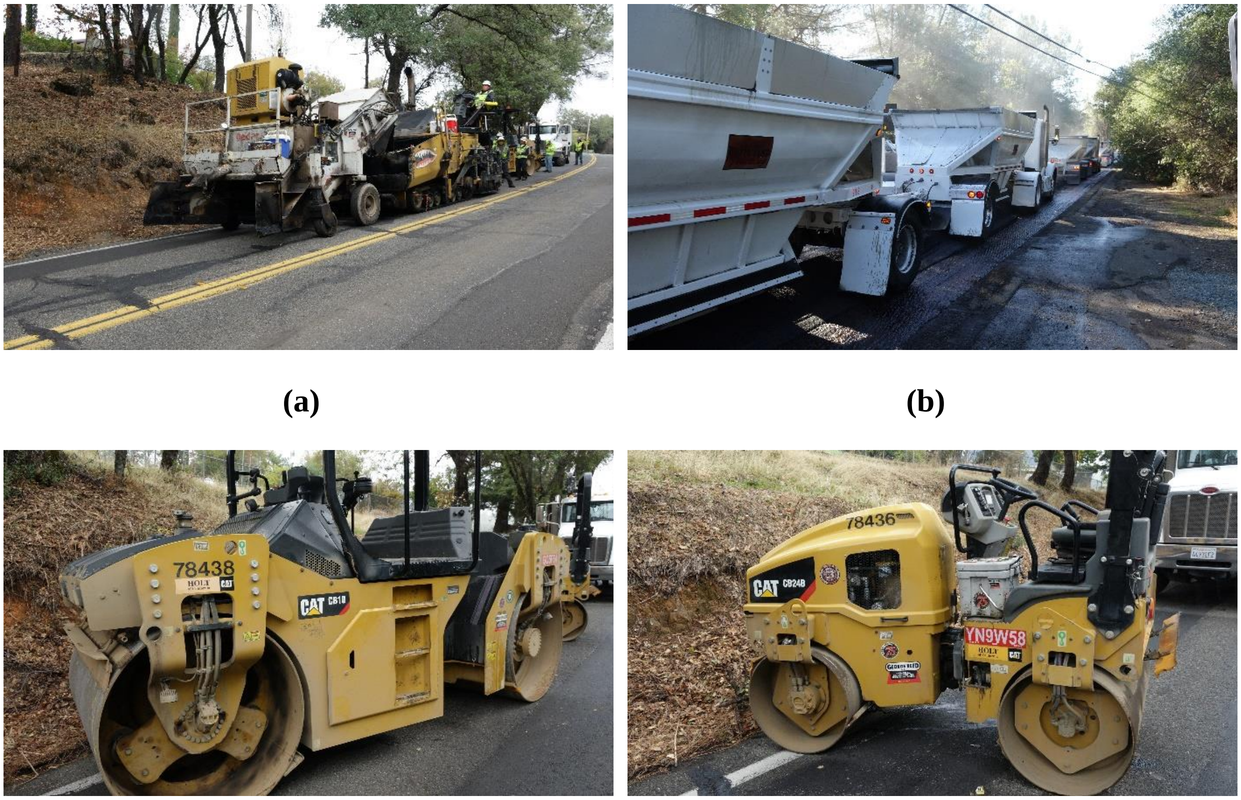
PLACEMENT AND PAVING

The surface layer was milled using an ANRAK Corporation machine. A CSS1-H tack coat was applied before laydown of the new asphalt layer. Approximately 1.8 inches of pavement was milled off and tack was applied at a rate of 0.09 gal/sq yd. The tack coat appeared uniform and sufficient. The milling machine and tack application are shown in Figure B-5.

(a) **(b)**

Figure B-5. Milling: (a) Milling Machine, (b) Tack Coat.

Lanes were paved downhill in the southbound direction for all 4 test sections. Asphalt mixtures were delivered in live double bottom dump trucks. The HMA plant was located approximately 51 miles from the job site, and travel time by truck was approximately 70 minutes. Trucks were tarped during transit. Hot plant mix was dumped in windrows and fed into the paver by a BOMAG MS2 pickup machine. A CAT AP1055F paver was operated at approximately 25 feet/minute during paving. This paver operates on tracks with a 9' 10"-19' 6" paving range. Breakdown compaction was done using a 10-ton CAT CB10 double drum compactor. The roller was set to high for 1 pass and low for two additional passes. No intermediate roller was used. Finnish rolling was completed using a 3-ton CB24B in both static and dynamic mode. Paving equipment is shown in Figure B-6.



(a) (b)

(c) (d)

Figure B-6. Paving Equipment: (a) Paver and Pickup Device, (b) Delivery Trucks, (c) Breakdown Roller, (d) Finish Roller.

Caltrans collected loose mix and cores from each test section to verify the material quality and assure compliance with the current job mix formula (JMF). Not all QC/QA data is available as tests are ongoing. QA IDEAL-CT results are reported in Table B-6.

Table B-6. QA IDEAL-CT Test Results during Construction.

Section No.	Mixture	CT Index (Average)	Air Voids (%)
1	Control	158.6	7.0
2	RAS Only w/ Rejuvenator	110.9	6.9
3	Conventional RAP	98.2	7.2
4	RAP/RAS w/ Rejuvenator	150.8	7.0

SAMPLE COLLECTION

PG 64-22 and PG 58-28 asphalt binders were sampled from storage tanks at the mixing plant as per AASHTO T40. Aggregates were sampled from stockpiles at the plant site as per AASHTO T2. RAP and RAS were sampled from a processed stockpile at the plant site using AASHTO T2. A blended RAP/RAS stockpile was created and sampled as well. Cores were sampled from the driving lane once the pavement was sufficiently cooled. There were 32 cores sampled for TTI research, and other cores were sampled for Caltrans QA and for UC Davis research. The materials sampling scheme is listed in Table B-7.

Table B-7. Materials Sampling Scheme.

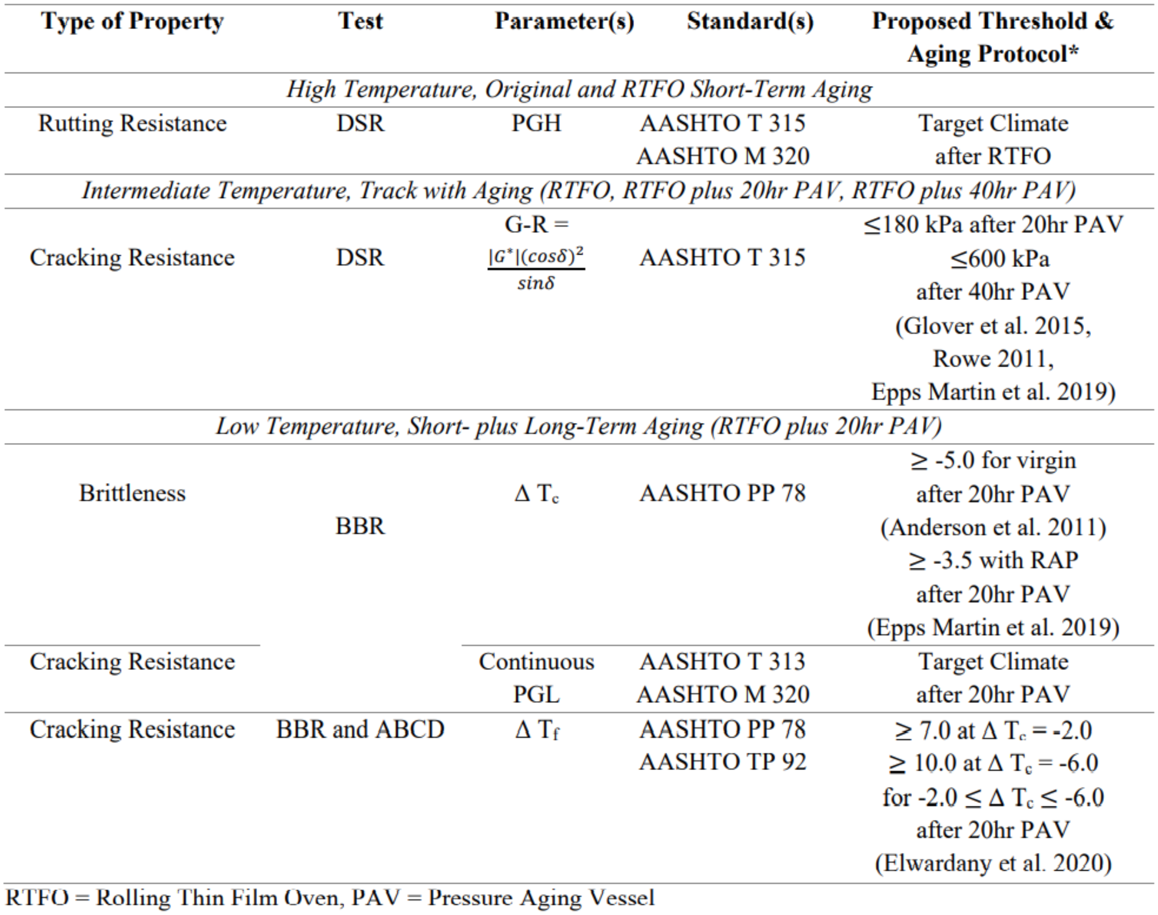
Sample Type	Material	Point of Sampling	Amount
Lab-Mixed, Lab-Compacted	1/4" Rock Dust	Stockpile at Plant	11 (5-gal buckets)
	3/8" Crushed Rock	Stockpile at Plant	10 (5-gal buckets)
	1/2" Crushed Rock	Stockpile at Plant	6 (5-gal buckets)
	Mineral Filler	Stockpile at Plant	3 (5-gal buckets)
	RAS	Processed Stockpile at Plant	2 (5-gal buckets)
	RAP	Processed Stockpile at Plant	2 (5-gal buckets)
	RAP/RAS	At Plant After Blending	2 (5-gal buckets)
	PG 64-16 Asphalt	Storage Tank at Plant	3 (5-gal buckets)
	PG 58-22 Asphalt	Storage Tank at Plant	3 (5-gal buckets)
Plant-Mixed, Field-Compacted	Road Cores	Travel Lane	32 (Cores), 8 From Each Section

LABORATORY TEST PLAN

Laboratory tests will be conducted on the selected binder blends and their corresponding laboratory-mixed laboratory-compacted (LMLC) mixtures as shown in Table B-8 and B-9, respectively, and their performance will be assessed based on thresholds when available. These evaluation tools are specified in the AASHTO Draft Standard Practice (NCHRP Report 927) with a few changes/additions based on recent research and/or equipment availability.

As shown in Table B-8, the rheological properties of the binder blends will be characterized by performing dynamic shear rheometer (DSR) and bending beam rheometer (BBR) tests. Four different aging states will be considered: unaged (original), short-term aging in the rolling thin film oven (RTFO) to simulate aging during production and construction, and long-term aging with additional time in the PAV of 20 hours and 40 hours to simulate field aging. DSR results will be used to evaluate cracking and rutting resistance based on the G-R parameter at 15°C and 0.005 rad/sec (with aging in Black space) and continuous PGH, respectively. BBR results will be used to evaluate brittleness and cracking resistance characteristics of the binder blends. Brittleness will be evaluated based on ΔT_c, or the difference in critical low temperatures for S and m-value by BBR testing, respectively, after 20 hours PAV and 40 hours PAV for comparison with G-R results, although a threshold after 40 hours PAV is not currently available. Cracking resistance will also be assessed based on continuous PGL and ΔT_f defined as the difference between critical low temperature for BBR stiffness and binder cracking temperature measured in the Asphalt Binder Cracking Device (ABCD).

Table B-8. Proposed Binder Evaluation.



Type of Property	Test	Parameter(s)	Standard(s)	Proposed Threshold & Aging Protocol*
High Temperature, Original and RTFO Short-Term Aging				
Rutting Resistance	DSR	PGH	AASHTO T 315 AASHTO M 320	Target Climate after RTFO
Intermediate Temperature, Track with Aging (RTFO, RTFO plus 20hr PAV, RTFO plus 40hr PAV)				
Cracking Resistance	DSR	G-R = $\frac{\lvert G^*\rvert(\cos\delta)^2}{\sin\delta}$	AASHTO T 315	≤180 kPa after 20hr PAV ≤600 kPa after 40hr PAV (Glover et al. 2015, Rowe 2011, Epps Martin et al. 2019)
Low Temperature, Short- plus Long-Term Aging (RTFO plus 20hr PAV)				
Brittleness	BBR	ΔT_c	AASHTO PP 78	≥ -5.0 for virgin after 20hr PAV (Anderson et al. 2011) ≥ -3.5 with RAP after 20hr PAV (Epps Martin et al. 2019)
Cracking Resistance		Continuous PGL	AASHTO T 313 AASHTO M 320	Target Climate after 20hr PAV
Cracking Resistance	BBR and ABCD	ΔT_f	AASHTO PP 78 AASHTO TP 92	≥ 7.0 at ΔT_c = -2.0 ≥ 10.0 at ΔT_c = -6.0 for -2.0 ≤ ΔT_c ≤ -6.0 after 20hr PAV (Elwardany et al. 2020)

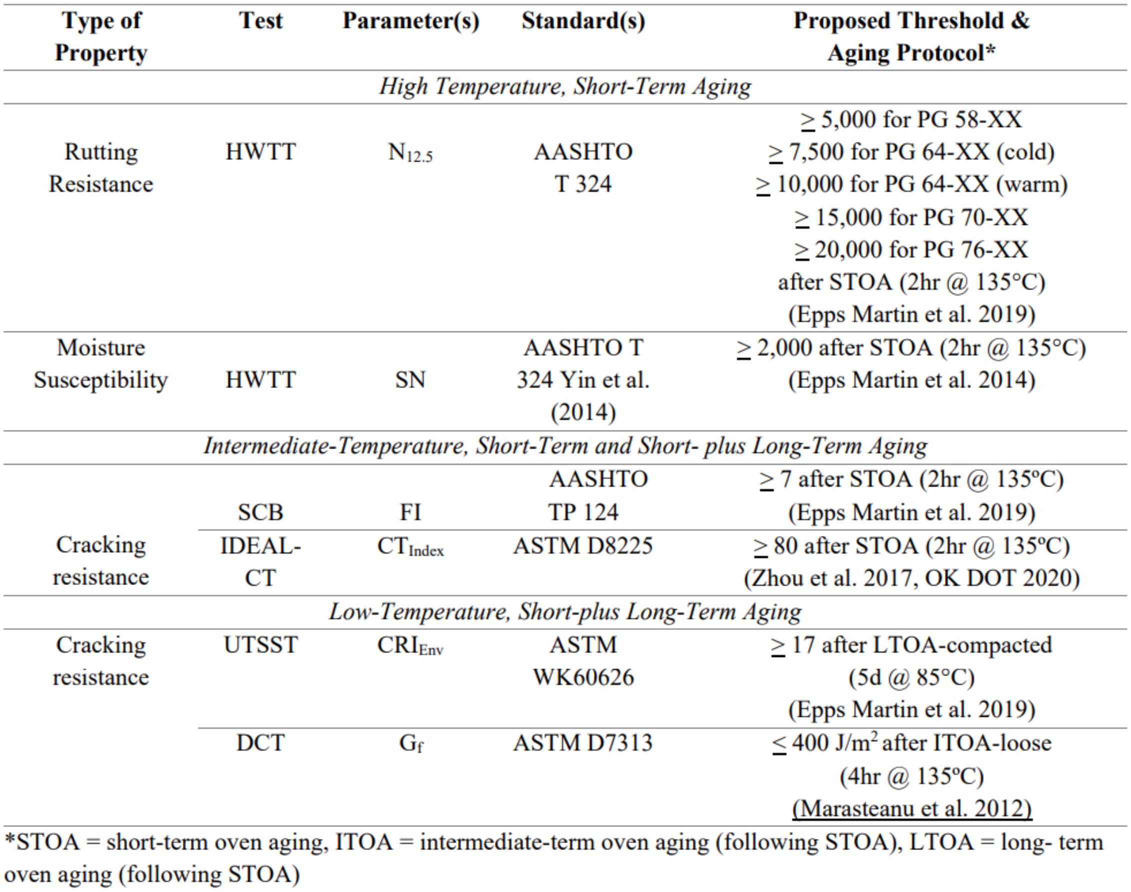
RTFO = Rolling Thin Film Oven, PAV = Pressure Aging Vessel

As shown in Table B-9, mixtures will be evaluated for rutting resistance, moisture susceptibility and cracking resistance. Rutting resistance and moisture susceptibility will be measured after short term oven aging (STOA) at high temperatures to determine the number of cycles to 12.5mm rut depth ($N_{12.5}$) and stripping number (SN), respectively, using the Hamburg Wheel-Tracking Test (HWTT). Cracking resistance will be evaluated at both intermediate and low temperatures. The intermediate-temperature cracking resistance will be assessed by measuring the Flexibility Index (FI) using the semi-circular bend (SCB) test and the CT_{Index} from the (IDEAL-CT test after STOA protocols as defined in Table B-9. Low- temperature mixture cracking resistance will be measured by determining the cracking resistance index-environmental (CRI_{Env}) in the uniaxial thermal stress and strain test (UTSST) and the fracture energy (G_f) in the disc-shaped compact tension (DCT) test after different longer-term aging protocols as defined in Table B-8. Alternate thresholds are also available to evaluate mixtures at intermediate temperatures after yet another different longer-term aging protocol (e.g., FI $\geq$ 5 after long term oven aging (LTOA) compacted 3d at 95ºC (Al-Qadi et al. 2019)). These aging protocols and thresholds are tied to field performance.

Field cores will also be used for a subset of the proposed laboratory tests. The contractor provided eight cores per section with 32 total cores. Four cores per section will be used for the HWTT Test. Two cores will be used for the I-FIT test, and Stiffness (M_R) will also be determined prior to IDEAL-CT testing. The final two cores will be used for a low temperature

DCT test to determine fracture energy (G_f). Data from all four sections and different specimen types (LMLC and cores) will be compared in the final evaluation.

Table B-9. Proposed Mixture Evaluation.



Type of Property	Test	Parameter(s)	Standard(s)	Proposed Threshold & Aging Protocol*
High Temperature, Short-Term Aging				
Rutting Resistance	HWTT	$N_{12.5}$	AASHTO T 324	≥ 5,000 for PG 58-XX ≥ 7,500 for PG 64-XX (cold) ≥ 10,000 for PG 64-XX (warm) ≥ 15,000 for PG 70-XX ≥ 20,000 for PG 76-XX after STOA (2hr @ 135°C) (Epps Martin et al. 2019)
Moisture Susceptibility	HWTT	SN	AASHTO T 324 Yin et al. (2014)	≥ 2,000 after STOA (2hr @ 135°C) (Epps Martin et al. 2014)
Intermediate-Temperature, Short-Term and Short- plus Long-Term Aging				
Cracking resistance	SCB	FI	AASHTO TP 124	≥ 7 after STOA (2hr @ 135ºC) (Epps Martin et al. 2019)
	IDEAL-CT	CT_{Index}	ASTM D8225	≥ 80 after STOA (2hr @ 135ºC) (Zhou et al. 2017, OK DOT 2020)
Low-Temperature, Short-plus Long-Term Aging				
Cracking resistance	UTSST	CRI_{Env}	ASTM WK60626	≥ 17 after LTOA-compacted (5d @ 85°C) (Epps Martin et al. 2019)
	DCT	G_f	ASTM D7313	≤ 400 J/m² after ITOA-loose (4hr @ 135ºC) (Marasteanu et al. 2012)

*STOA = short-term oven aging, ITOA = intermediate-term oven aging (following STOA), LTOA = long- term oven aging (following STOA)

Analysis will include a comparison of information obtained with current Caltrans control mixtures and that obtained by applying the AASHTO Draft Standard Practice (NCHRP Report 927) for the rejuvenated sections to determine the effectiveness and needed revisions. Comparisons will also be made between the control sections and the rejuvenated sections, and the available performance thresholds will be evaluated, if possible, with limited early field performance. Knowledge gained from this field project will be utilized to recommend revisions to the AASHTO Draft Standard Practice (NCHRP Report 927) and prepare a guide for all DOTs toward nationwide implementation.

University of California, Davis will be performing a subset of tests on plant-mixed laboratory-compacted (PMLC) specimens. True binder grade will be determined from binder extracted off plant mix. The Flexibility Index (FI) value will be measured using the semi-circular bend (SCB) test and the CT_{Index} value will be determined from the IDEAL-CT test. Four-Point Bending Fatigue (4PB) will be measured to characterize the fatigue behavior of the asphalt mixtures. The asphalt mixture performance tester (AMPT) will be used to run the repeated load triaxial (RLT) and dynamic modulus (DM) tests. Results will be shared and used for comparison and additional analysis.

APPENDIX C—REVISED DRAFT AASHTO STANDARD PRACTICE

Appendix C has been removed. Appendix C delivered to AASHTO.