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2021 Cold Recycling Pilot Projects: Construction and Quality Control

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2021 Cold Recycling Pilot Projects: Construction and Quality Control

Authors:

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Partnered Pavement Research Center (PPRC) Project 4.78 (DRISI Task 3817)

Updated Guidance and Specifications for In-Place Recycling

PREPARED FOR:

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16. ABSTRACT
The construction of three partial-depth recycling (PDR) pilot projects was monitored in late 2021. These studies focused on the benefits of adding supplemental aggregates to PDR materials, comparison of emulsified asphalt (EA) and foamed asphalt (FA) recycling agents in PDR applications, comparison of the gradations produced by single- and multi-unit recycling trains, and the effect of recycling train forward speed on gradation. Initial findings from the study can be summarized as follows:

- Statistical analyses of quality control results on in-place recycling projects are challenging given the variability in materials and pavement structure along the length of the project. The problem is intensified on pilot projects with multiple experimental sections on which performance is being compared.
- Supplemental aggregates can be used to reliably increase the density and strength of PDR layers without increasing the recycling agent or active filler contents and by not requiring pre-milling of the road to accommodate the materials without changing grade height.
- There was no discernable difference in the density and strengths of PDR layers produced with the single- and multi-unit trains. The main benefit of the multi-unit train is better control of maximum aggregate size by the on-board screens and crushing unit. However, the crushing unit does not appear to change or improve the finer portion of the gradation (i.e., material passing the #4 [4.75 mm] sieve), which will have a larger influence on compaction density, air-void content, strength, and moisture resistance.
- On coarse gradations, higher foamed asphalt contents were required to achieve the minimum indirect tensile strength requirement compared to emulsified asphalt. This is attributed in part to the coating action provided by emulsion treatments being more effective than the "spot welding" action provided by foam treatments on coarse, high air-void content gradations.
- Marshall compaction overestimated the in-place density of PDR layers to a greater extent than gyratory compaction.
- Rerolling can result in a small increase in density on PDR-EA layers. The timing of rerolling will influence the extent of this increase.
- The densities recorded on specimens produced for strength and stability tests were not always consistent with the density results measured on the layer. This difference was attributed in part to inherent variability in the materials and pavement structure, sampling and handling procedures, and different specimen preparation procedures used by the contractors.
- Relationships between gradations of field samples and field densities were inconsistent, which was also attributed to inherent variability in the materials that may not be captured in the small samples taken to represent a relatively large area of the layer.

The pilot projects should be monitored to evaluate long-term performance. Monitoring should include annual visual surveys, annual or biannual falling weight deflectometer testing, and biannual coring and dynamic cone penetrometer testing. This study has highlighted a number of issues and suggested changes within the PDR mix design and quality control procedures followed in these projects (CT 315), which have been discussed with the method owner.

17. KEYWORDS
Partial-depth recycling, cold in-place recycling

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7. PROPOSALS FOR IMPLEMENTATION

Continue monitoring the pilot studies and the laboratory testing on adding supplemental aggregates to improve the gradation of PDR layers. Update CT 315 with recommended changes.

8. RELATED DOCUMENTS

None

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None

10. LABORATORY ACCREDITATION

The UCPRC laboratory is accredited by AASHTO re:source for the tests listed in this report

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11. SIGNATURES

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- Caltrans for arranging and approving the pilot projects and providing the research funding for the UCPRC to study and monitor them.
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- The UCPRC laboratory staff for assisting with sampling and data collection.

PROJECT OBJECTIVES

This study is a continuation of PPRC Projects 4.65 (FDR Microcracking), 4.69 (FDR Guidance), and 4.70 (PDR Guidance). The objective of this project is to update guidance and mechanistic-empirical design procedures for cold recycling. This will be achieved through the following tasks:

Task 1: Continued long-term monitoring of existing and new field cold recycling pilot projects to assess stiffness, cracking, rutting/densification, freeze-thaw, moisture sensitivity, and other observed distresses. The effects of rubberized hot mix asphalt and fabrics in the recycled layer will be assessed where possible. Pilot studies to assess the potential benefits of adding supplemental fines in partial-depth recycled (PDR) projects, and to compare emulsified and foamed asphalt recycling agents and single- and multi-unit recycling trains on the same project will also be motivated and assessed. Rapid quality control/quality assurance tests developed during the NCHRP 9-62 project will be assessed on selected construction projects.

Task 2: Completion of Heavy Vehicle Simulator (HVS) and associated laboratory testing to assess mechanistic behavior and performance properties of cold central plant recycled (CCPR) materials.

Task 3: Literature reviews and laboratory testing to refine mix design procedures, including methods to determine maximum dry density and raveling resistance, to assess the use of supplemental aggregates in PDR and CCPR mixes (including the potential use of fines derived from waste forest biomass), to determine limits for stockpiling of CCPR materials, to investigate the benefits of tack coats between the recycled and underlying layers on PDR projects, and to assess the implications of old rubberized hot mix asphalt materials (this has been evaluated for one material in the previous HVS study testing full-depth recycling [FDR] treatments) and geosynthetics in recycled layers. Literature reviews on other new developments in cold recycling will also be undertaken, with recommendations for further investigation if funding permits.

Task 4: Field monitoring and associated laboratory testing of deep-lift FDR-C projects, including an assessment of when this should be modeled and designed as FDR and when it should be modeled and designed as stabilized subgrade or subbase.

Task 5: Updated guidance, *CalME* models, and *CalME* materials library.

This report covers work undertaken on three pilot studies as part of Task 1.

EXECUTIVE SUMMARY

Overview

The three partial-depth recycling (PDR) pilot projects discussed in this report focused on the following:

- The benefits of adding supplemental aggregates in PDR layers
- Comparison of emulsified and foamed asphalt recycling agents in PDR applications
- Comparison of gradations produced with single- and multi-unit recycling trains
- The effect of recycling train forward speed on gradation

Initial Conclusions from Pilot Study Construction

The addition of supplemental aggregates, the choice of recycling train type (i.e., single- or multi-unit), and the effect of recycling unit forward speed are factors that can potentially affect the gradation of PDR materials, which in turn influences compaction density, strength, stability, stiffness, and moisture sensitivity. Results from this study showed that the largest increase in in-place density was measured when supplemental aggregates were added, with densities up to 11 pcf (176 kg/m^3) higher than the control. Changes in recycling train type and forward speed had little to no effect on in-place density.

Improvements to PDR material gradations typically result in higher indirect tensile strengths and Marshall stabilities for the same recycling agent and active filler contents. Reductions in forward speed typically control the maximum aggregate size but have limited effect on the finer portion of the gradation (i.e., material passing the #4 [4.75 mm] sieve). Multi-unit trains, with appropriate screens on the processing unit, have an extra level of control of maximum aggregate size than single-unit trains, which rely only on forward speed. Results from this study showed that single-unit trains generally produce coarser gradations in the coarse portion of the envelope (i.e., passing the 1.0 in. [25 mm] and retained on the #4 [4.75 mm] sieves) than multi-unit trains, but this did not have a significant effect on in-place density, which is more dependent on the finer fractions that fill voids in the coarser aggregate skeleton. The addition of sufficient supplemental aggregates to fill voids provided the most control over gradation. Pre-milling should not be required to accommodate the supplemental aggregates given that this material is only used to fill voids, which should not increase grade height.

Increases in indirect tensile strength (ITS) with supplemental aggregates were not as significant as the increase in in-place density, especially in terms of wet strength results. These differences could be attributed to variability along the project, specimen dimensions (representative volume element), variability in specimen preparation, material breakdown during Marshall compaction, and precision and bias of the tests. This should be further studied in the laboratory to determine if adding supplemental fines to improve gradation/fill voids alone can increase moisture resistance, or if these improvements are primarily affected by the active filler.

The two recycling agents typically used in PDR, namely foamed asphalt and emulsified asphalt, were also compared in one of the pilot studies. Test results indicated that the sections treated with emulsified asphalt had higher densities than those treated with foamed asphalt, with the same recycling machine and recycling speed. However, there was considerable variability in materials and pavement structure along the length of the project, which likely had an influence on all results.

The quality control test results analyzed in this report provided data on the density, ITS, and Marshall stability determined during construction. The initial findings from the study can be summarized as follows:

- Statistical analyses of quality control results on in-place recycling projects are challenging given the variability in materials and pavement structure along the length of the project. The problem is intensified on pilot projects with multiple experimental sections on which performance is being compared.
- Supplemental aggregates can be used to reliably increase the density and strength of PDR layers without increasing the recycling agent or active filler contents and by not requiring pre-milling of the road to accommodate the materials without changing grade height.
- There was no discernable difference in the density and strengths of PDR layers produced with the single- and multi-unit recycling trains. The main benefit of the multi-unit train is better control of maximum aggregate size by the on-board screens and crushing unit. The crushing unit does not appear to change or improve the finer portion of the gradation (i.e., material passing the #4 [4.75 mm] sieve), which has a larger influence on compaction density, air-void content reduction, strength, and moisture resistance.
- On coarse gradations, higher foamed asphalt contents were required to achieve the minimum ITS requirement compared to emulsified asphalt. This is attributed in part to the coating action provided by emulsion treatments being more effective than the “spot

welding" action provided by the foam treatments on coarse, high air-void content gradations.
- Marshall compaction (AASHTO T 245) overestimated the in-place density of PDR layers to a greater extent than gyratory compaction (AASHTO T 312).
- Rerolling can result in a small increase in density on PDR-EA layers. The timing of rerolling will influence the extent of this increase.
- The densities recorded on specimens produced for strength and stability tests were not always consistent with the density results measured on the layer in the vicinity of where the samples were taken. This was attributed in part to inherent variability in the materials and pavement structure along the project, sampling and handling procedures, and different specimen preparation procedures used by the contractors.
- Relationships between gradations of field samples and field densities were inconsistent, which was also attributed to inherent variability in the materials which may not be captured in the small samples taken to represent a relatively large area of the layer.

Initial Recommendations from Pilot Study Construction

The three pilot projects should be monitored to evaluate long-term performance to determine if the factors assessed influence this parameter. Monitoring should include, but not be limited to, the following:

- Annual visual surveys to assess rutting, cracking, and any other distresses along with likely causes. The first assessment should include coring, dynamic cone penetrometer testing, and subbase/subgrade characterization to characterize the pavement structure and underlying materials.
- Annual or biannual falling weight deflectometer (FWD) testing, which should include a range of temperatures to determine any temperature sensitivity in the material.
- Biannual coring in conjunction with FWD testing to assess strength and stiffness changes in the PDR layer. Additional cores should be taken across any cracks to determine their origin, depth, and likely cause. Results should be used to update *CalME* performance models. If feasible, beams should be cut from the layer after two and five years to measure damage properties of the layer in the laboratory to provide additional performance parameters for *CalME* models.

This study highlighted the following issues and suggested changes within the PDR mix design and quality control procedures followed in these projects (CT 315). These changes have been discussed with the method owner at Caltrans Materials Engineering and Testing Services (METS):

- Different conditioning procedures are specified for testing Marshall stability on emulsified and foamed asphalt specimens. These procedures should be standardized to allow more direct comparisons of the two recycling agents in Marshall stability and ITS test results.
- The two compaction methods, Marshall (AASHTO T 245) and gyratory (AASHTO T 312), both produce specimens with bulk densities that exceed typical dry densities measured on compacted PDR layers. Marshall compaction generally produces specimens with a higher density than gyratory compaction. One specified compaction method should be standardized for mix design and quality control/quality assurance testing.
    - Gyratory compaction is recommended for mix design specimen preparation because the densities of specimens produced with this method are closer to (but still higher) than the densities that will be achieved on the project.
    - Gyratory or vibrating hammer compaction are recommended for specimen preparation for quality control testing, using the breakover densities achieved on the sample lot to determine the quantity of material added to the mold. Although following this procedure should produce strength and stability results that are representative of those on the project, they will typically be lower than the mix design results, given than mix design gyratory-determined densities will be higher than breakover densities, which typically results in higher strengths and stabilities.
- Tensile strength retained should not be used as a mix design or quality control procedure. Instead, minimum wet and minimum dry strengths should be required. The addition of supplemental aggregates tends to have a larger influence on dry strengths than on wet strengths. Although higher wet strengths are typically recorded, the larger difference between dry and wet strengths leads to lower retained strengths, which could result in unnecessarily high recycling agent and active filler contents to meet the retained strength requirements.

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LIST OF ABBREVIATIONS

AB	Aggregate base
AC	Asphalt concrete
AASHTO	American Association of State Highway and Transportation officials
ANOVA	Analysis of variance
ASTM	American Society for Testing Materials
Caltrans	California Department of Transportation
CAPM	Capital preventive maintenance
CCPR	Cold central plant recycling
CT	California Test
DCP	Dynamic cone penetrometer
DRISI	Division of Research, Innovation, and System Information
EA	Emulsified asphalt
FA	Foamed asphalt
FDR	Full-depth recycling
FHWA	Federal Highway Administration
FWD	Falling weight deflectometer
HVS	Heavy Vehicle Simulator
ITS	Indirect tensile strength
MAS	Maximum aggregate size
MDL	Maximum density line
METS	Caltrans Materials Engineering and Testing Services
NMAS	Nominal maximum aggregate size
PDR	Partial-depth recycling
PM	Post mile
PPRC	Partnered Pavement Research Center
RAP	Recycled asphalt pavement
RHMA-G	Gap-graded rubberized hot mix asphalt
SAMI	Stress absorbing membrane interlayer
SSE	Sum of the square of the error
TSR	Tensile strength retained
UCPRC	University of California Pavement Research Center

TEST METHODS CITED IN THE TEXT

AASHTO

T 11	Standard Method of Test for Materials Finer than 75-um (No. 200) Sieve in Mineral Aggregate by Washing
T 166	Standard Method of Test for Bulk Specific Gravity (G_{mb}) of Compacted Asphalt Mixtures Using Saturated Surface-Dry Specimens
T 209	Standard Method of Test for Theoretical Maximum Specific Gravity (G_{mm}) and Density of Asphalt Mixtures
T 245	Standard Method of Test for Resistance to Plastic Flow of Asphalt Mixtures Using Marshall Apparatus
T 27	Standard Method of Test for Sieve Analysis of Fine and Coarse Aggregates
T 283	Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage
T 312	Standard Method of Test for Preparing and Determining the Density of Asphalt Mixture Specimens by Means of the Superpave Gyratory Compactor

ASTM

E380	Standard Practice for Use of the International System of Units (SI)

CT

202	Method of Test for Sieve Analysis of Fine and Coarse Aggregates
216	Method of Test for Relative Compaction of Untreated and Treated Soils and Aggregates
226	Method of Test for Determination of Moisture Content of Soils and Aggregates by Oven Drying
231	Method of Test for Relative Compaction of Untreated and Treated Soils and Aggregates Using Nuclear Gages
315	Provisional Method of Test for Mixture Design and Testing of Partial Depth Recycling (PDR) of Asphalt Pavements Using Bituminous Recycling Agents and Additives - Expires 12/23/2023
375	Determining the In-Place Density and Relative Compaction of Hot Mix Asphalt Pavement Using Nuclear Gages

CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in.	Inches	25.40	millimeters	mm
ft.	Feet	0.3048	meters	m
yd.	Yards	0.9144	meters	m
mi.	Miles	1.609	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.09290	square meters	m^2
yd^2	square yards	0.8361	square meters	m^2
ac.	Acres	0.4047	hectares	ha
mi^2	square miles	2.590	square kilometers	km^2
		VOLUME		
fl. Oz.	fluid ounces	29.57	milliliters	mL
gal.	Gallons	3.785	liters	L
ft^3	cubic feet	0.02832	cubic meters	m^3
yd^3	cubic yards	0.7646	cubic meters	m^3
		MASS		
oz.	Ounces	28.35	grams	g
lb.	Pounds	0.4536	kilograms	kg
T	short tons (2000 pounds)	0.9072	metric tons	t
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	(F-32)/1.8	Celsius	°C
		FORCE and PRESSURE or STRESS		
lbf	pound-force	4.448	newtons	N
lbf/in^2	pound-force per square inch	6.895	kilopascals	kPa
		APPROXIMATE CONVERSIONS FROM SI UNITS		
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.03937	inches	in.
m	Meters	3.281	feet	ft.
m	Meters	1.094	yards	yd.
km	Kilometers	0.6214	miles	mi.
		AREA		
mm^2	square millimeters	0.001550	square inches	in^2
m^2	square meters	10.76	square feet	ft^2
m^2	square meters	1.196	square yards	yd^2
ha	Hectares	2.471	acres	ac.
Km^2	square kilometers	0.3861	square miles	mi^2
		VOLUME		
mL	Milliliters	0.03381	fluid ounces	fl. Oz.
L	Liters	0.2642	gallons	gal.
m^3	cubic meters	35.31	cubic feet	ft^3
m^3	cubic meters	1.308	cubic yards	yd^3
		MASS		
g	Grams	0.03527	ounces	oz.
kg	Kilograms	2.205	pounds	lb.
t	metric tons	1.102	short tons (2000 pounds)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C + 32	Fahrenheit	°F
		FORCE and PRESSURE or STRESS		
N	Newtons	0.2248	pound-force	lbf
kPa	Kilopascals	0.1450	pound-force per square inch	lbf/in^2

* SI is the abbreviation for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised April 2021)

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1 INTRODUCTION

1.1 Background

Partial-depth recycling (PDR) has been widely used in California as a maintenance strategy to address top-down distresses in asphalt concrete surface layers. It is a cost-effective method, with potential lower environmental impacts, to perform maintenance on pavements with surficial distresses. PDR, when done correctly, can remove existing distresses from the pavement.

PDR is a process where the top distressed asphalt layers of a pavement are recycled in place to a depth of between 0.25 and 0.45 ft. (75 and 135 mm). Emulsified or foamed asphalt is used as the recycling agent in combination with an active filler (usually cement in California). The recycled material is spread with a paver and compacted. An asphalt concrete (AC) overlay is paved on the PDR as a wearing course.

Two methods of performing PDR are currently used in California, using either single-unit or multi-unit recycling trains. A single-unit train consists of a recycling machine that pulverizes the old asphalt concrete, injects water and recycling agent, and mixes pre-spread active fillers with the recycled asphalt pavement (RAP) before feeding the homogenous mix to a paver in a windrow or by belt feed. Multi-unit trains typically consist of a milling machine that feeds a towed processing plant that screens the milled material, crushes any oversized, injects the recycling agent, and mixes all materials (including pre-spread active filler), before depositing it in a windrow ahead of a paver that spreads it.

The benefits of single-unit trains include better maneuverability and less material handling that can cause variability in gradations. However, single-unit trains can only control maximum aggregate size (MAS) by adjusting forward speed. The benefits of multi-unit trains include the ability to screen materials (including oversized and chunks of rubberized asphalt and fabrics) and to control maximum aggregate size. Forward speed may still need to be controlled by the screening and crushing processes.

The two recycling agents used in PDR are emulsified and foamed asphalt. Emulsified asphalt tends to coat the recycled particles and cement them together, while foamed asphalt tends to “spot-weld” fines into a mastic that binds larger uncoated particles together. They provide similar long-term performance, and the choice of which to use is usually based on experience, preference, and/or cost. Cement is the only type of active filler currently specified in California and is typically added at a ratio of 2.5:1 recycling agent to active filler.

One concern with PDR is the coarse gradation produced by the recycling processes. The RAP millings typically have low percentages of intermediate material (passing the #4 [4.75 mm] sieve) and little to no fines (i.e., passing the #200 [0.75 mm] sieve). Although reducing forward speed will control oversize material, slowing recycling trains has little effect on the intermediate and fine portions. Coarse gradations typically result in high air-void contents and lower densities in the compacted layer, which can lead to densification/rutting, moisture sensitivity, and overall lower pavement strengths and stiffnesses.

1.2 Study Objective

The work discussed in this report is part of a larger study on cold recycling of pavements with the objective of updating guidance and mechanistic-empirical design procedures for cold recycling. Task 1 of this larger project includes continued long-term monitoring of existing and new field cold recycling pilot projects to assess stiffness, cracking, rutting/densification, freeze-thaw, moisture sensitivity, and other observed distresses. The effects of rubberized hot mix asphalt and fabrics in the recycled layer will be assessed where possible. Pilot studies to assess the potential benefits of adding supplemental fines in PDR projects and to compare emulsified and foamed asphalt recycling agents and single- and multi-unit recycling trains on the same project will also be motivated and assessed. Rapid quality control/quality assurance tests developed during the NCHRP 9-62 project will be assessed on selected construction projects.

1.3 Pilot Project Proposals

Three PDR pilot projects were proposed by contractors to evaluate adding supplemental aggregates to improve material gradation and thereby compaction densities, to compare gradations produced with single- and multi-unit recycling trains, to compare the effect of recycling train forward speed on gradations, and to compare layer properties and performance where both emulsified and foamed asphalt recycling agents were used. The three pilot projects discussed in this report include the following:

- GLE-162: Assessment of addition of supplemental aggregates to improve gradation and thereby compaction density, strength, and potentially layer stiffness. Two supplemental aggregate types were considered: Class 2 aggregate base and rock dust passing a #4 (4.75 mm) sieve. Foamed asphalt was used as the recycling agent. The target maximum aggregate size was 1.25 in. (32 mm), which was controlled by the forward speed of the single-unit train.
- SB-135: Comparison of single- and multi-unit trains, with forward speeds on both trains adjusted to control the target maximum aggregate size 1.25 in. Emulsified and foamed asphalt recycling agents were also compared.
- SBD-2: Comparison of single- and multi-unit trains to achieve three different target maximum aggregate sizes (1.25, 1.0, and 0.75 in.). Emulsified asphalt was specified for the recycling agent.

Project details are summarized in Table 1.1.

Table 1.1: Pilot Project Summary

Pilot Study	EA Number	Road	Post Miles	Length (mi.)	Construction Dates	Equipment	Recycling Agents	Recycling Depth (ft.)
Supplemental aggregates	03-2G1104	GLE-162	67.20-76.67	9.47	07/21/2021 - 07/30/2021	Single-unit	Foamed asphalt	0.25
Equipment and recycling agent	05-1N1704	SB-135	1.00-7.23	6.23	08/23/2021-09/03/2021	Single- and multi-unit	Foamed & emulsified asphalt	0.25
Equipment and gradation	08-1L6604	SBD-2	3.27-5.90	2.63	08/25/2021-09/02/2021	Single- and multi-unit	Emulsified asphalt	0.25

1.4 Monitoring Program

The UCPRC was involved in the construction phase of the pilot projects in the following capacities:

- Provided guidance on determining the blending ratios that were used on the GLE-162 project.
- Performed FWD testing prior to construction on all three projects.
- Monitored the construction of the PDR layers on all three projects.
- Collected untreated millings produced by the different recycling trains and forward speeds during construction on each project for laboratory testing.
- Collected and analyzed mix design and quality control testing results from the contractors, which will serve as a baseline for future evaluations of the projects.

Long-term performance of the three projects will be evaluated if funding is available. These evaluations will include:

- Annual visual surveys to assess rutting, cracking, and any other distresses along with likely causes. The first assessment should include coring, dynamic cone penetrometer (DCP) testing, and subbase/subgrade characterization to characterize the pavement structure and underlying materials and to determine a baseline stiffness.
- Annual or biannual FWD testing, which should include a range of temperatures to determine any temperature sensitivity in the material.
- Biannual coring in conjunction with FWD testing to assess strength and stiffness changes in the PDR layer. Additional cores should be taken across any cracks to determine the origin, depth, and likely cause. Results should be used to update *CalME* performance models. If feasible, beams should be cut from the layer after two and five years to measure additional damage properties of the layer in the laboratory to provide an additional performance parameter for *CalME* models.

1.5 Measurement Units

Although Caltrans has returned to the use of US standard measurement units, metric units have always been used by the UCPRC in the design and layout of test tracks, laboratory and accelerated wheel load testing, field measurements, and data storage. In this report, both English and metric units (provided in parentheses after the English units) are provided in general discussion. A conversion table is provided on page xix at the beginning of this report.

2 GLE-162 (EA 03-2G114): SUPPLEMENTAL AGGREGATE STUDY

2.1 Project Description

This project is located on GLE-162, east of Willows, between post mile (PM) 67.2 and PM 76.2. The project showed extensive crack sealing, signs of regular interval alligator B (Figure 2.1) and alligator C cracking (Figure 2.2), pumping (Figure 2.3), and wheel path rutting (Figure 2.4). Construction of the PDR layer took place between 07/19/2021 and 07/30/2021.

Figure 2.1: GLE-162: Alligator B cracking.

Figure 2.2: GLE-162: Alligator C cracking.

Figure 2.3: GLE-162: Pumping of fines through unsealed cracks.

Figure 2.4: GLE-162: Wheelpath rutting.

2.2 Pavement Structure

The structural pavement investigation was limited to cores and dynamic cone penetrometer (DCP) tests. The assumed pavement structure at the time of investigation is illustrated in Figure 2.5. The pavement had a thin (0.1 ft. [30 mm]) gap-graded rubberized asphalt concrete

(RHMA-G) overlay (Figure 2.6) over dense-graded asphalt concrete that ranged in thickness from 0.1 to 0.7 ft. (30 to 210 mm) (Figure 2.7), with an average thickness of 0.4 ft. (120 mm) (Figure 2.8). Deteriorated asphalt-treated base (Figure 2.9) was present below the thinner cores, to a depth of about 0.7 ft. (210 mm).

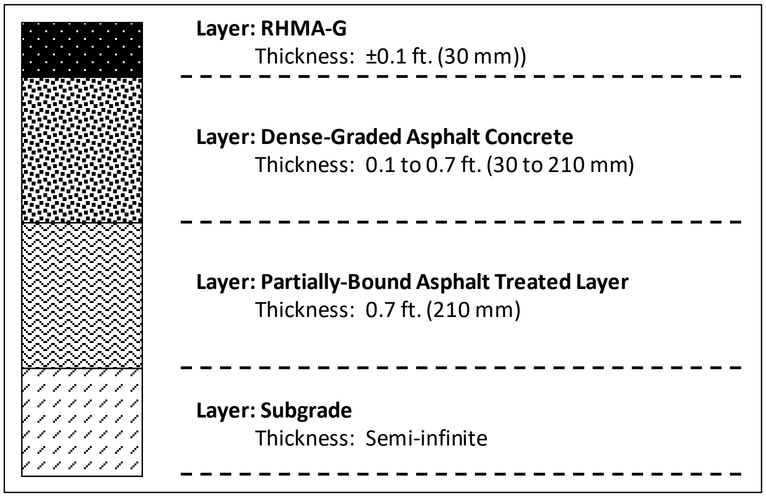

Figure 2.5: GLE-162: Assumed pavement structure from limited coring and DCP testing.

Figure 2.6: GLE-162: Core from RHMA-G overlay.

Figure 2.7: GLE-162: Core from thicker section with multiple asphalt concrete layers.

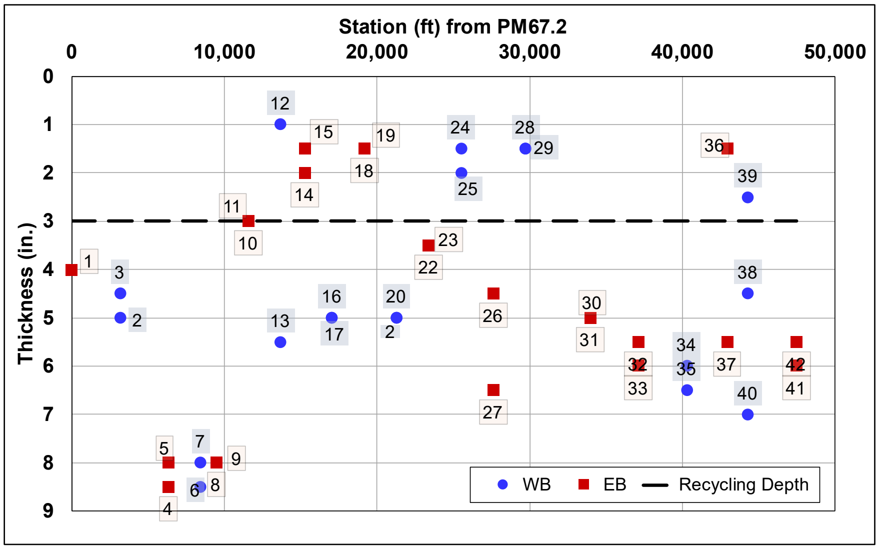

Figure 2.8: GLE-162: Asphalt concrete thickness along the project from core data.

Figure 2.9: GLE-162: Unbound asphalt-treated base material.

DCP testing was done between PM 74.26 and PM 75.46 through 1 in. (25 mm) holes drilled with a rotary hammer drill to depths between 7 and 14 in. (180 and 355 mm). The results are plotted in Figure 2.10 and Figure 2.11. The DCP testing indicated the presence of a stiff layer down to about 1.3 ft. (390 mm) based on the low DCP penetration rate between 0.7 and 1.3 ft. (210 and 390 mm). The stiff layer was directly on the subgrade.

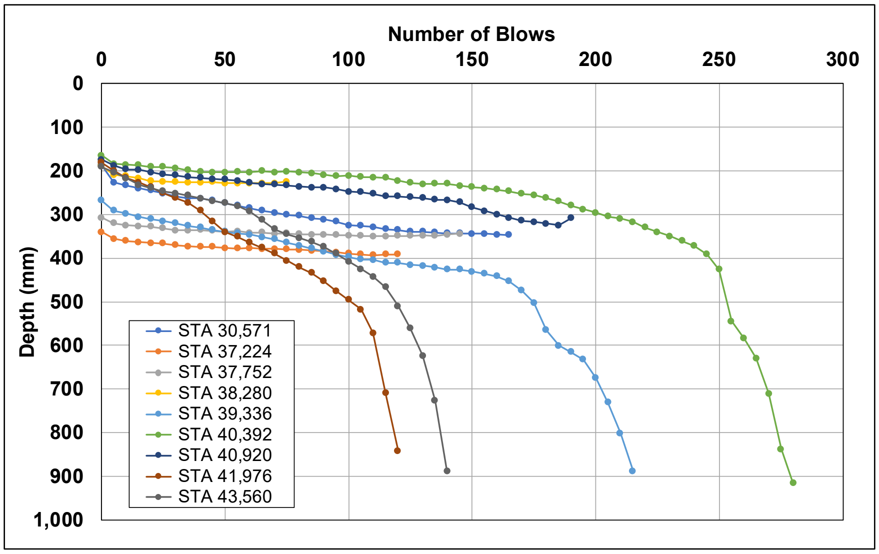

Figure 2.10: GLE-162: DCP plots between station 30,500 and 43,500.

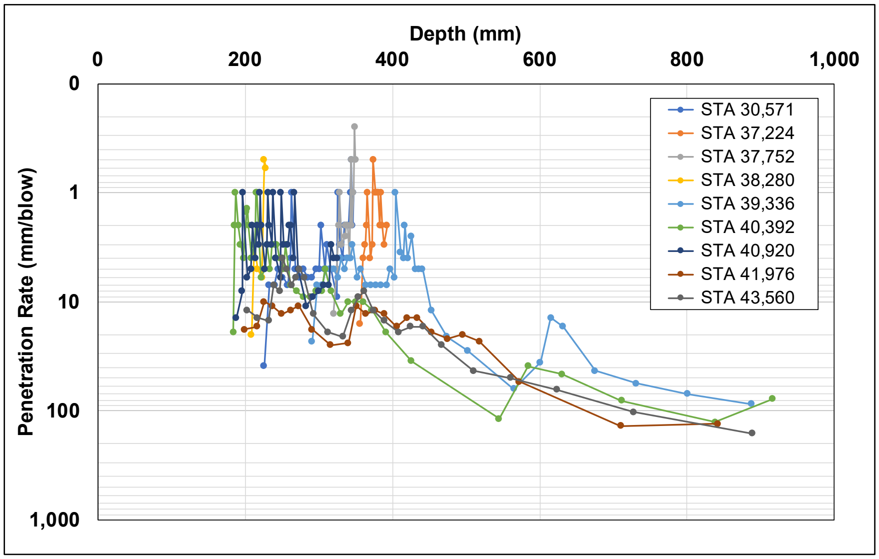

Figure 2.11: GLE-162: DCP penetration rates.

A 0.25 ft. (75 mm) recycling depth was specified for the project.

2.3 Pilot Study Experimental Design

The aim of this experiment was to investigate whether modifications to PDR gradations by addition of supplemental aggregates will improve the performance of the rehabilitated pavement through improved compaction and lower air voids. To facilitate this experiment, the following needed to be addressed:

- Locate sources of suitable supplemental material close to the project.

- Establish a baseline gradation produced by the recycling machine that could be used to determine optimal blends.
- Select a blending ratio between the RAP and supplemental aggregates.

2.3.1 Blending Ratios

No guidance was found in the literature for blending supplemental aggregates in PDR projects. The Virginia Department of Transportation recently supplemented the gradation in a cold central plant recycling (CCPR) project with 15% quarry by-products passing the #10 (2 mm) sieve *(1)*, but no information was provided on the method used to determine this blend. The specifications for this project provided guidance on the mix design gradation, but only stipulated a maximum aggregate size (MAS) of 1.25 in. (31 mm) for the material produced during recycling.

Gradation control on PDR projects is often difficult because of the inherent variability of the existing layers along the length of the project. Other factors that influence gradation of the PDR layer include the type of recycling train used, milling drum configuration, forward speed, pavement temperature, patches, digouts, and other changes in asphalt concrete materials due to factors such as maintenance and the presence of rubberized layers. The ability to select the gradation of the supplemental aggregates may be limited to what is available at nearby sources.

The contractor identified two supplemental aggregate types for this project from the Knife River Quarry in Orland, 25 miles (40 km) from the project. These materials were rock dust passing a 0.25 in. (6.7 mm) sieve and Class 2 aggregate base (AB). The gradations of the rock dust and aggregate base are plotted in Figure 2.12. Using rock dust was proposed as a means of increasing the fine portion of the blended gradation, which would likely have the largest impact on material property improvement. The aggregate base material was selected based on the contractor's past experience with incorporating similar materials to improve gradation on a previous PDR project. The RAP gradation in Figure 2.12, used in determining the blends, was based on previous PDR projects, since gradations from this project were not available at the time of this analysis.

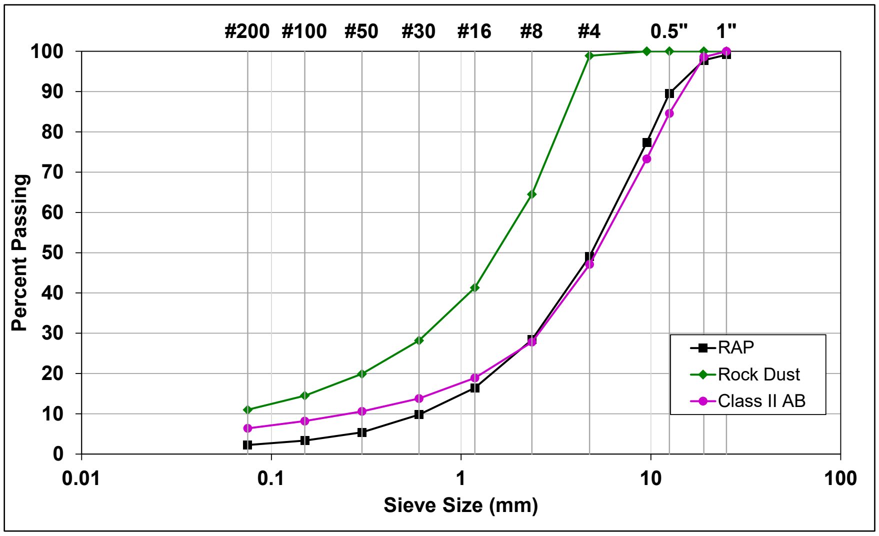

Figure 2.12: GLE-162: Blend selection gradations.

The methodology for determining the blending ratio of RAP to supplemental material was based on the optimization of the 0.45 power maximum density line (MDL) using the Fuller and Thompson Equation (Equation 2.1), with *n* adjusted to 0.45 based on a Federal Highway Administration (FHWA) recommendation *(2)*. Theoretical blends of material with incrementally different ratios were assessed in a desktop study. A corresponding maximum aggregate size for each ratio of blended material was calculated to compare the specific gradation to the appropriate maximum density line. The sum of the square of the error (SSE) between the blend and the corresponding maximum density line was calculated for each ratio. The ratio with the lowest SSE was selected as the blend that would produce the highest density.

$$P = \left({}^{d}\!/_{D}\right)^{n} \tag{2.1}$$

Where:

P = % finer than the sieve
d = aggregate size considered
D = maximum aggregate size
n = 0.45

The maximum aggregate size (D) used in Equation 2.1 in this study was based on the Superpave definition for this parameter, which is the standard sieve size larger than the nominal maximum aggregate size (NMAS). The NMAS is defined as one standard size larger than the first sieve to retain more than 10% of the material.

The family of blended gradations for the RAP with rock dust and RAP with aggregate base are provided in Figure 2.13 and Figure 2.14, respectively. The change in MAS and NMAS with the different blend ratios of the RAP with rock dust are provided in Table 2.1. The MAS of the RAP with aggregate was 1.0 in. and did not change as the proportion of aggregate base increased. The SSE values are provided in Figure 2.15 for the two blends. The RAP/rock dust blend produced two local minima where the density could be optimized: a ratio of 80% RAP and 20% rock dust to produce a 0.75 in. MAS gradation, and 44% RAP with 56% rock dust to produce a 0.5 in. MAS gradation. Reducing the target MAS below 1.25 in. was not considered due to the reduction in strength as the MAS reduces and difficulty with consistently producing a smaller MAS with a recycling train. The group of RAP/AB blends did not provide an optimal blend ratio, but density increased with increasing amounts of aggregate base, with the maximum density achieved with 100% aggregate base and no RAP. The final ratios were based on being able to import the lowest percentage of supplemental aggregates that would maximize the density. The final blending ratios selected for the pilot study were 75% RAP with 25% rock dust, and 50% RAP with 50% aggregate base.

Table 2.1: GLE-162: Changes in Nominal Maximum Aggregate Size of Rock Dust Blends

Blend Ratio (RAP/Rock Dust)	Maximum Aggregate Size		Nominal Maximum Aggregate Size	
	(in.)	(mm)	(in.)	(mm)
0/100	0.38	9.5	#4	4.75
20/80	0.5	12.5	0.38	9.5
30/70	0.5	12.5	0.38	9.5
40/60	0.5	12.5	0.38	9.5
50/50	0.75	19.0	0.5	12.5
60/40	0.75	19.0	0.5	12.5
70/30	0.75	19.0	0.5	12.5
75/25	0.75	19.0	0.5	12.5
80/20	0.75	19.0	0.5	12.5
90/10	0.75	19.0	0.5	12.5
100/0	1.0	25.0	0.75	19.0

2.3.2 Section Locations

The contractor allocated four 0.5 mile (0.8 km) long sections for the pilot study. These sections were in the westbound lane and were distributed to allow for control sections in the same lane between the experimental sections (Figure 2.16). This allowed for comparison of experimental and standard practice on similar materials and pavement structure.

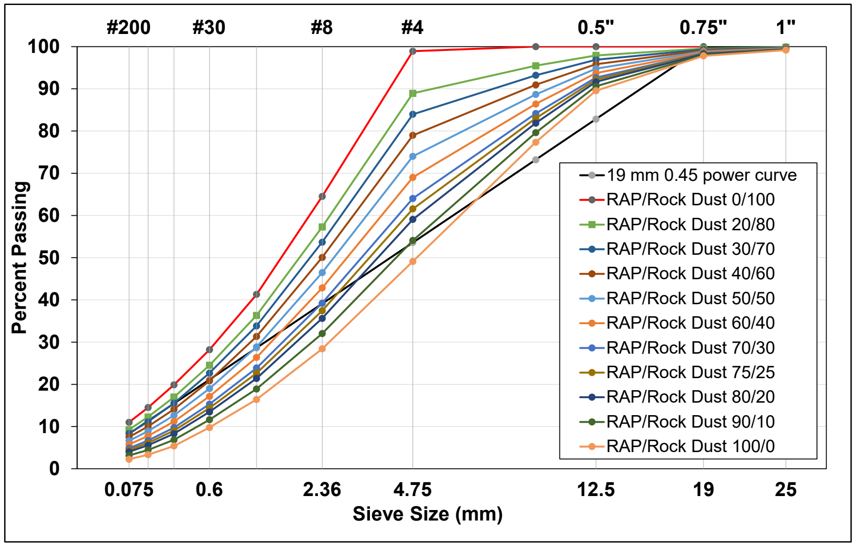

Figure 2.13: GLE-162: Family of rock dust with RAP gradations (0.75 in. MDL reference).

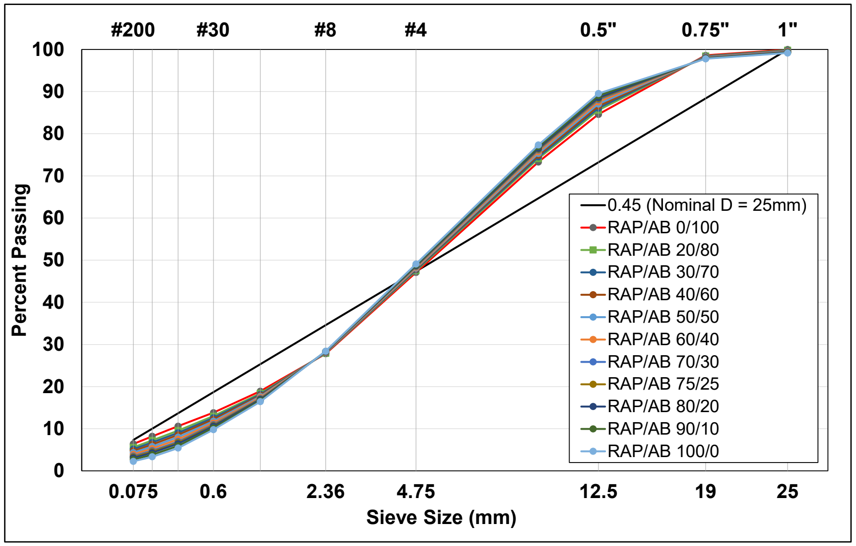

Figure 2.14: GLE-162: Family of aggregate base with RAP gradations (1.0 in. MDL reference).

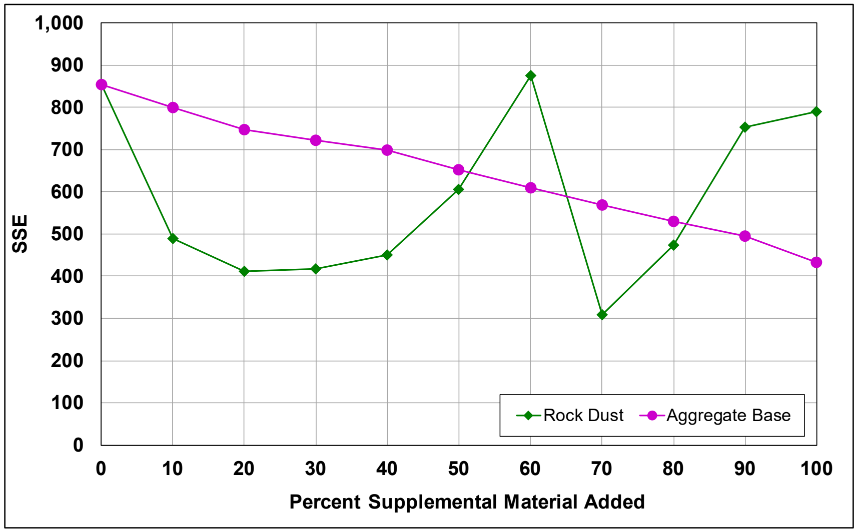

Figure 2.15: GLE-162: SSE of different ratios of RAP with supplemental aggregates.

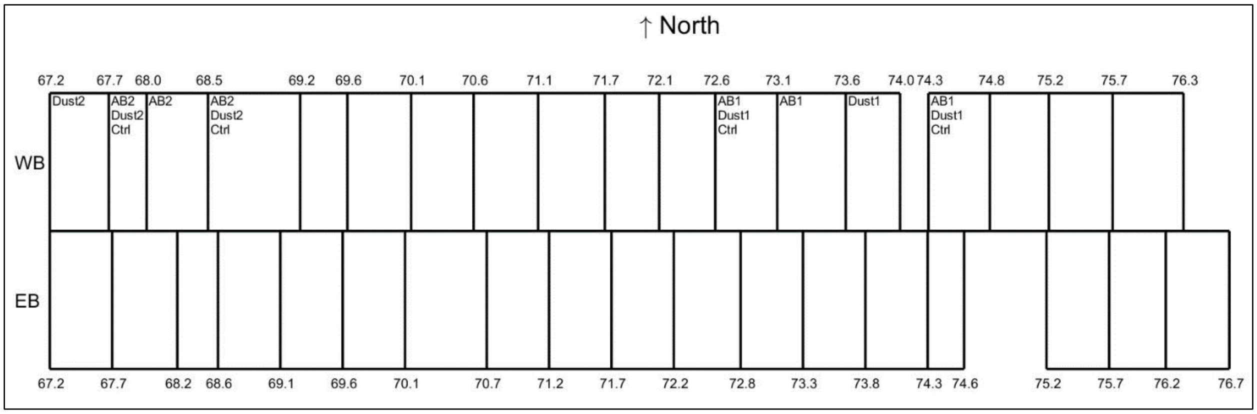

Figure 2.16: GLE-162: As-built lot layout showing experimental sections.

2.4 Mix Design

The mix designs were performed following CT 315. The RAP gradation was produced by crushing cores sampled from the project. Supplemental aggregates were sampled from stockpiles at the Knife River Quarry. The RAP gradation, 75% RAP with 25% rock dust blend, and the 50% RAP with 50% aggregate base blend are plotted in Figure 2.17.

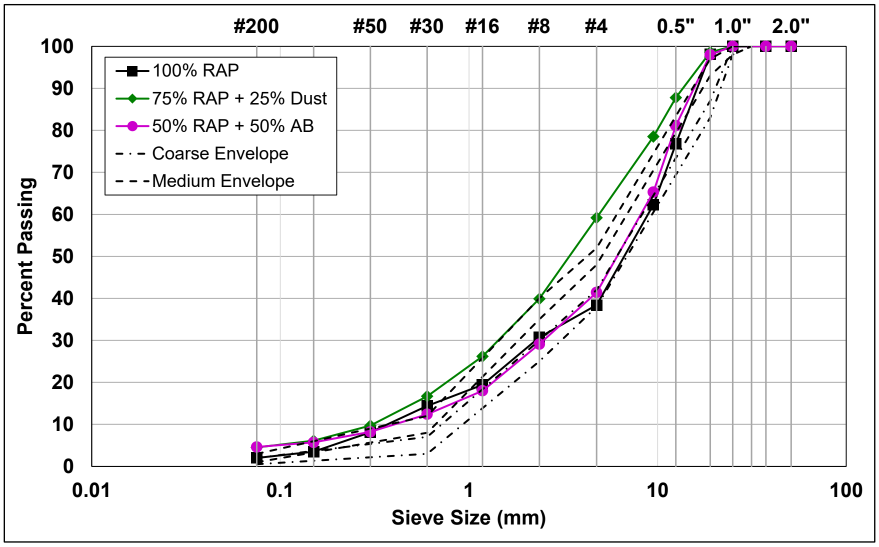

Figure 2.17: GLE-162: Gradations used in the mix design.

The RAP gradation was tested as-crushed and was not sieved and reconstituted to conform with the recommended coarse or medium gradations listed in CT 315. However, the RAP gradation plotted between the upper limit of the medium gradation and the lower limit of the coarse gradation. The optimum moisture content was determined using Marshall compaction

(AASHTO T 245). Marshall compaction was also used to prepare the indirect tensile strength (ITS) and Marshall stability specimens.

The mix design results are summarized in Table 2.2 and show that 2.5% foamed asphalt with 1.0% cement using this compaction method satisfied the 35 psi (240 kPa) minimum limit for wet ITS for the different materials. Compacted specimens had average air-void contents of 2.3%, 4.2%, and 6.3% for the 100% RAP, 75% RAP with 25% rock dust blend, and 50% RAP with 50% aggregate base blend, respectively. The CT 216 tests performed on the different materials showed that the RAP with rock dust had a density 4.7% greater than the 100% RAP, while the RAP with aggregate base only had a 1.0% increase in density compared to the 100% RAP.

Table 2.2: GLE-162: Mix Design Results

Parameter	Design			
	PDR	75% RAP+ 25% Rock Dust	50% RAP+ 50% AB	Specification
Foamed asphalt content (%)	2.5	2.5	2.5	n/a
Cement content (%)	1.0	1.0	1.0	n/a
Optimum moisture content (%)	4.0	4.0	4.0	n/a
CT 216 density (pcf) [g/cm^3]	126.9 (2.033)	132.9 (2.129)	127.9 (2.049)	n/a
Specimen compaction method	AASHTO T 245	AASHTO T 245	AASHTO T 245	n/a
Specific gravity (AASHTO T 209)	2.268	2.380	2.474	n/a
Bulk density (pcf) [g/cm^3]	138.3 (2.215)	142.3 (2.280)	144.5 (2.315)	n/a
Average air-void content (%)	2.0	4.0	6.3	n/a
Average dry ITS (psi) [kPa]	60.3 (416)	57.0 (393)	67.0 (462)	n/a
Average wet ITS (psi) [kPa]	52.3 (361)	42.0 (290)	53.0 (365)	>35 (240)
Tensile strength retained (%)	86.7	73.7	79.1	>70
Dry stability at 104°F (lbf) [kN]	Not reported	Not reported	Not reported	Report only
Wet stability (lbf) [kN]	1,612 (7.2)	3,051 (13.6)	3,547 (15.8)	Report only
Retained stability (%)	Not reported	Not reported	Not reported	Report only

2.5 Construction

The PDR layer construction was monitored by the UCPRC from 07/26/2021 to 07/28/2021. The construction sequence was typical of PDR projects and consisted of the following:

- Cement was distributed in front of the recycling train.
- The recycler recycled the pavement and mixed the RAP with recycling agent and cement and water.
- The mixed material was windrowed behind the recycling train.
- The windrowed material was collected by a pickup machine and fed into a paver that spread the material.

- Three rollers were used to compact the PDR layer, including a breakdown roller, pneumatic-tired roller, and finish roller.
- The compacted mat was fog sealed followed by spreading of sand.
- Temporary lines were painted on the surface.
- The processed section was opened to traffic at the end of the day.

The change to the construction methodology for the experimental sections occurred mainly in front of the recycling train:

- The experimental sections were pre-milled with a 12 ft. (3.7 m) wide milling machine (0.75 in. [19 mm] deep for the rock dust sections, and 1.5 in. [38 mm] deep for the aggregate base sections) (Figure 2.18).
- Supplemental aggregates were imported, and end-dumped into a paver to pave the supplemental aggregates in the pre-milled areas (Figure 2.19).
- The recycling train then proceeded to recycle the layer as discussed above.

Figure 2.18: GLE-162: Pre-milling in front of the recycling train.

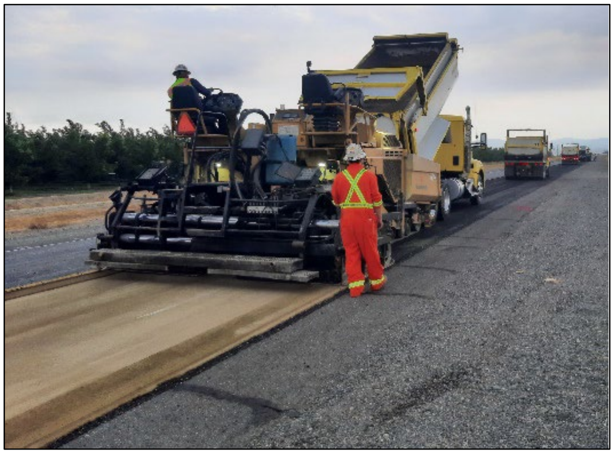

Figure 2.19: GLE-162: Paving supplemental rock dust material.

Design placement thicknesses for the supplemental aggregates were met except on the first rock dust section, where the first approximately 100 ft. (30 m) was paved to a thickness of 1.0 in. (25 mm) instead of the design 0.75 in (19 mm). This was left in place with start and end points noted for further monitoring.

The construction schedule is provided in Table 2.3.

Table 2.3: GLE-162: Construction Schedule

Eastbound					Westbound				
Lot	**Date**	**Factorial**	**Start**	**End**	**Lot**	**Date**	**Factorial**	**Start**	**End**
1	7/19/21	PDR	67.22	67.72	19	7/23/21	PDR	76.31	75.74
2			67.72	68.24	20	7/26/21		75.74	75.23
3			68.24	68.57	21			75.23	74.76
4	7/20/21		68.57	69.07	22		PDR (Control for Dust1 & AB1)	74.76	74.27
5			69.07	69.57	23	7/27/21	Dust1[a]	74.04	73.60
6			69.57	70.07	24		AB1[b]	73.60	73.05
7			70.07	70.72	25		PDR (Control for Dust1 & AB1)	73.05	72.56
8	7/21/21		70.72	71.22	26		PDR	72.56	72.11
9			71.22	71.72	27	7/28/21	PDR	72.11	71.67
10			71.72	72.22	28	7/29/21	PDR	71.67	71.14
11			72.22	72.76	29			71.14	70.62
12	7/22/2021		72.76	73.26	30			70.62	70.12
13			73.26	73.76	31			70.12	69.61
14			73.76	74.26	32			69.61	69.23
15			74.26	74.55	33	7/30/21	PDR (Control for Dust2 & AB2)	69.23	68.49
16	7/23/21		75.21	75.71	34		AB2[b]	68.49	68.00
17			75.71	76.17	35		PDR (Control for Dust2 & AB2)	68.00	67.69
18			76.17	76.68	36		Dust2[b]	67.69	67.22

[a] 75% RAP + 25% rock dust [b] 50% RAP + 50% AB

Observations during construction related to the pilot study included the following:

- The forward speed of the recycler varied between 19.7 and 29.5 fpm (6.0 and 9.0 m/min) (Figure 2.20).
- Some large oversize material (>2.0 in. [50 mm]) was present in the windrow behind the recycler (Figure 2.21).
- The material gradation appeared to get coarser during the day as the pavement temperature increased and the forward speed changed.
- Segregation was evident in the PDR layer along the centerline of the lane attributed to problems with the paver (Figure 2.22).

Figure 2.20: GLE-162: Recycler control box display during recycling.

Figure 2.21: GLE-162: Coarse material in windrow.

Figure 2.22: GLE-162: Segregation along centerline of lane behind paver.

- The rubberized layer did not recycle well and tended to break into chunks, especially as the pavement temperature increased.

The production parameters reported by the contractor using recordings from the recycler control box at the start of each day are summarized in Table 2.4. Reported speeds were generally lower than those observed. Mixing water used during construction was, on average, 3.3% higher than the mix design optimum moisture content. Mixing water is typically adjusted during construction based on the in situ moisture content and on how well the layer is compacting. The recycling agent and foaming water are often adjusted to account for variability in the materials.

Table 2.4: GLE-162: Reported Recycler Control Box Project Summary

Parameter	Minimum	Average	Maximum
Forward speed (fpm) (m/min)	12.1 (3.7)	13.5 (4.1)	15.7 (4.8)
Mixing water (%)	6.6	7.3	8.0
Recycling agent (%)	2.4	2.5	2.8
Foaming water (%)	2.6	2.9	3.0

2.6 Quality Control Test Results and Analysis

A summary of the quality control test results provided by the contractor are summarized in Table 2.5. Figure 2.23 provides a visual layout of where the tests were performed and what samples were collected for testing.

Variability in the quality control data were expected and, consequently, analyses were undertaken to determine if the differences in means were significant using either analyses of variance (ANOVA) or a t-test, depending on the number of variables. The means were then compared, grouped, and ranked using a pairwise comparison of the means method (Tukey's test) to determine if the means were statistically equivalent.

Table 2.5: GLE-162: Quality Control Data Collected During Construction

Description	Test Method	Minimum Test Frequency
Compacted field density	CT 231	2 tests per lot
Reference density	CT 216	1 test per lot
Coarse sieve analysis on mixed material	CT 202	1 per day
Maximum theoretical density	AASHTO T 209	1 per day
Bulk specific gravity of compacted samples	AASHTO T 166	1 per lot
Wet/dry gradations on clean RAP	AASHTO T27/T11	1 per day
Indirect tensile strength on mixed material	AASHTO T 283	1 per lot
Moisture content	CT 226	2 per lot

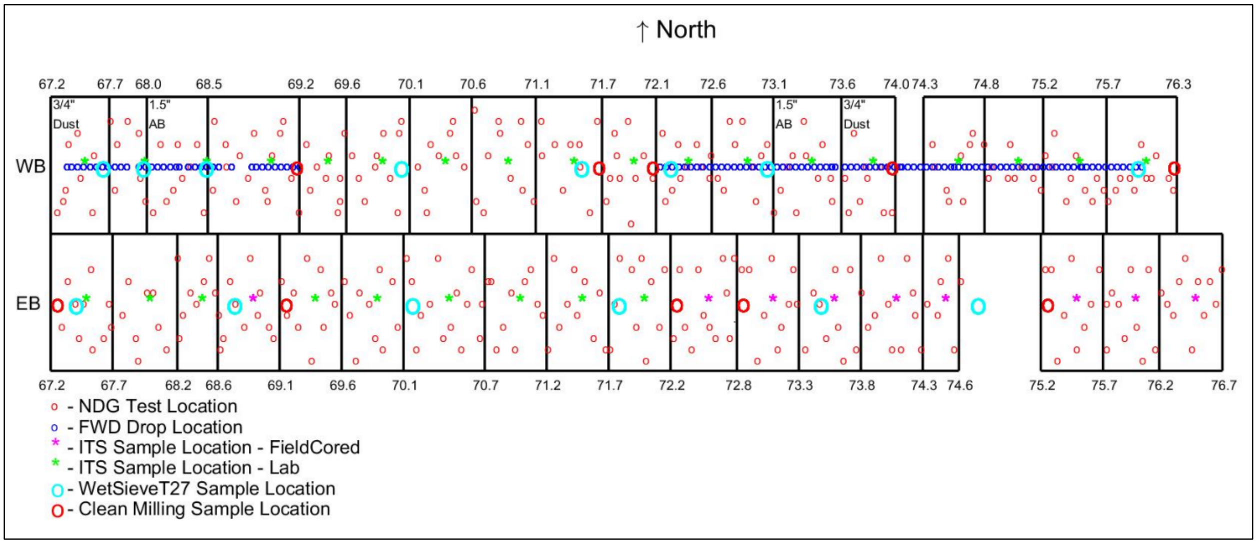

Figure 2.23: GLE-162: Quality control and research testing locations.

In the ANOVA, the null hypothesis was that the means of the different variables were equal, and the alternate hypothesis was that the means were not all equal. In the t-test, the null hypothesis was that the difference in group means was zero, and the alternate hypothesis was that the difference was not zero. Tukey's test determines which means are statistically equivalent and assigns a letter to equivalent groups; means with the same letter are not significantly different at a confidence level of 95% (α = 0.05).

2.6.1 In-Place Wet Density and Relative Compaction

Quality Control Test Results

In-place wet density was measured with a nuclear density gauge following CT 231. The reference density was determined according to CT 216. Results are plotted in Figure 2.24 as measured over the length of the project. The control result represents the PDR layer with no supplemental aggregates. The in-place densities of the PDR layer, with no supplemental aggregates, ranged between 118.1 and 138.7 pcf. (1,892 and 2,222 kg/m^3), with a project average of 125.0 pcf (2,002 kg/m^3) and a standard deviation of 3.5 pcf (56 kg/m^3). The experimental lots with supplemental aggregates had overall higher densities than the adjacent control sections with no supplemental aggregates.

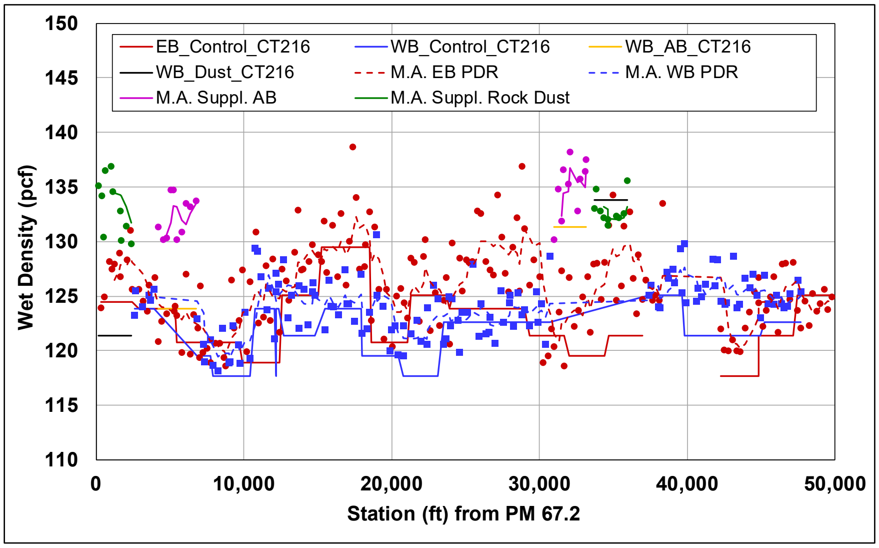

Figure 2.24: GLE-162: Wet density test results.

Table 2.6 and Figure 2.25 summarize the wet densities for the different sections. The results show that the in-place wet densities in the experimental lots were higher than those in the control lots. The lots with rock dust had average density increases of 6.6% over the untreated lots, and the lots with AB had increases of 8.4%, with corresponding decreases in air-void content. The CT 216 results on the second set of experimental lots were much lower than the first set of lots and were similar to the control section densities. The reasons for this are not clear, but it could have been the result of unrepresentative samples or faster recycling speeds in these locations.

Table 2.6: GLE-162: Compaction Results (US units)

Factorial	CTM 231 (pcf)			CTM 216 (pcf)			Percent Compaction		Void Ratio (%)		
	Average	Std. Dev	% Change	Average	Std. Dev	% Change	Average	Std. Dev	Average	Std. Dev	% Change
EB_PDR	125.8	3.9	—	122.7	3.0	—	102.5	3.0	16.3	2.6	—
WB_PDR	124.1	2.6	—	121.7	2.2	—	102.0	2.1	15.3	2.1	—
Dust1	132.9	1.3	6.3	133.8	0.0	8.0	99.3	1.0	13.7	0.8	0.1
Dust1_Ctrl	125.0	2.2		123.9	1.3		100.9	1.6	13.7	1.6	
Dust2	133.2	2.7	9.5	121.4	0.0	1.2	109.7	2.2	14.2	1.7	-18.4
Dust2_Ctrl	121.6	2.6		119.9	2.8		101.5	1.4	17.5	1.1	
AB1	134.9	2.6	8.0	131.3	0.0	6.0	102.8	2.0	13.3	1.6	-2.9
AB1_Ctrl	125.0	2.2		123.9	1.3		100.9	1.6	13.7	1.6	
AB2	132.3	1.9	8.7	123.9	0.0	3.3	106.8	1.5	11.7	1.2	-32.9
AB2_Ctrl	121.6	2.6		119.9	2.8		101.5	1.4	17.5	1.1	

Table 2.6: GLE-162: Compaction Results (metric units)

Factorial	CTM 231 (kg/m^3)			CTM 216 (kg/m^3)			Percent Compaction		Void Ratio (%)		
	Average	Std. Dev	% Change	Average	Std. Dev	% Change	Average	Std. Dev	Average	Std. Dev	% Change
EB_PDR	2,015	62	—	1,965	48	—	102.5	3.0	16.3	2.6	—
WB_PDR	1,988	42	—	1,949	35	—	102.0	2.1	15.3	2.1	—
Dust1	2,129	21	6.3	2,143	0	8.0	99.3	1.0	13.7	0.8	0.1
Dust1_Ctrl	2,002	35		1,985	21		100.9	1.6	13.7	1.6	
Dust2	2,134	43	9.5	1,945	0	1.2	109.7	2.2	14.2	1.7	-18.4
Dust2_Ctrl	1,948	42		1,921	45		101.5	1.4	17.5	1.1	
AB1	2,161	42	8.0	2,103	0	6.0	102.8	2.0	13.3	1.6	-2.9
AB1_Ctrl	2,002	35		1,985	21		100.9	1.6	13.7	1.6	
AB2	2,119	30	8.7	1,985	0	3.3	106.8	1.5	11.7	1.2	-32.9
AB2_Ctrl	1,948	42		1,921	45		101.5	1.4	17.5	1.1	

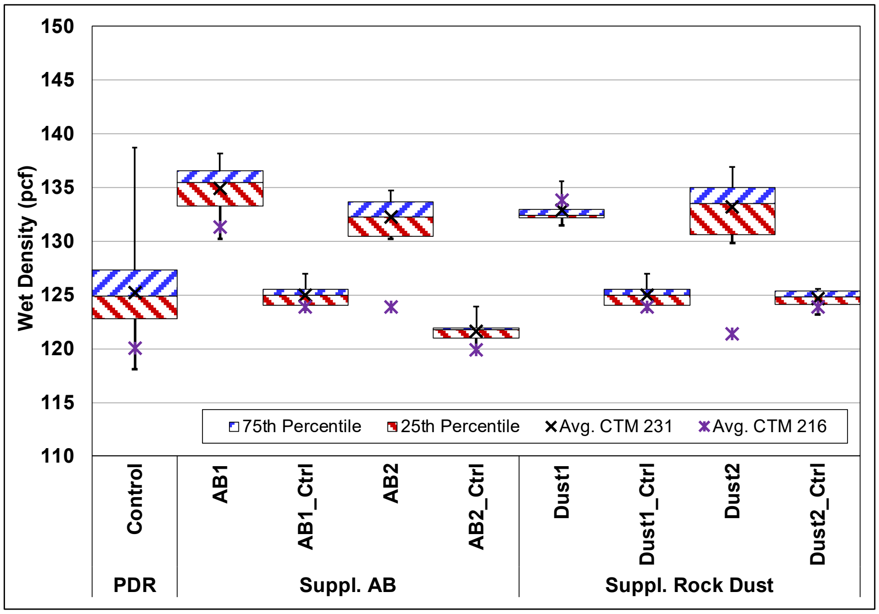

Figure 2.25: GLE-162: Box and whisker plot of wet density test results.

Analysis

In-place wet densities were analyzed to determine if the addition of supplemental aggregates had a significant effect on density. The ANOVA (Table 2.7) of the density results shows that adding supplemental aggregates had a significant effect, and that the means of the different groups were not all equal. The Tukey's test results in Table 2.8 indicate the following:

- There was no difference between the lots with supplemental aggregates, and these lots had significantly greater densities than the respective control lots.
- The average density of control section 1 was significantly higher than control section 2.

Table 2.7: GLE-162: ANOVA of In-Place Wet Density Results

Source	Degrees of Freedom	Sum of Squares	Mean of Squares	F-Value	Prob. (>Fcr)	Significant (α = 0.05)?
Supplemental aggregates	5	2,158	431.6	82.23	<2e-16	Yes
Residuals	74	388	5.2	—	—	—
Total	79	2,546	—	—	—	—

Table 2.8: GLE-162: Analysis of In-Place Density With and Without Supplemental Aggregates

Factorial	Mean Field Density		Sample Size	Group[a]
	pcf	kg/m^3		
Dust1	132.9	2,129	40	A
Dust2	133.2	2,134	10	A
AB1	134.9	2,161	10	A
AB2	132.3	2,119	40	A
Control1	125.0	2,002	10	B
Control2	121.6	1,948	10	C

[a] Means with the same letters are not significantly different.

2.6.2 Gradations

<u>Quality Control Test Results</u>

AASHTO T 11/T 27 sieve analyses were performed throughout the project on untreated material produced at the beginning of each day. Gradations are plotted in Figure 2.26. The unmodified RAP gradations are summarized by an envelope, and the gradations with 25% rock dust and with 50% aggregate base were computed based on the gradation produced by the recycling machine after pre-milling was completed and before the addition of the supplemental aggregates. Figure 2.26 also shows the difference between the production and CT 315-recommended mix design gradations. Observations from these results include the following:

- The RAP production gradation envelope generally fell within the recommended medium gradation envelope.
- The 75% RAP with 25% rock dust was finer than the medium gradation.
- The 50% RAP with 50% aggregate base production blend was generally finer than the medium gradation, except for the material between the #4 and #16 sieves, where it was coarser than the medium gradation.

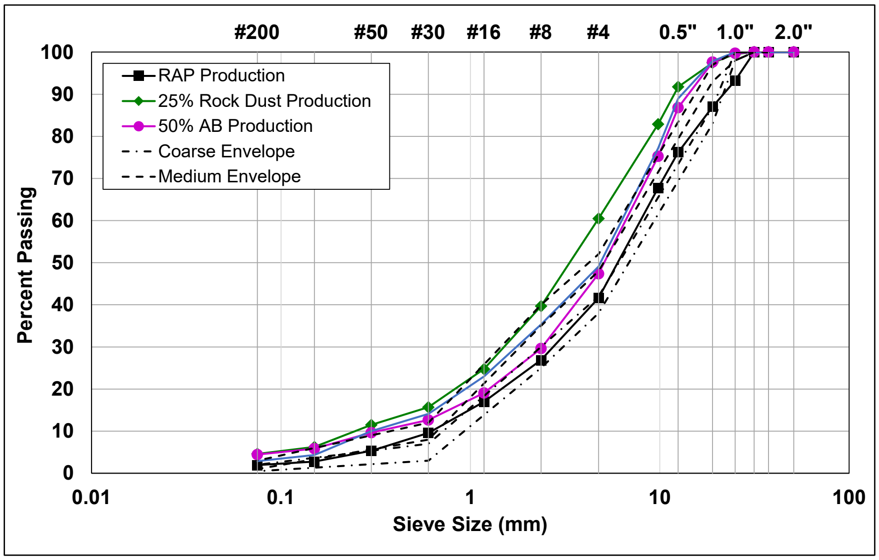

Figure 2.26: GLE-162: Average gradations during construction.

The wet sieve results (a report-only requirement) are plotted in Figure 2.27 and show that the maximum aggregate size measured in the unmodified material was 1.25 in. The 75% RAP with 25% rock dust had the finest gradation, while the 50% RAP with 50% aggregate base had a similar gradation to the finest RAP gradation.

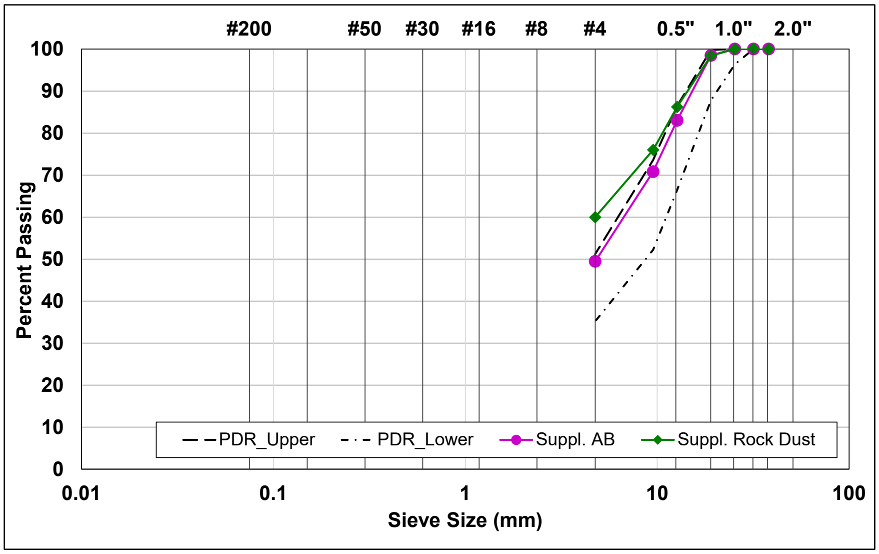

Figure 2.27: GLE-162: Wet sieve test results.

Analysis

The gradations produced during recycling are plotted in Figure 2.28 along with the maximum density lines for three different maximum aggregate sizes. Figure 2.29 shows the square of the error (SSE) between the production gradations and the corresponding maximum density line. Observations include the following:

- The RAP with no supplemental aggregates produced lower SSEs in production compared to the gradation used in the design phase, where an SSE of 900 was possible.

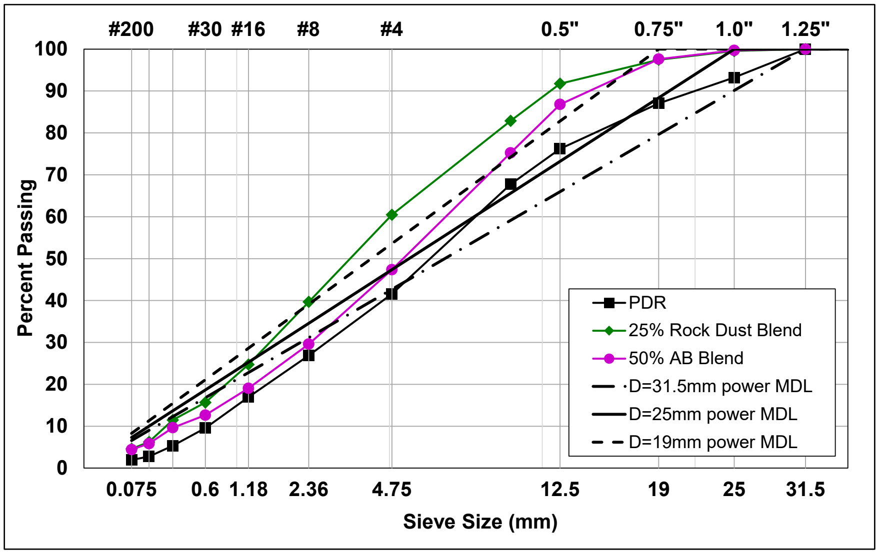

Figure 2.28: GLE-162: Production gradation 0.45 maximum density line.

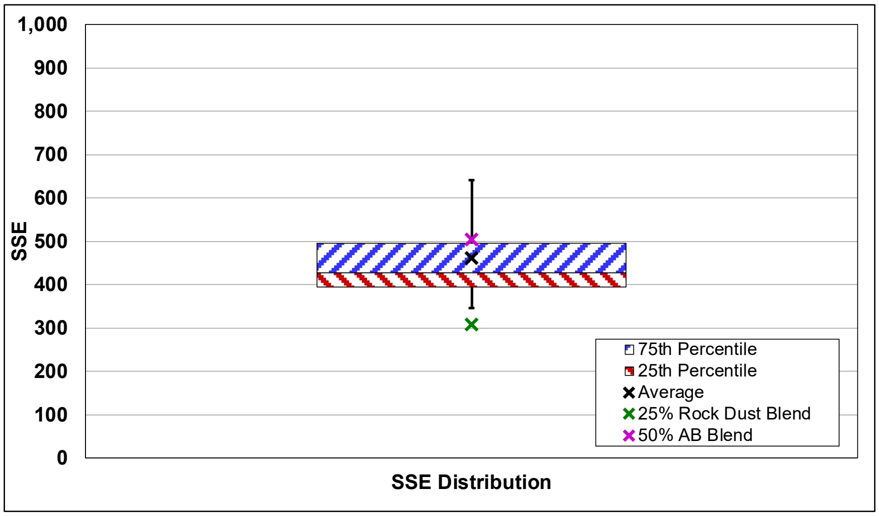

Figure 2.29: GLE-162: Difference distribution between production gradations and MDL.

- The 75% RAP with 25% rock dust blend, which had an SSE of 400 in the design phase, had an SSE of 300 in production.
- The aggregate base blend had an SSE of 600 in the design phase, but a lower SSE of 500 in production.
- The production RAP SSE varied between 345 and 640, but the resultant increase in density was not realized in the field. It is possible that the variability associated with PDR materials obscured the potential density improvement, or that the samples used for the gradations were not fully representative of what was compacted.

Figure 2.30 provides the SSE for adding the rock dust to the RAP gradation envelope produced during this project (maximum, average, and minimum RAP gradations). In the case of the fine RAP gradation, the addition of 10% rock dust could have maximized the density. The addition of rock dust to the coarse gradation moved the gradation further away from the maximum density line, which implies that adding supplemental aggregates with specific gradations could theoretically have a negative effect on the density of the PDR layer in certain situations.

The authors acknowledge that this grading optimization method will have some limitations in this application (e.g., absence of allowances for recycling agent, active filler, and variability), but it provides a simple approach to show what potential effect supplemental aggregates could have on PDR materials with variability in the RAP gradation. Optimization methods are currently being studied at the UCPRC under controlled conditions to determine the most appropriate procedure of identifying minimum optimal supplemental aggregate requirements for meeting an achievable grading envelope that improves density, moisture resistance, and stiffness of the recycled layer at minimum additional cost.

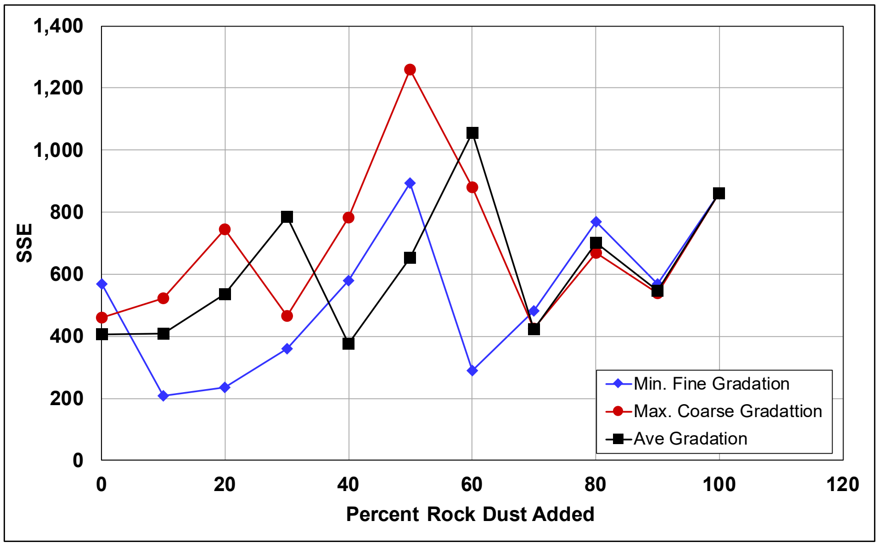

Figure 2.30: GLE-162: Effect of supplemental aggregates on production RAP SSE.

2.6.3 Indirect Tensile Strength

Mix was sampled from the windrow behind the recycler, once per lot, for ITS specimen preparation. Marshall compaction, following AASHTO T 245, was used to compact six specimens. The specimens were left to cure in the sun on the day of construction before being taken to a laboratory, where they were placed in a forced draft oven at 104°F (40°C) for 72 hours. Three of the specimens were dry cured for a further 24 hours at 77°F (25°C) while the remaining three specimens were soaked for 24 hours with a water temperature of 77°F. The specimens were then tested according to AASHTO T 283. Tests on some of the lots in the eastbound lane were done on cores removed from the pavement, and not from laboratory-prepared specimens, due to problems with the laboratory-prepared specimens and insufficient material to repeat the tests.

Test results are summarized in Table 2.9 and plotted in Figure 2.31. Tensile strength retained (TSR) results are plotted in Figure 2.32. Dry and wet ITS results are also plotted according to distance in Figure 2.33 and Figure 2.34, respectively.

Table 2.9: GLE-162: Indirect Tensile Strength Results

Experiment Factor	Condition	Avg. ITS		% Change	Avg. Bulk Density		% Change	Avg. Air Voids (%)	% Change
		Psi	kPa		pcf	kg/m³			
PDR lab.-compacted	Dry	65.8	454	—	129.2	2,070	—	12.6	—
	Wet	49.4	341	—	129.5	2,074		12.2	
PDR field-cored	Dry	44.1	304	-33.0	128.5	2,058	-1.9	15.0	28.3
	Wet	47.6	328	-3.6	125.3	2,007		16.8	
Dust1	Dry	89.4	616	25.5	138.9	2,225	6.9	10.1	-15.3
	Wet	56.8	392	7.4	138.9	2,225		10.1	
Dust1_ Control	Dry	71.3	492	—	129.8	2,079	—	12.3	—
	Wet	52.8	364	—	130.1	2,084		11.6	
Dust2	Dry	81.5	562	22.2	138.5	2,219	6.5	11.1	-10.8
	Wet	54.7	377	10.0	137.1	2,196		12.0	
Dust2_ Control	Dry	66.7	460	—	129.1	2,068	—	13.1	—
	Wet	49.7	343	—	129.6	2,076		12.8	
AB1	Dry	80.1	552	12.3	134.2	2,150	2.9	14.0	20.0
	Wet	63.4	437	19.9	133.3	2,135		14.6	
AB1_ Control	Dry	71.3	492	—	129.8	2,079	—	12.3	—
	Wet	52.8	364	—	130.1	2,084		11.6	
AB2	Dry	84.5	583	26.7	138.7	2,222	7.1	7.7	-39.6
	Wet	55.8	385	12.2	138.3	2,215		7.9	
AB2_ Control	Dry	66.7	460	—	129.1	2,068	—	13.1	—
	Wet	49.7	343	—	129.6	2,076		12.8	

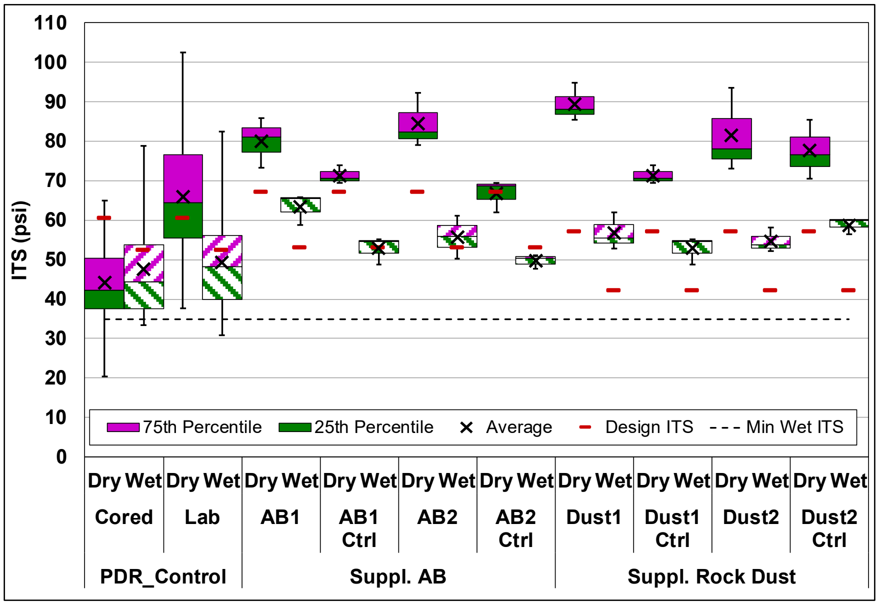

Figure 2.31: GLE-162: Box and whisker plot of indirect tensile strength results.

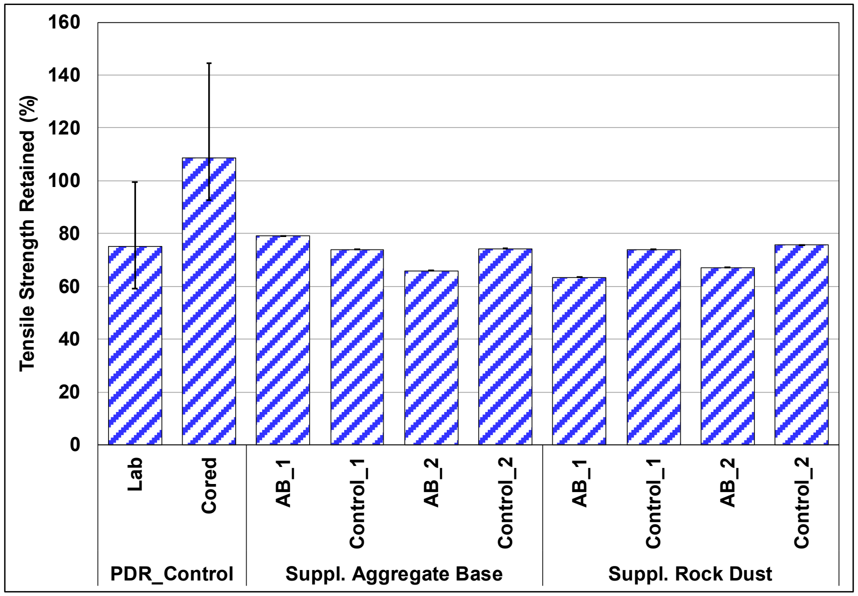

Figure 2.32: GLE-162: Tensile strength retained.

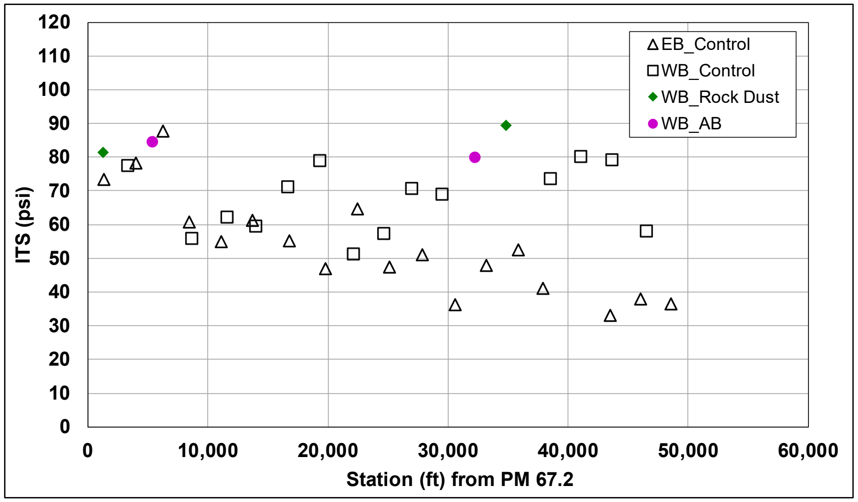

Figure 2.33: GLE-162: Dry indirect tensile strength results per location.

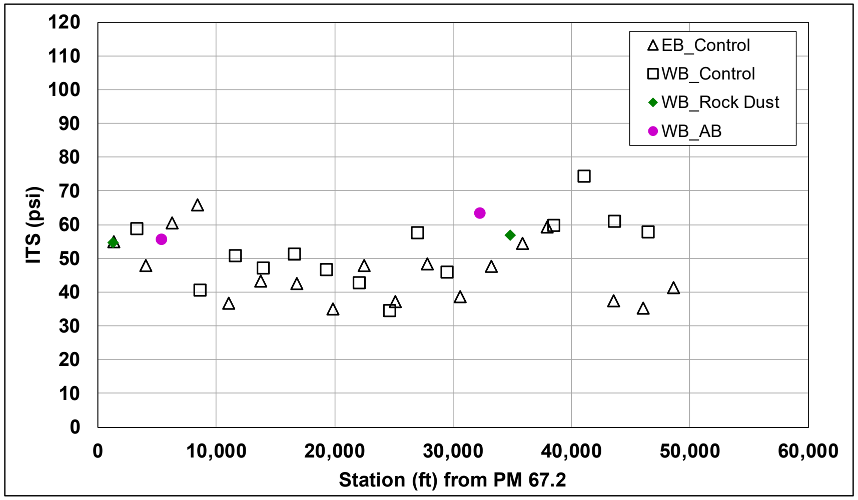

Figure 2.34: GLE-162: Wet indirect tensile strength results per location.

The results clearly show the benefits of adding supplemental aggregates, based on the following observations:

- The dry strengths increased by 12% and 26% on the two AB lots, and by 5% and 25% on the two rock dust lots.
- The wet strengths increased by 19% and 12% for the two AB lots. The first rock dust section had an increase in wet strength, while the second section did not.
- The specimens with supplemental aggregates had lower TSR values than the control specimens. Since the supplemental material increased the dry strength to a greater extent compared to the wet strength, the TSR reduced.
- The quality control specimens had higher strengths than the mix design specimens, which was unexpected due to the higher bulk densities of the mix design specimens (discussed below).
- There was considerable variability along the project. When considering results per lane, the westbound lane appeared to be more consistent than the eastbound lane where strengths decreased with increasing station location. It should be noted that some of the eastbound lane results were from cores and not from laboratory-prepared specimens.
- The first set of experimental lots, between stations 30,000 and 40,000, had higher dry strengths than the adjacent lots with no supplemental aggregates. The second set of experimental lots had similar results to the first set, but the control section between the rock dust and aggregate base lots had comparable strength to the experimental lots.
- The wet ITS results were less variable than the dry ITS results.

Compaction Densities of Indirect Tensile Strength Specimens

The densities of the quality control specimens are plotted in Figure 2.35. The bulk densities achieved during the mix design, as well as the average in-place density (wet and dry), measured with a nuclear gauge, are provided for reference. Dry density was calculated using the range of water contents applied during construction based on the recycler's control box output (gravimetric moisture contents were not determined at each density test location). This dry density result is provided to enable direct comparison between the dry densities of the quality control specimens and the densities measured along the project, but it is acknowledged that this value will not be the true density. The in-place dry densities, with an average of 117.4 pcf (1,881 kg/m^3), were lower than the bulk densities of the quality control specimens, with an average of 129.6 pcf (2,076 kg/m^3) (Figure 2.35). This difference of 12.2 pcf (195 kg/m^3) can be attributed to the high compaction effort of the AASHTO T 245 Marshall hammer.

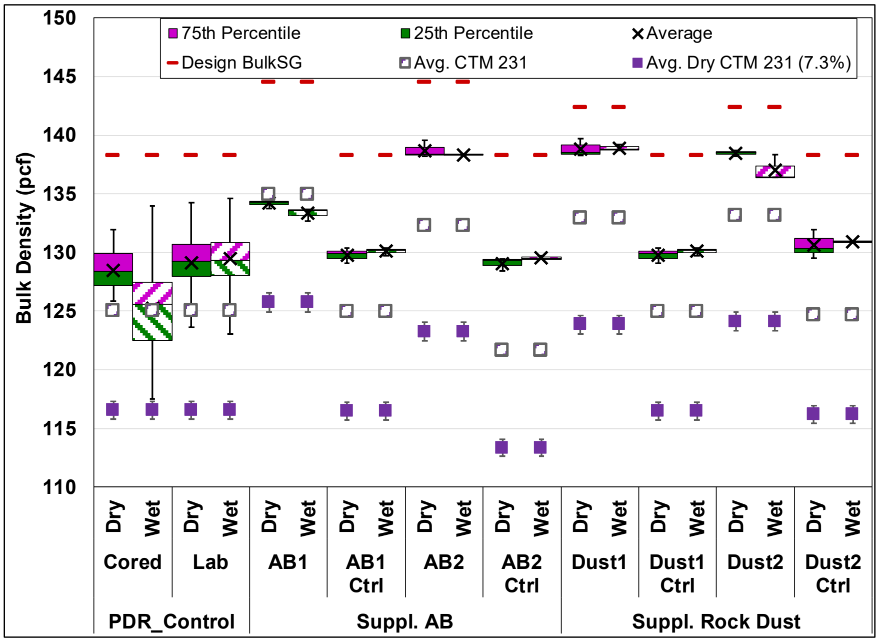

Figure 2.35: GLE-162: Box and whisker plot of ITS specimen compacted bulk densities.

The results further show that:

- The quality control specimens with supplemental aggregates had higher densities/lower air-void contents than the control specimens.
- The bulk densities achieved in the mix design could not be achieved in the quality control specimens, likely due to differences between the laboratory-crushed and in-place recycled materials.

<u>Analysis</u>

The ITS results were analyzed to determine if supplemental aggregates and the test condition had a significant effect on strength. The ANOVA of the ITS results (Table 2.10) shows that both the supplemental aggregates and the test condition had a statistically significant effect on ITS, and that the means of the different groups were not all equal.

Table 2.10: GLE-162: ANOVA of Indirect Tensile Strength Results

Source	Degrees of Freedom	Sum of Squares	Mean of Squares	F-Value	Prob. (>Fcr)	Significant (α = 0.05)?
Supplemental material	5	1,530	306	4.35	0.00287	Yes
Test condition (dry/wet)	1	5,798	5,798	82.46	<0.0001	Yes
Residuals	41	2,883	70	—	—	—
Total	47	10,211	—	—	—	—

The Tukey's test results in Table 2.11 show that the wide variability in the ITS results resulted in only two statistically different groups among the dry ITS results and only one group in the wet ITS results. The experiment factors with two letters belong to both letter groups due to the wide variability in their respective results. The Tukey's test results show the following:

- The first rock dust section had the highest dry ITS.
- Despite the groupings, the ITS results for the supplemental aggregate specimens were notably higher than those of the controls.
- The second control lots had the lowest dry ITS results.
- There was no difference between the wet ITS results.

Table 2.11: GLE-162: Analysis of ITS Results With and Without Supplemental Aggregates

Factor	Dry				Wet			
	Average ITS		Sample Size	Group[a]	Average ITS		Sample Size	Group[a]
	psi	kPa			psi	kPa		
Dust1	89.4	616	3	A	57	393	3	A
Dust2	81.5	562	3	AB	55	379	3	A
AB1	80.1	552	3	AB	63	434	3	A
AB2	84.5	583	3	AB	56	386	3	A
Control1	71.3	492	6	AB	53	365	6	A
Control2	66.7	460	6	B	50	345	6	A

[a] Means with the same letters are not significantly different.

Relationship between Indirect Tensile Strength and Density

The relationship between ITS and bulk density is plotted in Figure 2.36. The ITS and density have a wide range, but the data show that dry and wet strengths have a positive trend with increasing density. The reduction in TSR was attributed to the higher rate of strength gain of the dry ITS specimens with increased density, resulting in the lower ratio of dry to wet strength.

2.6.4 Summary of Analysis Factors

The supplemental aggregate blends resulted in increased density and strength compared to the control material with no supplemental aggregates. Trends in the results indicate that air-void contents decreased with the addition of supplemental aggregates, although some inconsistencies in these trends were noted.

The gradation optimization used to determine target gradations for materials with supplemental aggregates showed that modifications would increase the theoretical density of the material.

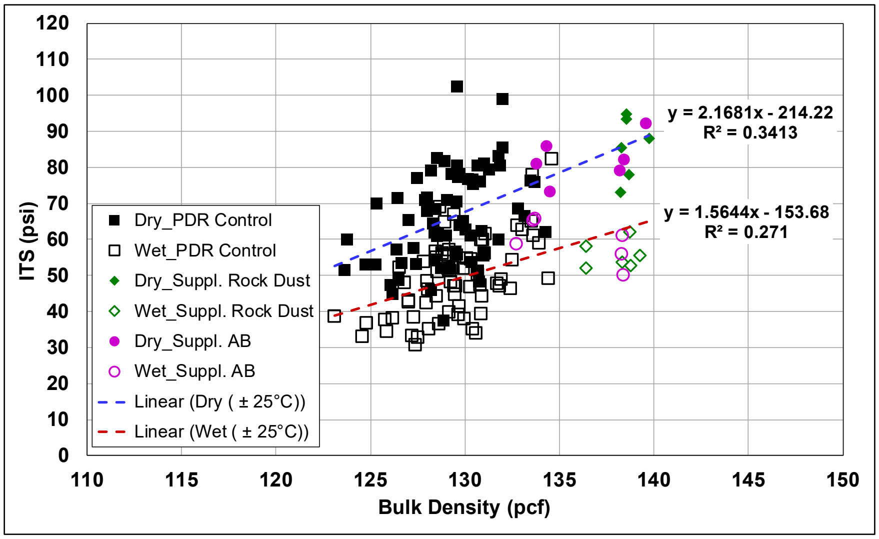

Figure 2.36: GLE-162: Relationship between indirect tensile strength and bulk density.

The following additional observations were made from the quality control results:

- In-place wet density:
  - Adding supplemental aggregates to the PDR layer resulted in a significant increase in in-place wet density. The first set of sections with supplemental aggregates had an increase of 8.9 pcf (143 kg/m^3) (different between Control1 and the average of Dust1 and AB1), while the second set of sections had an increase of 11.1 pcf (178 kg/m^3). These increases were achieved without changing rolling pattern or the forward speed of the recycling train.
- Indirect tensile strength:
  - Adding supplemental aggregates resulted in notably higher dry ITS results and marginally higher wet ITS results. Statistically, the differences were not as significant as they appeared, which was attributed to the following:
    - A limited number of samples were tested on the pilot study sections.
    - The ITS specimens were smaller than the representative volume element and therefore specimen size may have affected the result.
    - The Marshall compaction effort, with an energy level greater than that of CT 216 and consequently greater than the energy applied during rolling, can result in material breakdown during compaction. As a result, the specimens may not be representative of the PDR-layer construction.

2.7 Conclusions

The conclusions from this pilot study include the following:

- The gradation optimization method used on this project can potentially be used to guide engineers in identifying suitable supplemental aggregate sources that are close to the project location and what percentage to add. Verifying the effectiveness of this method is challenging with the limited data collected on this project, but ongoing research on the topic under controlled laboratory conditions should provide useful results and direction.
- The mix design densities were higher than the densities achieved on the project. The mix design specimens had low air-void contents that were not representative of the field results.
- Incorporating supplemental aggregates resulted in increased in-place wet density compared to the control material with no supplemental aggregates but with the same recycling agent and active filler contents.
- The difference in dry ITS between the sections with and without supplemental aggregates was not always significant, which could be attributed to the compaction method used to produce specimens not being representative of the field conditions.
- There was no significant difference in wet ITS for the different sections. This could similarly be a result of the compaction method.
- The increases in dry ITS, with increased density, were larger than the increases in wet ITS with increased density, which resulted in lower retained tensile strengths. This is of limited concern given that Caltrans will require minimum dry and wet strengths rather than only a minimum wet strength and a minimum TSR.
- There were large differences between the mix design densities, in-place densities, and quality control ITS specimen densities. This was attributed to changes in material along the project and the high compaction effort achieved with Marshall compaction compared to compaction achieved on the layer.
- CT 216 provided a reasonable estimate of the target compaction density, but there is always the possibility that additional compaction can be achieved over the CT 216 result. This observation is of limited concern given that Caltrans has moved to accepting compaction on breakover density rather than on CT 216.

3 SB-135 (EA 05-1N1704): RECYCLING TRAIN AND AGENT COMPARISON

3.1 Project Description

This pilot project is located on SB-135, west of Los Alamos, between PM 1.0 and PM 7.23. Lanes in both directions over much of the project were narrow, measuring between 10 and 11 ft. (3.0 and 3.4 m), with shoulder width varying from a few inches to 1 ft. The project had several wheelpath and lane-width patches (Figure 3.1 and Figure 3.2). Other locations had transverse cracks at regular intervals (Figure 3.3), with spalling observed on several of them (Figure 3.4). Alligator B cracking was noted along the outside wheel paths (Figure 3.5) on portions of the road, with some of these cracks sealed (Figure 3.6), especially between PM 1 and PM 2. Several locations had severe fatigue cracking along the shoulder of the pavement (Figure 3.7), with some loose blocks in the pattern.

The PDR construction took place between 08/23/2021 and 09/03/2021.

3.2 Pavement Structure

No core or DCP data within the project limits were made available by the contractor at the time of writing this report.

Figure 3.1: SB-135: Wheelpath patches.

Figure 3.2: SB-135: Lane-width patches.

Figure 3.3: SB-135: Transverse cracking.

Figure 3.4: SB-135: Spalling on cracks.

Figure 3.5: SB-135: Alligator B cracking.

Figure 3.6: SB-135: Sealed Alligator B cracking.

Figure 3.7: SB-135: Severe alligator cracking along the edge of the pavement.

3.3 Pilot Study Experimental Design

The aim of this project was to compare the performance of emulsified and foamed asphalt recycling agents when processed with a single-unit train (Figure 3.8) and a multi-unit train (Figure 3.9). A recycling depth of 0.25 ft. (75 mm) was specified for the project.

Figure 3.8: SB-135: Single-unit recycling train.
(Water tanker and cement spreader, asphalt tanker, recycling unit).

Figure 3.9: SB-135: Multi-unit recycling train.
(Water tanker and cement spreader, milling machine, crushing and processing unit, asphalt tanker).

A secondary goal was to assess if changing the forward speed of the recycling train would reduce the maximum aggregate size (MAS), improve the gradation, and lower the air-void content. Three different speeds were proposed for testing on different selected sections along the project. However, only two speeds (15 and 20 fpm [4.6 and 6 m/min]) with the single-unit train were assessed, both on the first day of construction. The forward speed for the remainder of the project was maintained at 20 fpm. The layout of the sections (as built) is provided in Figure 3.10.

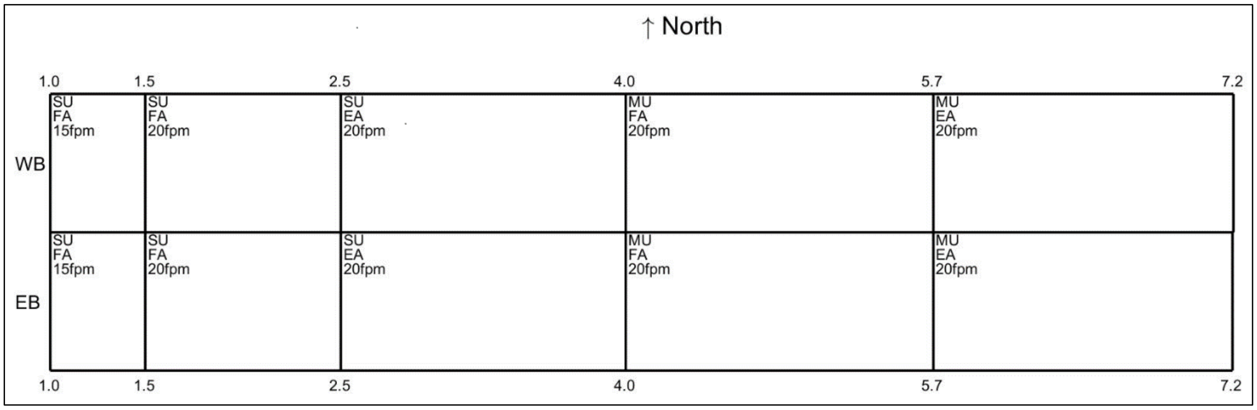

Figure 3.10: SB-135: As-built factorial sections.

This layout is not ideal for comparing the different sections because the various experiments are relatively far apart and variability along the project could have an influence on the results.

3.4 Mix Design

Mix designs were performed following CT 315. Coarse and medium gradations were constituted from crushed cores sampled on the project. Gyratory compaction following AASHTO T 312 was used to compact the specimens. The mix design results are summarized in Table 3.1 and Table 3.2 for the emulsified and foamed asphalt mix designs, respectively.

Table 3.1: SB-135: Mix Design Results: Emulsified Asphalt

Design Parameter	Gradation		
	Medium	Coarse	Specification
Emulsified asphalt content (%)	3.5	3.5	n/a
Residual asphalt (%)	2.3	2.3	n/a
Cement (%)	0.5	0.5	n/a
Optimum moisture content (%)	4.8	4.8	n/a
Specific gravity (AASHTO T 209)	2.264	2.274	n/a
Compaction method	AASHTO T 312[a]	AASHTO T 312[a]	n/a
Bulk density (pcf) [kg/m^3]	117.9 (1,889)	119.1 (1,908)	n/a
Air-void content (%)	16.6	16.2	n/a
Dry stability at 104°F (lbf) [kN]	2,894 (12.9)	3,119 (13.9)	>1,500 (6.7)
Wet stability (lbf) [kN]	1,961 (8.7)	1,897 (8.4)	n/a
Retained stability (%)	67.7	60.8	>70
Average dry indirect tensile strength (psi) [kPa]	42.8 (295)	47.1	Report only
Average wet indirect tensile strength (psi) [kPa]	35.6 (245)	32.9	Report only
Retained indirect tensile strength (%)	83.2	69.9	Report only

[a] 30 gyrations [600 kPa at 1.16°] in a 100 mm mold.

Table 3.2: SB-135: Mix Design Results: Foamed Asphalt

Design Parameter	Gradation		
	Medium	Coarse	Specification
Foamed asphalt (%)	3.5	3.5	n/a
Cement (%)	1.0	1.0	n/a
OMC (%)	6.0	6.0	n/a
Specific gravity (AASHTO T 209)	2.212	2.234	n/a
Compaction method	AASHTO T 312[a]	AASHTO T 312[a]	n/a
Bulk density (pcf) [kg/m^3]	116.9 (1,872)	1,868 (116.6)	n/a
Air-void content (%)	15.7	16.4	n/a
Average dry indirect tensile strength (psi) [kPa]	38.0 (262)	35.3 (243)	n/a
Average wet indirect tensile strength (psi) [kPa]	36.3 (250)	37.0 (255)	>35 (241)
Retained indirect tensile strength (%)	95.5	104.8	>70
Dry stability at 104°F (lbf) [kN]	4,136 (18.4)	4,001 (17.8)	Report only
Wet stability (lbf) [kN]	2,940 (13.1)	3,059 (13.6)	Report only
Retained stability (%)	71.1	76.5	Report only

[a] 30 gyrations [600 kPa at 1.16°] in a 100 mm mold.

The specimen density was, on average, 117.6 pcf (1,884 kg/m^3), with an air-void content of 16.2%. The emulsified asphalt mix design required 3.5% emulsified asphalt (2.3% residual asphalt) with 0.5% cement to exceed the minimum specified dry stability of 1,500 lbf (6.7 kN) as well as to achieve a soaked ITS of 35 psi (240 kPa) (report only). The foamed asphalt mix design required 3.5% foamed asphalt with 1.0% cement to achieve the specified minimum soaked ITS of 35 psi.

3.5 Construction

Construction of the PDR layer was monitored by the UCPRC from 08/23/2021 to 09/03/2021. The construction sequence was typical of PDR projects (similar to that described in Section 2.5). The construction schedule is provided in Table 3.3. The first 0.5 mi. (0.8 km) of the project, in both lanes, were recycled at a consistent speed of 15 fpm (4.6 m/min) using the single-unit train. The remainder of the project was recycled with a consistent forward speed of 20 fpm (6.1 m/min), using the two different recycling trains. A 1.25 in. screen was used on the multi-unit train for all sections. For research testing purposes, the recycling contractor produced millings at the different speeds proposed for this project by recycling short 10 ft. (3 m) long sections with each unit at different locations on the project. Research samples had not been processed or tested at the time of writing this report.

Table 3.3: SB-135: Construction Schedule

Factorial	Date	Westbound		Eastbound	
		Start	End	Start	End
Single-Unit_FA_15fpm	8/23/2021	1	1.5	n/a	n/a
Single-Unit_FA_20fpm		1.5	2.53	n/a	n/a
Single-Unit_FA_15fpm	8/24/2021	n/a	n/a	1	1.5
Single-Unit_FA_20fpm		n/a	n/a	1.5	2.53
Single-Unit_EA_20fpm	8/25/2021	n/a	n/a	2.53	4.03
Single-Unit_EA_20fpm	8/26/2021	2.53	4.03	n/a	n/a
Multi-Unit_FA_20fpm	8/31/2021	n/a	n/a	4.03	5.65
Multi-Unit_FA_20fpm	9/2/2021	4.03	5.65	n/a	n/a
Multi-Unit_EA_20fpm		n/a	n/a	5.65	7.225
Multi-Unit_EA_20fpm	9/3/2021	5.65	7.23	n/a	n/a

The following observations were made during construction:

- Recycling in the area with narrow lanes was challenging. On the eastbound lane, recycling included a portion of the westbound lane to accommodate the 12 ft. (3.7 m) milling width without incorporating unbound shoulder soil. On the adjacent westbound lane, the inside overlap ended on the original centerline, which required milling up to 1 ft. (0.3 m) of the unbound, silty-clay shoulder soil. Figure 3.11 shows the overlap into the westbound lane as well as the extent of the milling drum over the shoulder. The contractor adjusted the angle of the drum to minimize the amount of soil that was incorporated into the mix, which resulted in a deeper cut on the inside edge to produce sufficient material to pave the 0.25 ft. (75 mm) thick layer. Figure 3.12 shows a 1 ft. (0.3 m) wide strip of soil and limited depth of the cut on the outer edge of the lane. Despite the contractor's efforts, some clumps of silty-clay soil were observed in the windrow and these did not appear to blend well with the RAP. Given that the PDR layer is not supported by any pavement structure in these areas, cracking and other outer wheelpath distresses will likely occur in the future.

Figure 3.11: SB-135: Narrow lane showing center overlap and milling of shoulder material.

Figure 3.12: SB-135: Native soil in outer 1 ft. (0.3 m) of recycle cut.

- The PDR depth was at the interface between two asphalt concrete layers. This resulted in thin debonded layers that could easily be lifted by hand (Figure 3.13).
- Transverse reflective cracks were evident in the cut behind the recycling machine (Figure 3.14).
- A common observation on both train types was the presence of residual fines along the edges of the cut (Figure 3.15). This fine material was not collected by the pickup machine and could potentially lead to debonding of the recycled layer from the underlying layer.
- The section of road recycled on 08/25/2021 was wider than most of the project and had a wider shoulder. A 4 ft. (1.2 m) wide milling machine was used to pre-mill the inside part of the lane ahead of the recycling train (Figure 3.16). This milling machine progressed initially at a rate that produced RAP chunks in excess of 4 in. (100 mm) (Figure 3.17). The single-unit train was unable to reduce the size of this large RAP. The resident engineer raised the issue with the operator, and the forward speed of the second mill was reduced.

- In the areas with severe alligator cracking, shown in Figure 3.7, the single-unit recycler could not reduce the size of all the loose blocks, resulting in some areas with oversize material in the windrow (Figure 3.18).

Figure 3.13: SB-135: Recycling depth at the interface between two lifts.

Figure 3.14: SB-135: Reflected transverse cracks in cut.

Figure 3.15: SB-135: Layer of fine material in the cut next to the windrow.

Figure 3.16: SB-135: Milling machine in front of recycling train.

Figure 3.17: SB-135: Oversize RAP from incorrect pre-milling speed.

Figure 3.18: SB-135: Oversize RAP from milling loose blocks in fatigue cracked areas.

Limited production parameters were available at the time of writing this report, but monitoring during construction, and photographs of the control box display (Figure 3.19 through Figure 3.24), showed that:

- The forward speed was consistent for the different experimental sections. Small, short-term deviations from the set speed were attributed to sudden changes in the properties or thickness of the asphalt concrete.
- The moisture content for the majority of the project was within 0.5% of the mix design determined optimum.
  - \+ On the emulsified asphalt sections, the moisture content on the eastbound single-unit train section was initially around 5% (3.9% + 35% water in 3.3% emulsified asphalt) at the start of production but was adjusted by mid-morning as ambient temperature increased, for a combined water content of 6%.
  - \+ On the foamed asphalt sections, the moisture content varied between 5.6% and 6.2%.

Figure 3.19: SB-135: 08/23/21 - single-unit train foamed asphalt at 15 fpm.

Figure 3.20: SB-135: 08/24/21 - single-unit train foamed asphalt at 15 fpm.

Figure 3.21: SB-135: 08/23/21 - single-unit train foamed asphalt at 20 fpm.

Figure 3.22: SB-135: 08/24/21 - single-unit train foamed asphalt at 20 fpm.

Figure 3.23: SB-135: 08/25/21 - single-unit emulsified asphalt at 20 fpm - start of section.

Figure 3.24: SB-135: 08/25/21 - single-unit emulsified asphalt at 20 fpm - middle of section.

3.6 Quality Control Test Results and Analysis

The quality control results provided by the contractor are summarized in Table 3.4. The test locations across the project are illustrated in Figure 3.25.

Table 3.4: SB-135: Quality Control Data Collected During Construction

Description	Test Method	Minimum Test Frequency
Field compacted wet density	CT 375	2 tests per lot
Breakover density	n/a	1 per day, then as needed
Coarse sieve analysis on mixed material	AASHTO T 27	1 per day
Maximum theoretical density	AASHTO T 209	1 per day
Wet/dry gradations on clean RAP	AASHTO T 27/T 11	1 per day
ITS of mixed material	AASHTO T 283	1 per lot
Marshall stability	AASHTO T 245	1 per lot

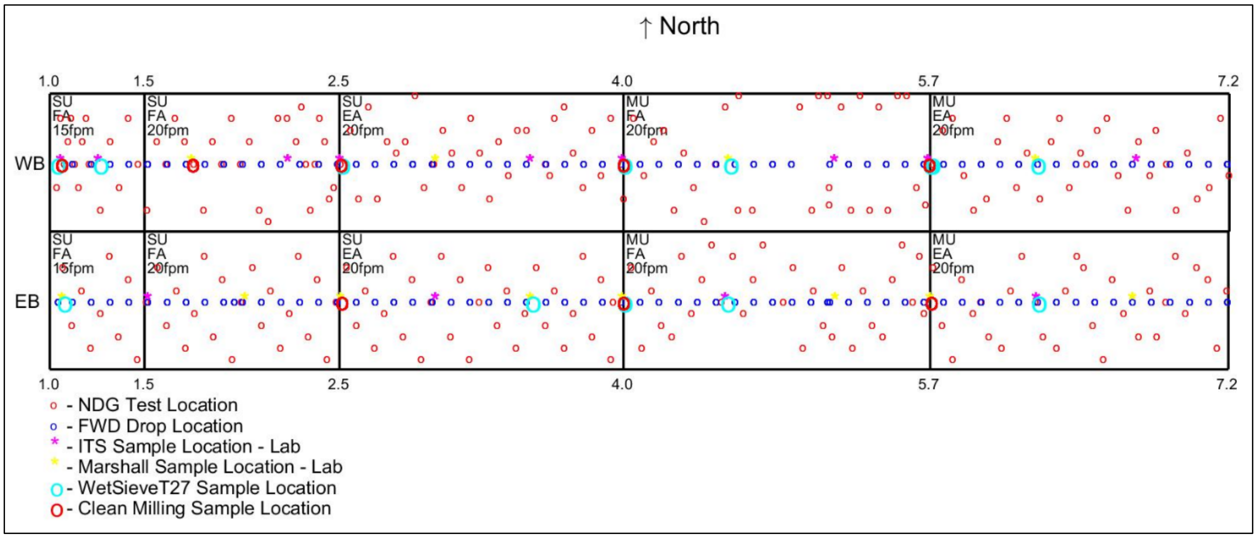

Figure 3.25: SB-135: Quality control data layout across the project.

Variability in the quality control data were expected and consequently analyses were undertaken to determine if the differences in means were significant using either analyses of variance (ANOVA) or a t-test, depending on the number of variables. The means were then compared, grouped, and ranked using a pairwise comparison of the means method (Tukey's test) to determine if the means were statistically equivalent.

In the ANOVA, the null hypothesis was that the means of the different variables were equal, and the alternate hypothesis was that the means were not all equal. In the t-test, the null hypothesis was that the difference in group means was zero, and the alternate hypothesis was that the difference was not zero. Tukey's test determines which means are statistically equivalent and assigns a letter to statistically equivalent groups. Means with the same letter are not significantly different at a confidence level of 95% (α = 0.05).

3.6.1 In-Place Wet Density and Relative Compaction

Quality Control Test Results

In place wet density results of the compacted PDR layer were collected following CT 375. The distribution of the results along the length of the project are provided in Figure 3.26.

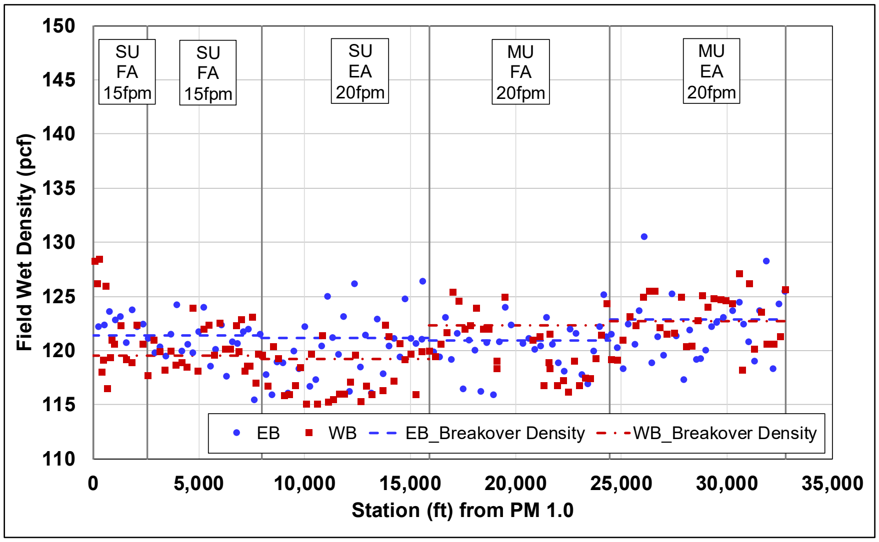

Figure 3.26: SB-135: Density results along the length of the project.

The target density was based on the breakover density determined at the beginning of each section. The density reading, prior to the reading when a roller pass causes the density to reduce, is considered the breakover density. At the same time, this method determines the rolling pattern to be used for the section. The in-place densities of the PDR layer, after construction, ranged between 113.5 and 132.6 pcf (1,818 and 2,124 kg/m^3), with a project average of 120.7 pcf (1,933 kg/m^3) and a standard deviation of 3.1 pcf (50 kg/m^3).

Per specification, the emulsified asphalt sections need to be rerolled approximately 48 hours after initial compaction. Foamed asphalt layers do not require rerolling. The single-unit train sections were rerolled on 9/7/2021, and the multi-unit train sections on 9/8/2021. A new breakover density was determined on each section to establish a rerolling pattern. Density on the single-unit train section increased after rerolling by approximately 1.9 pcf (30.4 kg/m^3) and on the multi-unit train section by 0.9 pcf (14.4 kg/m^3).

The in-place density results are further summarized in Table 3.5 and in the box and whisker plot in Figure 3.27. The average breakover density, per factor in the experiment factorial, is also provided for reference in Figure 3.28. The density of the PDR layer appeared to decrease towards the middle of the project and increase again near the end of the project. The average relative compaction of the sections ranged between 99% and 101.6% of the breakover density. The air-void contents ranged between 10.1% and 19.1%.

Table 3.5: SB-135: Compaction Results

Factor	Compaction Event	Field Wet Density				Relative Compaction (%)		Avg. Void Ratio (%)	No. of Tests
		Average		Std. Dev.					
		pcf	kg/m^3	pcf	kg/m^3	Avg.	Std. Dev.		
Single-Unit_FA_15fpm	Primary	122.1	1,956	3.6	58	101.6	2.5	10.1	48
Single-Unit_FA_20fpm	Primary	120.3	1,927	2.2	35	100.0	1.7	13.6	92
Single-Unit_EA_20fpm	Primary	118.9	1,905	3.3	53	99.5	2.2	17.1	120
	Reroll	120.9	1,937	2.9	47	99.6	2.3	N/A	60
Multi-Unit_FA_20fpm	Primary	120.3	1,927	2.5	40	99.0	2.1	19.1	120
Multi-Unit_EA_20fpm	Primary	122.4	1,961	2.8	45	99.9	2.2	14.0	120
	Reroll	123.3	1,975	1.9	30	100.1	1.5	N/A	60

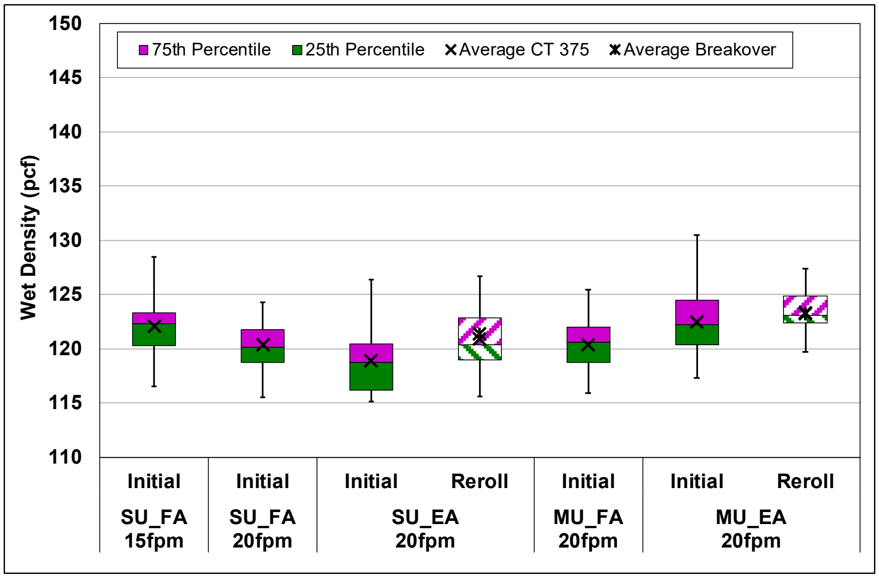

Figure 3.27: SB-135: Box and whisker plot of density results.

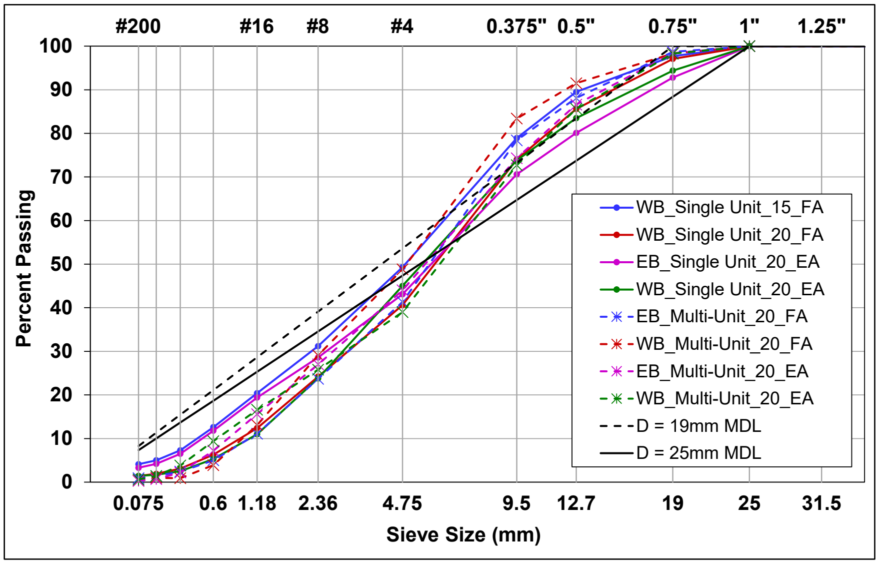

Figure 3.28: SB-135: Production gradations on 0.45 maximum density line.

The differences in average density between the different sections were small. Ranking the average density results after initial compaction and after rerolling (Table 3.6) shows that the multi-unit train emulsified asphalt section generally had the highest density after initial compaction and reroll. The second highest density was produced on the single-unit train foamed asphalt section with 15 fpm forward speed. The single-unit train emulsified asphalt section had the lowest density after initial compaction, but it increased after rerolling to exceed the densities of the two foamed asphalt sections constructed at 20 fpm. There was no difference in density between the single- and multi-unit train foamed asphalt sections.

Table 3.6: SB-135: Ranked Field Wet Density Results

After Initial Compaction			After Reroll		
Section	Field Wet Density		Section	Field Wet Density	
	pcf	kg/m^3		pcf	kg/m^3
Multi-Unit_EA_20fpm	122.4	1,961	Multi-Unit_EA_20fpm	123.3	1,975
Single-Unit_FA_15fpm	122.1	1,956	Single-Unit_FA_15fpm	122.1	1,956
Multi-Unit_FA_20fpm	120.3	1,927	Single-Unit_EA_20fpm	120.9	1,937
Single-Unit_FA_20fpm	120.3	1,927	Multi-Unit_FA_20fpm	120.3	1,927
Single-Unit_EA_20fpm	119.0	1,906	Single-Unit_FA_20fpm	120.3	1,927

<u>Analysis</u>

The ANOVA of the in-place density results (Table 3.7) considered the effects of recycling train, recycling agent, and forward speed on in-place density. The density of the emulsified asphalt sections after rerolling was used in the analysis. The results show that recycling agent and recycle speed had a significant effect on the density, but the type of recycling train did not.

Table 3.7: SB-135: ANOVA of In-Place Wet Density Results

Source	Degrees of Freedom	Sum of Squares	Mean of Squares	F-Value	Prob. (>Fcr)	Significant (α = 0.05)?
Recycling agent	1	170	170	23.92	<0.0001	Yes
Train	1	13	13	1.78	0.18	No
Speed	1	174	174	24.59	<0.0001	Yes
Residuals	376	2,665	7.1	—	—	—
Total	379	3,021	—	—	—	—

Table 3.8 provides the average density results for each variable grouped by the different parameters listed in the table. The ANOVA results show that the means of parameters under the recycling agent and speed are significantly different. This shows that the emulsified asphalt sections were significantly denser than the foamed asphalt sections, and that reducing the speed to 15 fpm on the single-unit train produced a gradation that compacted to a significantly higher density. The layers produced by the different recycling trains did not have significantly different densities.

The results of the Tukey's test in Table 3.9 show that the multi-unit train emulsified asphalt section and the single-unit train foamed asphalt section recycled at 15 fpm had similar results. There were no differences between the remaining sections.

Table 3.8: SB-135: Average In-Place Wet Density Results

Variable	Parameter	Mean Field Density		Sample Size
		pcf	kg/m^3	
Recycling agent	Emulsified asphalt	122.1	1,956	120
	Foamed asphalt	120.7	1,933	260
Recycling train	Single-unit	120.9	1,937	200
	Multi-unit	121.3	1,943	180
Speed (fpm)	15	122.1	1,956	48
	20	121.0	1,938	332

Table 3.9: SB-135: Tukey Test on Average Density Results

Factorial	Mean Field Density		Sample Size	Groups[a]
	pcf	kg/m^3		
Multi-Unit_EA_20fpm	123.3	1,975	60	A
Single-Unit_FA_15fpm	122.1	1,956	120	AB
Single-Unit_EA_20fpm	120.9	1,937	60	BC
Multi-Unit_FA_20fpm	120.3	1,927	48	C
Single-Unit_FA_20fpm	120.3	1,927	92	C

[a] Means with the same letters are not significantly different.

3.6.2 Gradations

Quality Control Test Results

Untreated RAP was collected at the start of each day's construction. Sieve analyses were performed on the RAP following AASHTO T 11/T 27. The MAS of each gradation was calculated as well as the SSE between the corresponding maximum density line and the gradation. The results are provided in Table 3.10.

Table 3.10: SB-135: Difference Between Production Gradations and Maximum Density Line

Section	Factor	Max. Aggregate Size (in.)	SSE
Eastbound	Single-Unit_20_EA	1.0	332
	Multi-Unit_20_FA	1.0	1,287
	Multi-Unit_20_EA	1.0	920
Westbound	Single-Unit_15_FA	1.0	689
	Single-Unit_20_FA	1.0	989
	Single-Unit_20_EA	1.0	948
	Multi-Unit_20_FA	0.75	1,216
	Multi-Unit_20_EA	1.0	828

The results show the following:

- The single-unit train foamed asphalt section recycled at 15 fpm produced the most fines passing the #200 (0.075 mm) sieve (4.3%).

- The single-unit train foamed asphalt section at 20 fpm in the eastbound lane produced 3.3% passing #200. The remaining sections had between 0.3% and 1.5% passing the #200 sieve.
- The multi-unit train tended to produce gradations with slightly finer coarse fractions (#4 [4.75 mm] and larger) but were generally similar to the single-unit train in the fine fractions.
- Only the westbound multi-unit train foamed asphalt section had a MAS of 0.75 in. The remaining sections all had 1.0 in. maximum size gradations.
- Gradations were likely effected by variation in lane width, with narrow sections having more fines due to the incorporation of soil from the shoulder.

Figure 3.29 shows the relationship between the SSE calculated in Table 3.10 for each gradation and the average in-place wet densities. There was no correlation between the SSE and the density, which is not unexpected when attempting to represent nine 0.5 mi. (0.8 km) sections with one gradation each and known large variability in the RAP.

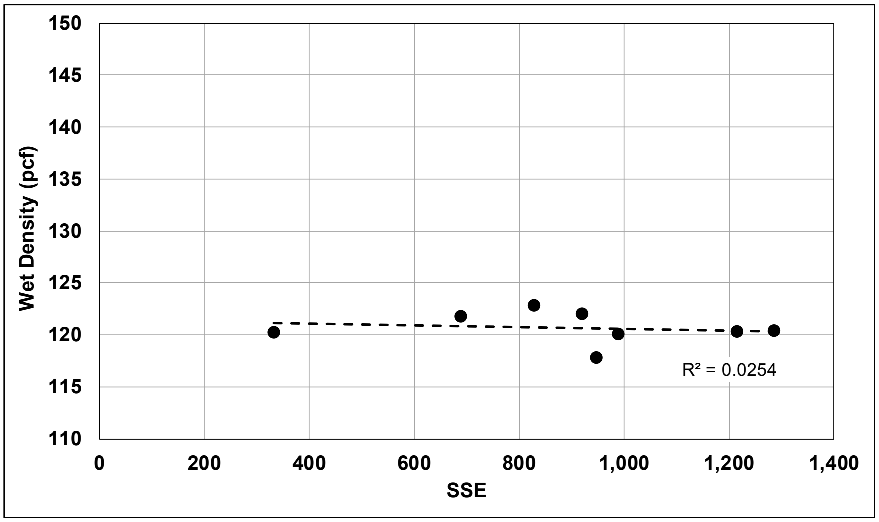

Figure 3.29: SB-135: Relationship between SSE and average field wet density.

Treated material was sampled to check the coarse portion of the gradations (Figure 3.30) for report-only purposes. The results show that the multi-unit train generally produced gradations finer than the single-unit train in this portion of the grading envelope.

3.6.3 Indirect Tensile Strength

Quality Control Test Results

Mix was sampled from the windrow, once per lot, to compact and test ITS specimens as described in Section 2.6.3.

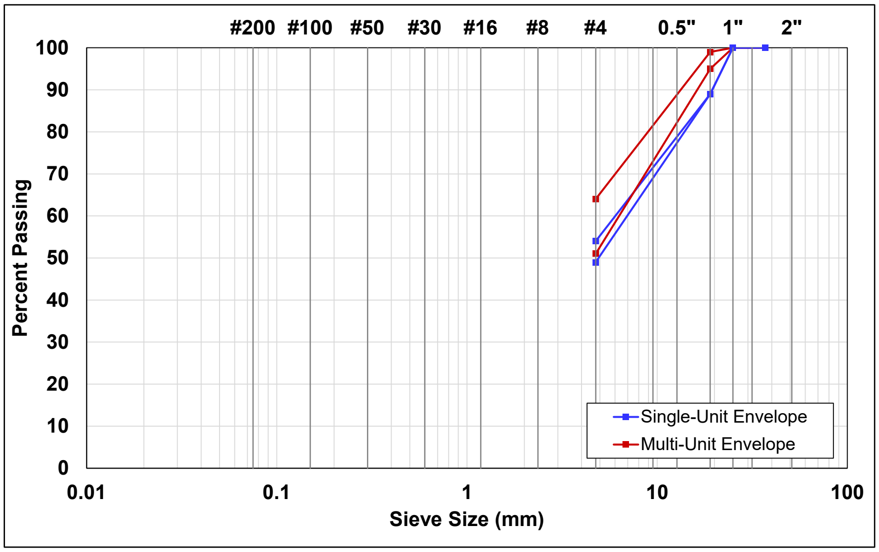

Figure 3.30: SB-135: Single- and multi-unit train wet gradation envelopes.

The ITS results of the quality control specimens, the mix design ITS results, and the minimum design strength are plotted in Figure 3.35. The quality control results were generally in agreement with the mix design results, except for the dry foamed asphalt results, where strengths exceeded the mix design results. The reason for the large increase in dry foamed asphalt strength is probably due to higher compaction densities.

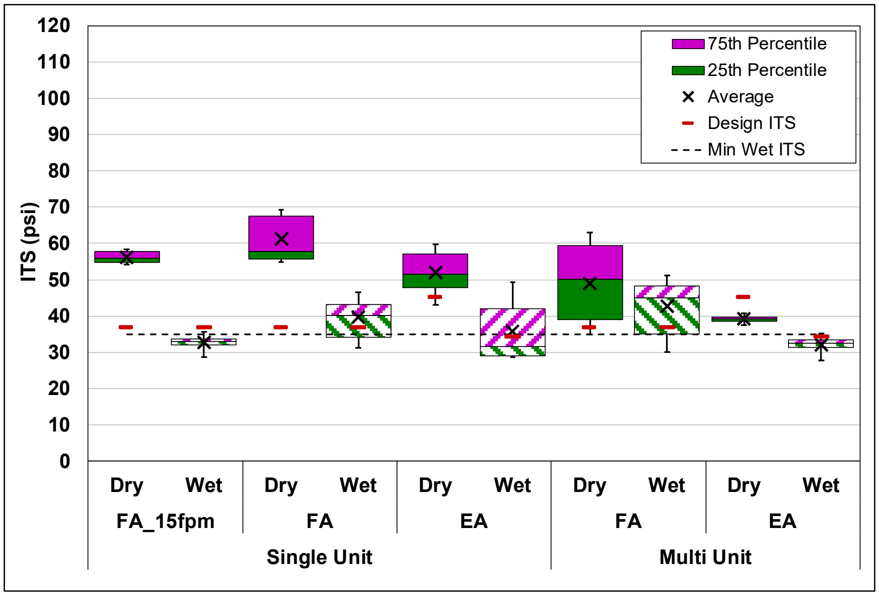

Figure 3.31: SB-135: Box and whisker plot of indirect tensile strength results.

A box and whisker plot of the quality control ITS specimen bulk densities, average mix design bulk densities, and average in-place wet and dry densities, assuming a moisture content of 6%, is provided in Figure 3.32. The quality control bulk densities were generally higher than the mix design bulk densities and the in-place dry densities. The densities of the quality control specimens followed a similar trend to the in-place densities, with the single-unit train emulsified asphalt specimens having the lowest densities. The difference between the quality control specimen densities and the in-place dry densities averaged about 6.5 pcf (104 kg/m^3).

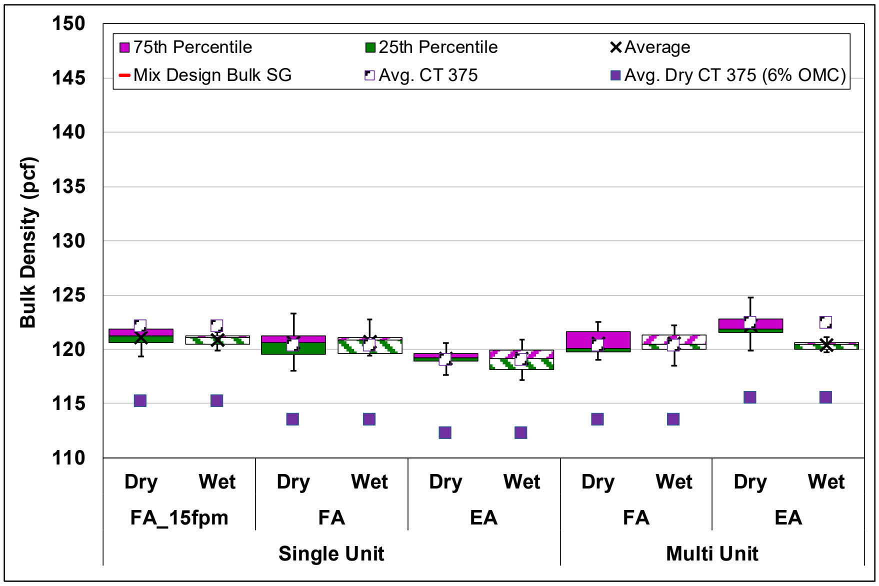

Figure 3.32: SB-135: Box and whisker plot of ITS specimen compacted bulk densities.

Analysis

The ITS results were grouped by the testing condition (wet/dry) and analyzed separately, given that testing condition was not a factor during construction. The ANOVAs of the dry and wet ITS results in Table 3.11 and Table 3.12, respectively, consider the effects of recycling agent, recycling train, and recycling speed on the ITS results.

Table 3.11: SB-135: ANOVA of Dry Indirect Tensile Strength Results

Source	Degrees of Freedom	Sum of Squares	Mean of Squares	F-Value	Prob. (>Fcr)	Significant (α = 0.05)?
Recycling agent	1	664	664	14.25	<0.0001	Yes
Train	1	1,170	1170	25.12	<0.0001	Yes
Speed	1	102	102	2.19	0.15	No
Residuals	35	1,631	47	—	—	—
Total	38	3,568	—	—	—	—

Table 3.12: SB-135: ANOVA of Wet Indirect Tensile Strength Results

Source	Degrees of Freedom	Sum of Squares	Mean of Squares	F-Value	Prob. (>Fcr)	Significant ($\alpha = 0.05$)?
Recycling agent	1	207	207	5.22	0.03	Yes
Train	1	44	44	1.10	0.30	No
Speed	1	280	280	7.05	0.01	Yes
Residuals	35	1,390	40	—	—	—
Total	38	1,921	—	—	—	—

The ANOVAs indicate that recycling agent and recycling train type had significant effects on the dry ITS results and that recycling agent and recycling speed had significant effects on the wet ITS.

The average dry and wet ITS results, for each variable, grouped by the different parameters, are provided in Table 3.13 and show the following:

- The foamed asphalt sections had significantly higher dry and wet ITS results than the emulsified asphalt results.
- The single-unit train sections had significantly higher dry ITS results than the multi-unit train sections.
- The sections recycled at 20 fpm had higher wet ITS results than the section recycled at 15 fpm.

Table 3.13: SB-135: Average Dry and Wet Indirect Tensile Strength Results

Variable	Factor	Dry			Wet		
		Average ITS		Sample Size	Average ITS		Sample Size
		psi	kPa		psi	kPa	
Recycling agent	Emulsified asphalt	46.9	323	15	34.3	236	15
	Foamed asphalt	55.3	381	24	39.0	269	24
Train	Single-unit	56.5	390	24	36.4	251	24
	Multi-unit	45.0	310	15	38.5	265	15
Speed (fpm)	15	56.2	387	6	32.7	225	6
	20	51.3	354	33	38.0	262	33

The Tukey's test grouping results in Table 3.14 show the following:

- The single-unit train foamed asphalt section recycled at 20 fpm had the highest dry ITS results, followed by the single-unit train foamed asphalt section recycled at 15 fpm, and then the single-unit train emulsified asphalt section at 20 fpm. The latter two strengths were not significantly different.
- The dry ITS results of the multi-unit train foamed asphalt section were lower than those on the single-unit train emulsified asphalt section.
- The multi-unit train emulsified asphalt section had the lowest dry ITS results.

- The wet ITS results did not follow the same trend as the dry ITS results. The multi-unit train foamed asphalt section had the highest wet strength, followed by the single-unit train foamed asphalt and the single-unit train emulsified asphalt sections.
- The single-unit train foamed asphalt section recycled at 15 fpm and the multi-unit train emulsified asphalt sections had similar wet ITS results.

Table 3.14: SB-135: Tukey Test on Average Indirect Tensile Strength Results

Factorial	Dry				Wet			
	Average ITS		Sample Size	Groups[a]	Average ITS		Sample Size	Groups[a]
	psi	kPa			psi	kPa		
Single-Unit_FA_20fpm	61.2	422	6	A	39.6	273	6	AB
Single-Unit_FA_15fpm	56.2	387	9	AB	32.7	225	9	B
Single-Unit_EA_20fpm	52.0	359	9	AB	35.7	246	9	AB
Multi-Unit_FA_20fpm	48.9	337	6	BC	42.7	294	6	A
Multi-Unit_EA_20fpm	39.1	270	9	C	32.1	221	9	B

[a] Means with the same letters are not significantly different.

Relationship between Indirect Tensile Strength and Density

The relationship between ITS and bulk density is plotted in Figure 3.33 and shows a very weak correlation between the two parameters on a project level. This is attributed to the differences in dry ITS results for the different recycling agents.

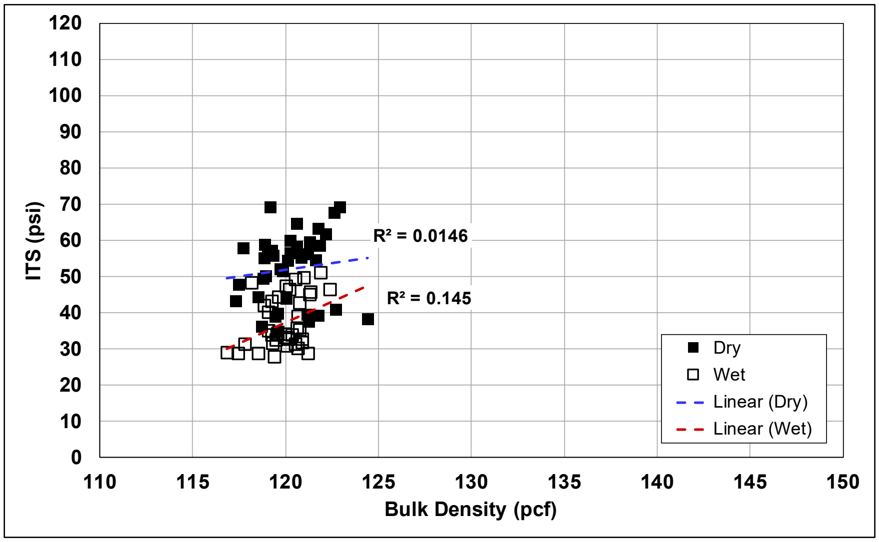

Figure 3.33: SB-135: Project-level relationship between indirect tensile strength and density.

When considering the results on a factorial basis (Table 3.15), the correlation improves for certain sections, especially the single-unit train emulsified asphalt section, with R^2 values of 0.54 and 0.64 for the wet and dry strengths, respectively. These results confirm that strengths are influenced by compaction density and that variability along the project had a considerable influence on the result.

Table 3.15: SB-135: Factorial-Level Effect of Density on Indirect Tensile Strength

Factorial	Condition	Slope (psi/pcf)	R^2
Single-Unit_20_FA	Dry	0.127	0.31
	Wet	0.155	0.24
Multi-Unit_20_EA	Dry	-0.007	0.02
	Wet	0.249	0.64
Multi-Unit_20_FA	Dry	0.456	0.68
	Wet	0.074	0.03
Single-Unit_15_FA	Dry	0.033	0.09
	Wet	-0.130	0.33
Single-Unit_20_EA	Dry	0.294	0.54
	Wet	0.321	0.64

3.6.4 Marshall Stability

Quality Control Test Results

Mix was also sampled to compact specimens for Marshall stability testing. Compaction and curing procedures were the same as for ITS testing; however, conditioning procedures differed as follows:

- Dry conditioning
  - + Specimens were conditioned in a chamber at 77°F (25°C) for 22 hours and then transferred to another chamber set to 104°F (40°C) for two hours prior to testing.
- Wet conditioning
  - + Specimens were vacuum saturated by applying a vacuum of 13 kPa to 67 kPa absolute pressure for a time duration required to vacuum saturate the samples to between 55% and 75%. The specimens were then soaked for 22 hours in a water bath maintained at 77°F (25°C), and for a further two hours in another bath at 104°F (40°C) prior to testing.

All of the specimens were then tested according to AASHTO T 245.

The Marshall stability results of the quality control specimens, mix design specimens, and the required minimum design dry stability are plotted in Figure 3.34. Due to the different conditioning procedures followed, it is not appropriate to compare the foamed and emulsified asphalt results, but the quality control results can be compared with the mix design results. The dry quality control stability results were similar to or higher than the mix design results. The wet quality control results were similar to or lower than the mix design results.

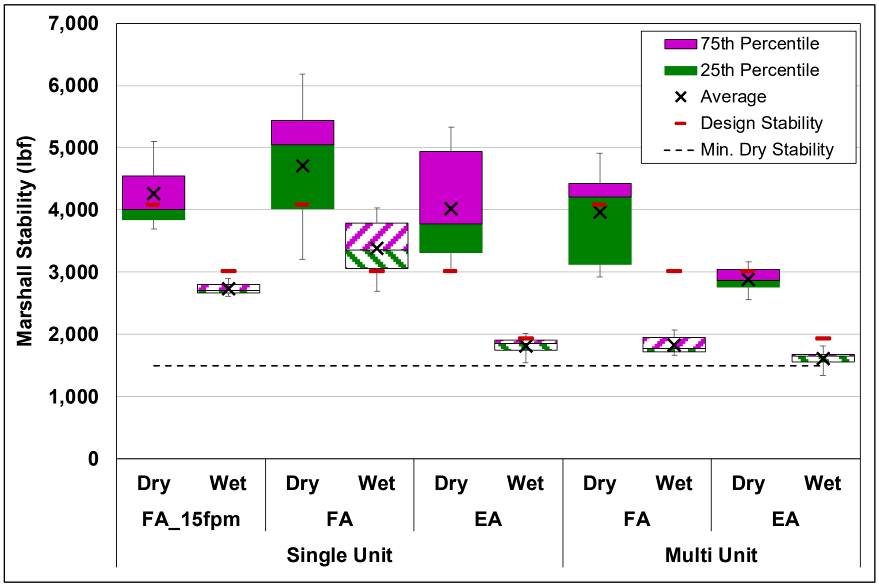

Figure 3.34: SB-135: Box and whisker plot of Marshall stability results.

The density results for the quality control specimens, the bulk density of the mix design specimens, and the wet and dry in-place densities, assuming a moisture content of 6%, are provided in Figure 3.35. The quality control bulk densities generally exceeded the mix design and in-place dry densities.

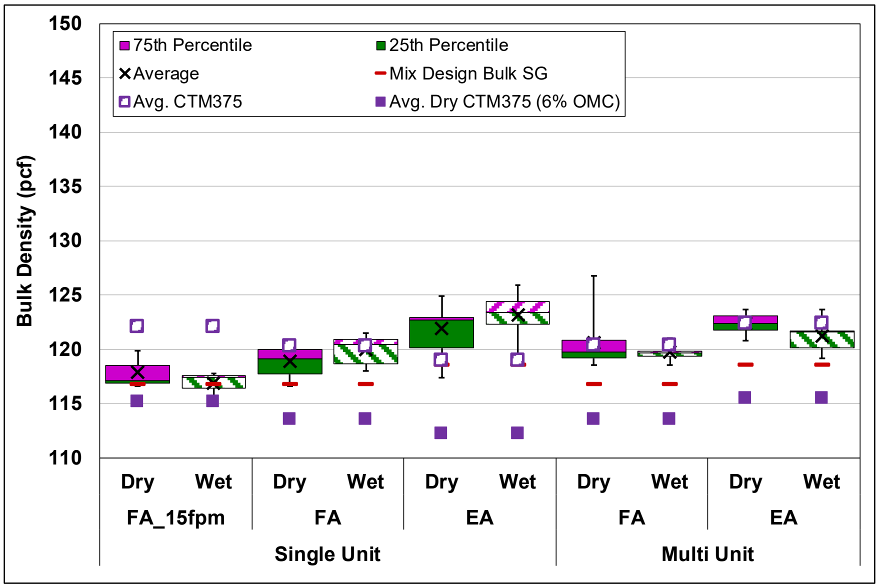

Figure 3.35: SB-135: Box and whisker plot of bulk densities of Marshall stability specimens.

Introduction to Analysis

The Marshall stability results were grouped by recycling agent for analyses due to the difference in conditioning procedures, and further grouped by testing condition, similar to the ITS results. The emulsified asphalt results were compared using a t-test since only train type was a factor. The foamed asphalt results were analyzed using an ANOVA due to there being two factors (train type and forward speed).

Analysis of Emulsified Asphalt Sections

The t-test results for the emulsified asphalt Marshall stability results are provided in Table 3.16 and show that recycling train type had a significant effect on stability. The sections recycled with the single-unit train had significantly higher dry and wet stability results than the sections recycled with the multi-unit train.

Table 3.16: SB-135: T-test of Emulsified Asphalt Marshall Stability Results

Test Condition	Train	Average Stability		Sample Size	t-stat	df	p-value	Significant ($\alpha = 0.05$)?
		lbf	kN					
Dry	Single-unit	3,985	17.7	9	-4.117	9.65	0.00225	Yes
	Multi-unit	2,851	12.7	6				
Wet	Single-unit	1,794	8.0	6	-2.465	8.59	0.0371	Yes
	Multi-unit	1,630	7.3	9				

Analysis of Foamed Asphalt Sections

The ANOVA results provided in Table 3.17 and Table 3.18 indicate that dry Marshall stability was not significantly affected by recycling train type or the recycling speed. The wet stability results were, however, significantly affected by both factors.

The average dry and wet Marshall stability results, for each variable, grouped by the different parameters, are provided in Table 3.19 and show the following:

- There was no difference between the dry Marshall stability results for the different parameters under each variable.
- The single-unit train sections had significantly higher wet stability results compared to the multi-unit train sections.
- The single-unit train 15 fpm section had significantly higher wet stability results compared to the 20 fpm sections.

Table 3.17: SB-135: ANOVA of Dry Marshall Stability Results

Source	Degrees of Freedom	Sum of Squares	Mean of Squares	F-Value	Prob. (>Fcr)	Significant (α = 0.05)?
Train	1	2,483,167	2,483,167	2.777	0.113	No
Speed	1	426,220	426,220	0.477	0.499	No
Residuals	18	16,096,651	894,258	—	—	—
Total	20	19,006,038	—	—	—	—

Table 3.18: SB-135: ANOVA of Wet Marshall Stability Results

Source	Degrees of Freedom	Sum of Squares	Mean of Squares	F-Value	Prob. (>Fcr)	Significant (α = 0.05)?
Train	1	11,016,267	11,016,267	76.751	<0.0001	Yes
Speed	1	844,574	844,574	5.884	0.026	Yes
Residuals	18	2,583,581	143,532	—	—	—
Total	20	14,444,422	—	—	—	—

Table 3.19: SB-135: Average Marshall Stability Results

Variable	Parameter	Dry			Wet		
		Average Stability		Sample Size	Average Stability		Sample Size
		lbf	kN		lbf	kN	
Train	Single-unit	4,854	21.6	12	3,396	15.1	12
	Multi-unit	4,159	18.5	9	1,933	8.6	9
Speed (fpm)	20	4,561	20.3	18	2,741	12.2	18
	15	4,527	20.1	3	2,937	13.1	3

The Tukey's test grouping results in Table 3.20 confirm the ANOVA results. There was no significant difference between the dry stability results. The ranking shows that the wet stability for the single-unit train foamed asphalt section recycled at 20 fpm was significantly higher than the section recycled at 15 fpm and that both were significantly higher than the stability on the multi-unit train foamed asphalt section.

Table 3.20: SB-135: Tukey Test on Foamed Asphalt Stability Results

Factorial	Dry				Wet			
	Average Stability		Sample Size	Groups[a]	Average Stability		Sample Size	Groups[a]
	lbf	kN			lbf	kN		
Single-Unit_FA_20fpm	4,963	22.1	9	A	3,550	15.8	9	A
Single-Unit_FA_15fpm	4,528	20.1	3	A	2,937	13.1	3	A
Multi-Unit_FA_20fpm	4,159	18.5	9	A	1,933	8.6	9	B

[a] Means with the same letters are not significantly different.

Relationship between Marshall Stability and Density

The relationship between Marshall stability and density plotted in Figure 3.36 shows the same trends as those between ITS and density. There does not appear to be a project-level relationship, indicating that recycling agent, active filler, and material variability, which is not accounted for in the figure, have a greater effect on the relationship than compaction. Reducing the data to the project level (Table 3.21) improved the correlations between density and stability, especially for the emulsified asphalt sections and for the single-unit train foamed asphalt section recycled at 15 fpm. Reducing the parameters and limiting the material variability to a single sampling location shows an improved correlation, confirming that compaction density is a critical parameter effecting stability.

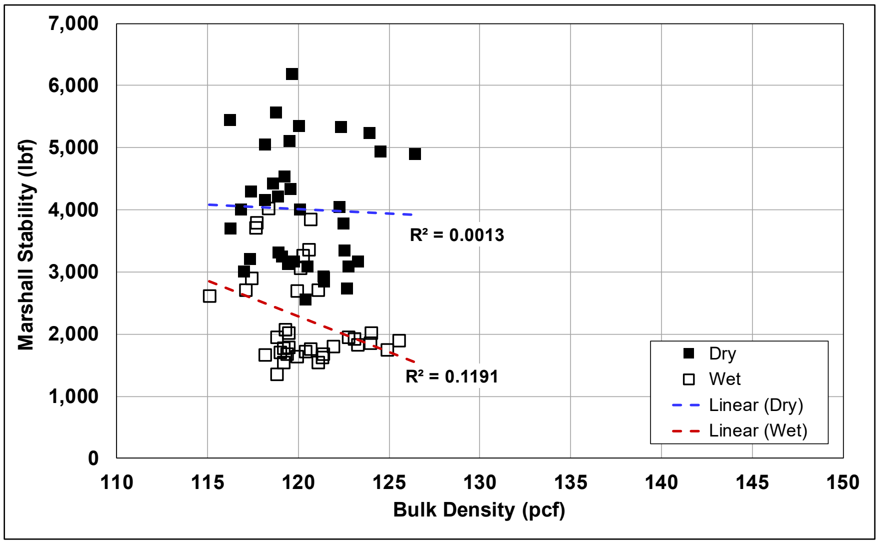

Figure 3.36: SB-135: Project-level relationship between Marshall stability and density.

Table 3.21: SB-135: Factorial-Level Effect of Density on Marshall Stability

Factorial	Condition	Slope (lbf/pcf)	R^2
Single-Unit_20_FA	Dry	6.13	0.02
	Wet	-14.17	0.37
Multi-Unit_20_EA	Dry	10.10	0.60
	Wet	4.79	0.59
Multi-Unit_20_FA	Dry	3.42	0.04
	Wet	-0.29	0.00
Single-Unit_15_FA	Dry	26.33	1.00
	Wet	5.76	0.71
Single-Unit_20_EA	Dry	17.87	0.58
	Wet	3.21	0.51

3.6.5 Summary of Analysis Factors

Possible explanations for the effects of each analysis variable on the material properties include the following:

- Effect of recycling agent on:
  - In-place wet density:
    - The average densities on the emulsified asphalt sections were higher than those on the foamed asphalt sections. This was attributed in part to the emulsified asphalt coating more of the RAP aggregates, which can assist with compaction.
    - Variability along the project, especially that associated with lane width, likely had a considerable influence on the results.
  - Indirect tensile strength:
    - Higher dry and wet strengths were recorded on the foamed asphalt specimens, but this was attributed to the higher residual binder and cement contents. The foamed asphalt mix design required 3.5% asphalt and 1.0% cement to achieve the minimum wet ITS of 35 psi (240 kPa). This combination resulted in an average wet ITS during production of 39 psi (269 kPa). The emulsified asphalt mix design required 2.3% residual asphalt binder and 0.5% cement to achieve the 35 psi requirement in the mix design and during production.
- Effect of recycling train type on:
  - In-place wet density:
    - Recycling train type had no significant effect on in-place wet density. Even though wet density is not an ideal parameter for this analysis, this finding indicates that the different recycling trains did not produce significantly different gradations and that any difference in the gradations would not have an effect on density.
  - Indirect tensile strength:
    - No significant differences were observed in wet strengths between the two types of recycling train. However, higher dry strengths were recorded on the samples taken behind the single-unit train. Wet strength is considered to be a better performance indicator than dry strength.
  - Marshall stability:
    - On this project, the wet foamed asphalt stability results, and both the dry and wet emulsified asphalt stability results showed that recycling train type affected the results, with the single-unit train appearing to produce material that resulted in higher stabilities than those produced with the multi-unit train. The effect of variability noted above is also relevant to this finding.
- Effect of forward speed on:
  - In-place density:
    - Reducing the forward speed to 15 fpm on the single-unit train resulted in a significant increase in density compared to the single-unit train at 20 fpm, which was attributed to the finer gradation produced at the slower speeds.

    - Indirect tensile strength:
        - Reducing the forward speed of the single-unit train to 15 fpm resulted in a significant decrease in strength compared to 20 fpm. The effect of variability noted above is also relevant to this finding.
    - Marshall stability:
        - Forward speed did not have any effect on the single-unit train foamed asphalt Marshall stability results (speed was not changed on the multi-unit train in this experiment).

The relationships between ITS, Marshall stability, and density indicated that increasing the density can increase the ITS and Marshall stability. The results discussed in this chapter have shown that higher densities can be achieved by reducing the forward speed of the recycling train. The differences in the gradations used to prepare specimens resulted in a range of densities that were positively correlated with increased strength and stability.

3.7 Conclusions

Key findings from this pilot study to date include the following:

- The quality control results did not show any discernable difference between the single- and multi-unit recycling trains. The single-unit train gradations were slightly coarser in the coarse portion of the gradation, but there was no consistent trend between the two trains to note any observable difference in fines or compacted density.
- The emulsified asphalt binder likely contributed to the increased density through better coating of the aggregate.
- The dry and wet ITS results for the foamed asphalt sections were higher than for the emulsified asphalt sections, as observed in the mix design and quality control results. However, direct comparisons between the two are difficult given the difference in the design asphalt binder and cement contents.
- The Marshall stability results for the emulsified asphalt and foamed asphalt specimens could not be compared due to the differences in conditioning procedures used for the two recycling agents in the mix designs.
- Reducing the forward speed produced a better gradation that resulted in better compaction densities, but it did not translate to higher strengths, which was expected.
- High variability along the project, especially in areas with narrow lanes, likely had a considerable influence on the results. Incorporating plastic fines from the shoulder into the PDR layer in these narrow areas, along with poor support under the outer edge of the recycled layer/asphalt overlay, will likely lead to early distresses appearing in the outer

wheelpaths. These observations support the need for doing site investigations to make informed decisions about the most appropriate capital preventive maintenance (CAPM) or rehabilitation strategy for any project.

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4 SBD-2: EA 08-1L6604 - RECYCLING TRAIN COMPARISON

4.1 Project Description

This pilot project is located on SBD-2, east of Wrightwood in San Bernardino County, between PM 3.27 and PM 5.9. The project had transverse and longitudinal cracking (Figure 4.1), block cracking (Figure 4.2), and alligator A and B cracking (Figure 4.3). Construction of the PDR layer took place between 08/25/2021 and 09/02/2021.

Figure 4.1: SBD-2: Transverse and longitudinal cracking.

Figure 4.2: SBD-2: Block cracking.

Figure 4.3: SBD-2: Alligator B cracking in the wheelpaths.

4.2 Pavement Structure

No core or DCP data within the project limits were made available by the contractor at the time of writing this report.

4.3 Pilot Study Experimental Design

The goals of this project were to compare single- and multi-unit recycling trains, using different forward speeds to control the maximum aggregate size (MAS) and reduce air-void contents. Forward speeds on both units, and screens on the multi-unit train, were adjusted to produce maximum aggregate sizes of 1.25, 1.0, and 0.75 in. (31, 25, and 19 mm). A recycling depth of 0.25 ft. (75 mm) was specified for the project. Emulsified asphalt was used as the recycling agent and cement was used as the active filler. The layout of the sections (as built) is provided in Figure 4.4.

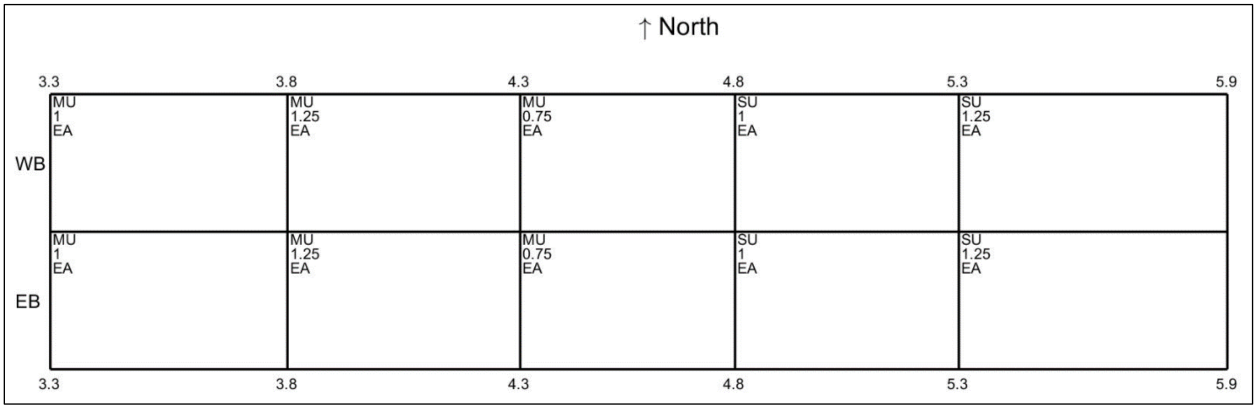

Figure 4.4: SBD-2: As-built factorial sections.

4.4 Mix Design

The mix design was performed following CT 315. Medium and coarse gradations were prepared from crushed cores sampled from the project. Gyratory compaction, following AASHTO T 312, was used to compact the specimens. The mix design results are summarized in Table 4.1. The average specimen density was 129 pcf (2,006 kg/m^3), with an air-void content of 11.2%. The mix design required 3.0% emulsified asphalt (1.9% residual asphalt) with 0.5% cement to meet the specified Marshall stability requirements. This mix did not achieve the minimum wet ITS of 35 psi (240 kPa), which is a report-only requirement for emulsified asphalt-treated materials.

4.5 Construction

Construction of the recycled layer was monitored by the UCPRC from 08/25/2021 to 09/02/2021. The construction sequence was typical of standard PDR projects (see Section 2.5). The construction schedule is provided in Table 4.2 along with forward speed and target MAS for each section. Forward speeds were consistent for each section.

Table 4.1: SBD-2: Mix Design Results

Parameter	Gradation		
	Medium	Coarse	Specification
Emulsified asphalt content (%)	3.0	3.0	n/a
Residual asphalt (%)	1.926	1.926	n/a
Optimum moisture content (%)	4.8	4.8	n/a
Cement (%)	0.5	0.5	n/a
Specific gravity (AASHTO T 209)	2.326	2.328	n/a
Bulk density (pcf) [kg/m^3]	128.9 (2,065)	129.0 (2,067)	n/a
Air-void content (%)	11.2	11.2	n/a
Dry stability at 104°F (40°C) (lbf) [kN]	2,925 (13.0)	2,970 (13.2)	>1,500 (6.7)
Wet stability after vacuum saturation (lbf) [kN]	2,285 (10.2)	2,320 (10.3)	n/a
Retained stability (%)	78.1	78.1	>70
Average dry indirect tensile strength (psi) [kPa]	49.1 (339)	52.1 (359)	Report only
Average wet indirect tensile strength (psi) [kPa]	26.2 (181)	28.6 (197)	Report only
Retained indirect tensile strength (%)	53.4	54.9	Report only

[a] 30 gyrations [600 kPa at 1.16°] in a 100 mm mold.

Table 4.2: SBD-2: Construction Schedule

Factorial	Date	Westbound		Eastbound		Forward Speed		MAS (in.)
		Start	End	Start	End	fpm	m/min	
Multi-Unit_1_EA	8/25/2021	3.27	3.8	n/a	n/a	20	6.1	1.0
Multi-Unit_1.25_EA	8/26/2021	n/a	n/a	3.8	4.32	23	7.0	1.25
Multi-Unit_1_EA	8/26/2021	n/a	n/a	3.27	3.8	20	6.1	1.0
Multi-Unit_1.25_EA	8/27/2021	3.8	4.32	n/a	n/a	23	7.0	1.25
Multi-Unit_0.75_EA	8/30/2021	n/a	n/a	4.32	4.8	10	3.0	0.75
Multi-Unit_0.75_EA	8/31/2021	4.32	4.8	n/a	n/a	10	3.0	0.75
Single-Unit_1.25_EA	9/1/2021	n/a	n/a	5.3	5.9	16	4.9	1.25
Single-Unit_1_EA	9/1/2021	n/a	n/a	4.8	5.3	12	3.7	1.0
Single-Unit_1.25_EA	9/2/2021	5.3	5.9	n/a	n/a	16	4.9	1.25
Single-Unit_1_EA	9/2/2021	4.8	5.3	n/a	n/a	12	3.7	1.0

Observations during construction included:

- Transverse cracks approximately 1 in. (25 mm) wide were visible along the length of the project in the underlying asphalt concrete layer after milling. Crack spacing was approximately 23 ft. (7 m) (Figure 4.5 and Figure 4.6).
- Longitudinal cracks along the centerline and shoulder striping often crumbled into the cut after the recycler pass (Figure 4.7). In most instances, the recycling crew removed these from the recycling cut prior to the windrow being spread by the paver.
- In some locations, the milling depth on the project coincided with an asphalt rubber chip seal stress absorbing membrane interlayer (SAMI). Remnants of the chip seal were visible in the cut behind the milling machine (Figure 4.8). Large chunks of the rubberized material

also accumulated on the screen of the multi-unit train on the section with the 0.75 in. MAS target (Figure 4.9).

Figure 4.5: SBD-2: Width of reflective transverse shrinkage cracks in cut.

Figure 4.6: SBD-2: Spacing of transverse cracking.

Figure 4.7: SBD-2: Material from centerline and shoulder cracks collapsing into cut.

Figure 4.8: SBD-2: Remains of asphalt rubber chip seal SAMI at bottom of milling cut.

Figure 4.9: SBD-2: Asphalt rubber chip seal millings on multi-unit train screen.

- Emulsion spills from the milling chamber on the single-unit train were observed on a few occasions (Figure 4.10) when the train moved down steeper gradients and the settings had not been adjusted for the conditions. These spills were addressed by the crew as soon as they were observed. It should be noted that the single-unit train had recently been purchased by the contractor and the crew was still familiarizing itself with the operation of it.
- Between PM 4.8 and PM 5.3, the outside 11 to 12 in. (275 to 300 mm) of the recycled lane, as well as the shoulder, appeared to have been constructed on compacted aggregate base (Figure 4.11). The center of the lane was over asphalt concrete. This was likely the result of past widening or realignment actions.
- The last approximately 30 ft. (10 m) at the end of each day's recycling were susceptible to raveling during the night following construction (Figure 4.12 and Figure 4.13). This was caused by a combination of factors associated with the distance between where the milling drum stopped and the windrow started, the paver exiting the cut, and completion of material leveling with the skid loader. Raveled sections were included in the following day's recycling.

Figure 4.10: SBD-2: Emulsified asphalt spilling out of recycling chamber.

Figure 4.11: SBD-2: Aggregate base next to old asphalt concrete in cut.

Figure 4.12: SBD-2: Raveling of PDR-EA layer constructed at end of day - 08/31/21.

Figure 4.13: SBD-2: Raveling of PDR-EA layer constructed at end of day - 09/01/21.

4.6 Quality Control Test Results and Analysis

The quality control results provided by the contractor are summarized in Table 4.3. The test locations along the project are illustrated in Figure 4.14.

Table 4.3: SBD-2: Quality Control Data Collected During Construction

Description	Test Method	Minimum Test Frequency
Field compacted wet density	CT 375	2 tests per lot
Breakover density	CT 216	1 test per lot
Coarse sieve analysis on mixed material	AASHTO T 27	1 per day
Maximum theoretical density	AASHTO T 209	1 per day
Wet/dry gradations on clean RAP	AASHTO T 27/T 11	1 per day
ITS of mixed material	AASHTO T 283	1 per lot
Marshall stability	AASHTO T 245	1 per lot

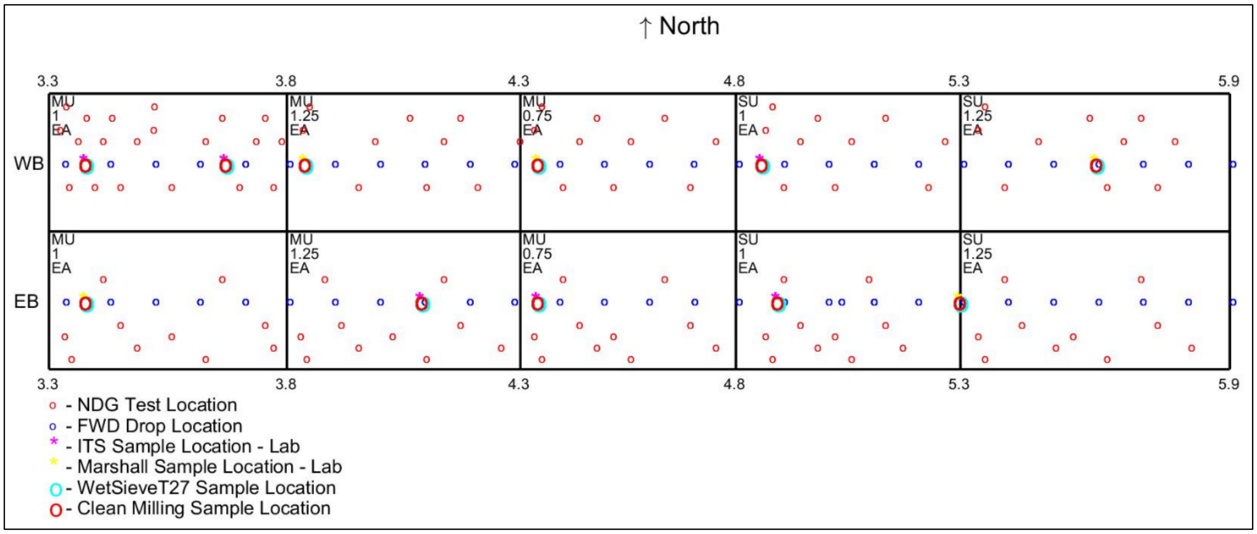

Figure 4.14: SBD-2: Quality control data layout across the project.

Variability in the quality control data was expected and consequently analyses were undertaken to determine if the differences in means were significant using either analyses of variance (ANOVA) or a t-test, depending on the number of variables. The means were then compared, grouped, and ranked using a pairwise comparison of the means method (Tukey's test) to determine if the means were statistically equivalent.

In the ANOVA, the null hypothesis was that the means of the different variables were equal, and the alternate hypothesis was that the means were not all equal. In the t-test, the null hypothesis was that the difference in group means was zero, and the alternate hypothesis was that the difference was not zero. Tukey's test determines which means are statistically equivalent and assigns a letter to statistically equivalent groups; means with the same letter are not significantly different at a confidence level of 95% (α = 0.05).

4.6.1 In-Place Wet Density and Relative Compaction

Test Results

In-place wet density of the compacted PDR layer was tested following CT 375. The target density was determined using the breakover density, determined at the beginning of each section. The in-place wet densities and the breakover densities are provided in Figure 4.15. The in-place densities of the PDR layer ranged between 115.5 and 124.5 pcf (1,850 and 1,994 kg/m^3), with a project average of 119.9 pcf (1,921 kg/m^3) and a standard deviation of 2.2 pcf (35 kg/m^3). No observable differences between the different sections was apparent.

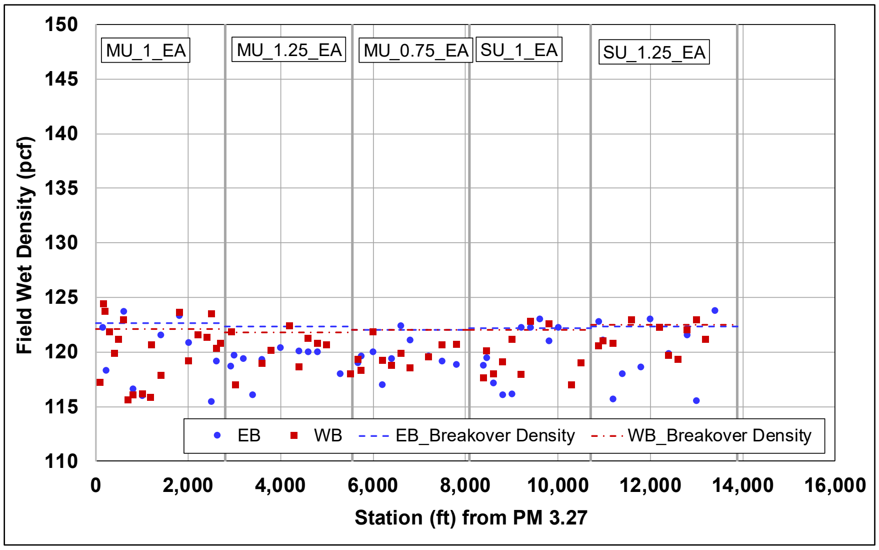

Figure 4.15: SBD-2: Longitudinal view of density results.

In-place density results are further summarized in the box and whisker plot in Figure 4.16 and in Table 4.4. The average breakover density per factorial element is also provided for reference. No noticeable differences in the in-place density results between the different sections was apparent. The multi-unit train lots with a target MAS of 0.75 in. had the lowest variability, but the mean densities were similar. Average relative compaction was 99.3%, with a minimum of 95.3% and a maximum of 102.7%. Air-void contents ranged between 17.9% and 20.1%. The lowest air-void contents were measured on the single-unit train lots with a target MAS of 1.0 in.

All of the sections were rerolled on 09/08/2021, between 6 and 14 days after initial compaction. Rerolling effectively increased the in-place density, with an average increase of 4.2 pcf (67 kg/m^3). After rerolling, higher densities were noted on the single-unit train sections than on the multi-unit train sections. This was likely primarily due to the shorter interval between initial compaction and rerolling on these sections (i.e., the single-unit train sections were the last to be constructed) and not to differences associated with the type of recycling train.

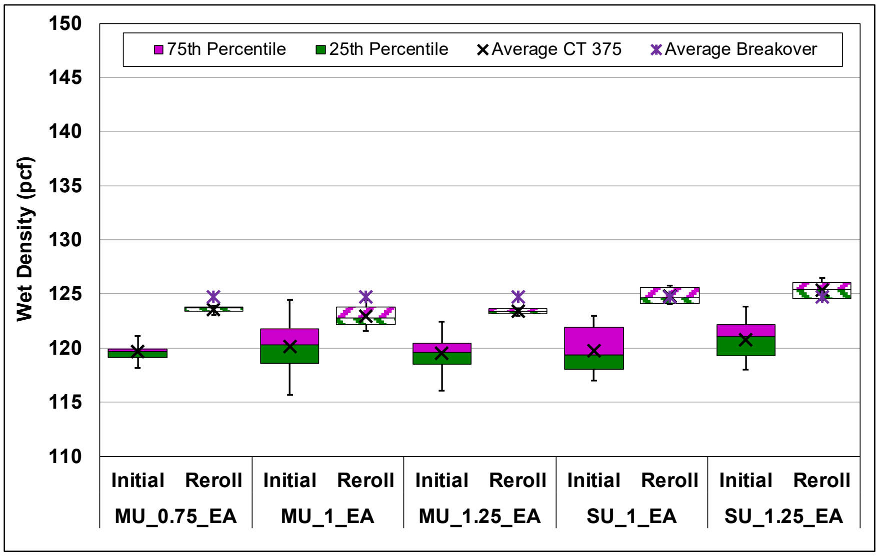

Figure 4.16: SBD-2: Box and whisker plot of density results, including reroll results.

Table 4.4: SBD-2: Compaction Results

Factorial	**Event**	**Field Wet Density**				**Rel. Compaction (%)**		**Void Ratio (%)**
		Average		**Std. Dev.**				
		pcf	**kg/m^3**	**pcf**	**kg/m^3**	**Avg.**	**Std. Dev.**	**Average**
Multi-Unit_ 1.25_EA	Construction	119.6	1,916	1.7	27	99.0	1.4	19.6
	Reroll	123.4	1,977	1.7	27	98.9	1.3	n/a
Multi-Unit_ 1_EA	Construction	120.0	1,922	3.2	51	99.0	2.4	18.6
	Reroll	123.0	1,970	2.1	34	98.6	1.5	n/a
Multi-Unit_ 0.75_EA	Construction	119.7	1,917	1.5	24	99.1	1.0	18.4
	Reroll	123.6	1,980	0.9	14	99.1	0.6	n/a
Single-Unit_ 1.25_EA	Construction	120.6	1,932	2.4	38	99.9	1.9	20.1
	Reroll	125.4	2,009	1.3	21	100.5	0.9	n/a
Single-Unit_ 1_EA	Construction	119.7	1,917	2.5	40	99.2	1.9	17.9
	Reroll	124.9	2,001	1.2	19	100.2	0.8	n/a

Analysis

The in-place wet densities were analyzed to determine if recycling train type, forward speed, and rerolling had significant effects on the density. The ANOVA (Table 4.5) of the density results shows that the recycling train type and rerolling had significant effects, while recycling speed did not.

Table 4.5: SBD-2: ANOVA of In-Place Density Results

Source	Degrees of Freedom	Sum of Squares	Mean of Squares	F-Value	Prob. (>Fcr)	Significant (α = 0.05)?
Train	1	117	117	24.21	<0.0001	Yes
Type	1	1,299	1299	269.39	<0.0001	Yes
Speed	1	1.2	1.2	0.24	0.624	No
Residuals	336	1,620	4.8	—	—	—
Total	339	3,036	—	—	—	—

The Tukey's test grouping results of the density results are provided in Table 4.6. The results confirm the ANOVA results, showing that the single-unit train results, after rerolling, were significantly higher than the multi-unit results. There was no significant difference between the density results immediately after construction. The grouping results also show that there was no statistically explainable difference between the density results for the sections with different recycling speeds.

Table 4.6: SBD-2: Ranked Average Density Results with Different Forward Speeds

Factorial	Mean Field Density		Sample Size	Groups[a]
	pcf	kg/m^3		
Single-Unit_1.25_EA_Reroll	125.4	2,009	30	A
Single-Unit_1_EA_Reroll	124.9	2,001	22	AB
Multi-Unit_0.75_EA_Reroll	123.6	1,980	20	AB
Multi-Unit_1.25_EA_Reroll	123.4	1,977	20	B
Multi-Unit_1_EA_Reroll	123.0	1,970	28	B
Single-Unit_1.25_EA_Construction	120.6	1,932	40	C
Multi-Unit_1_EA_Construction	120.0	1,922	60	C
Single-Unit_1_EA_Construction	119.7	1,917	40	C
Multi-Unit_0.75_EA_Construction	119.7	1,917	40	C
Multi-Unit_1.25_EA_Construction	119.6	1,916	40	C

[a] Means with the same letters are not significantly different.

4.6.2 Gradations

<u>Quality Control Test Results</u>

Untreated RAP was collected at the beginning of each day for gradation tests. The gradations are provided in Figure 4.17. The MAS of each sample was calculated as well as the sum of square error (SSE) between the corresponding maximum density line and the gradation. The results are provided in Table 4.7.

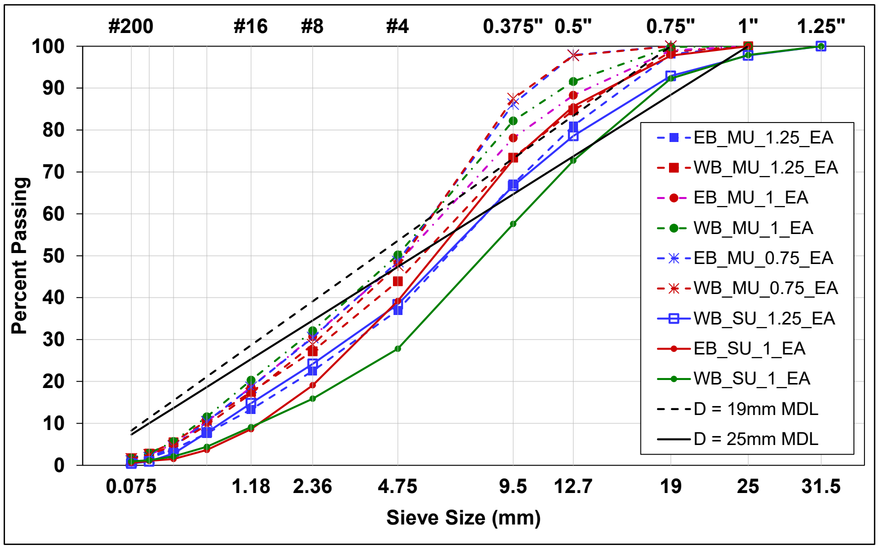

Figure 4.17: SBD-2: Production gradations on 0.45 power maximum density line.

Table 4.7: SBD-2: Difference Between Production Gradations and Maximum Density Line

Direction	Factorial	Max. Aggregate Size (in.)	SSE
EB	Multi-Unit_1.25_EA	1.0	882
EB	Multi-Unit_1_EA	1.0	799
EB	Multi-Unit_0.75_EA	0.75	957
EB	Single-Unit_1_EA	1.0	1,384
WB	Multi-Unit_1.25_EA	1.0	645
WB	Multi-Unit_1_EA	0.75	581
WB	Multi-Unit_0.75_EA	0.75	1,058
WB	Single-Unit_1.25_EA	1.0	718
WB	Single-Unit_1_EA	1.0	1,521

The sieve analyses show that the single-unit train generally produced gradations that were marginally coarser than the multi-unit train gradations for the same target MAS. The materials sampled from the multi-unit train lots with a design MAS of 0.75 in. and the westbound multi-unit train lot with a target design MAS of 1.0 in. did not have any aggregates larger than 0.75 in. The remaining sections, including those with a target MAS of 1.25 in., had aggregates up to 1.0 in. with no aggregates retained on the 1.0 in. sieve.

Similar to the observations discussed in Section 3.6.2, there did not appear to be a relationship between the SSE of the maximum density line and gradation and the density for this project, as shown in Figure 4.18.

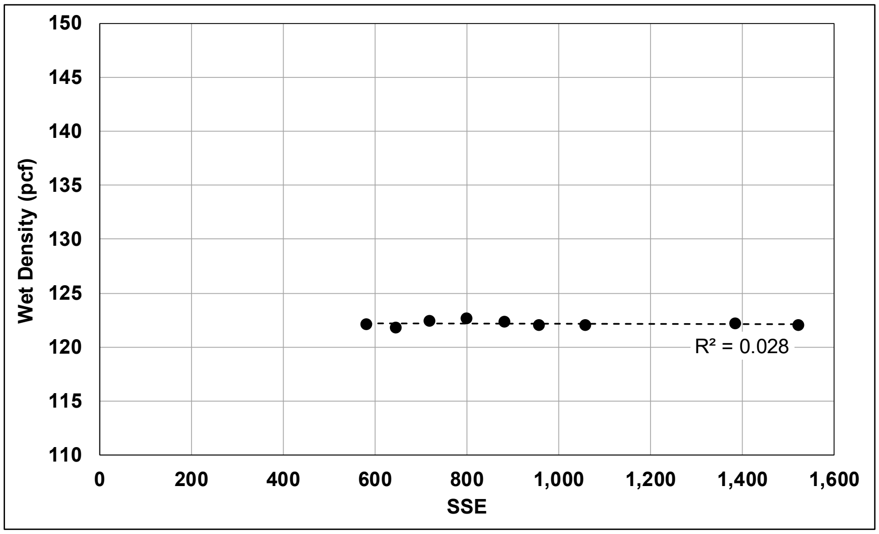

Figure 4.18: SBD-2: Relationship between SSE and average field wet density.

Sieve analyses for the untreated material are provided in Table 4.8 to support Figure 4.17. No consistent trend is apparent between the speed changes and machine type and increases in the percent passing the finer sieves. The multi-unit train did, however, produce gradations with higher percentages passing the #4 (4.75 mm).

Table 4.8: SBD-2: Untreated RAP Gradations

	Multi-Unit (% Passing)						**Single-Unit (% Passing)**		
Direction	**EB**	**WB**	**EB**	**WB**	**EB**	**WB**	**EB**	**WB**	**WB**
Speed (fpm)	**10**	**10**	**20**	**20**	**23**	**23**	**12**	**12**	**16**
Design MAS (in.)	**0.75**	**0.75**	**1.0**	**1.0**	**1.25**	**1.25**	**1.0**	**1.0**	**1.25**
1.25	100	100	100	100	100	100	100	100	100
1.0	100	100	100	100	100	100	100	97.9	97.8
0.75	100	100	99	99.9	98.1	98.7	97.8	92.3	92.9
0.5	97.9	97.8	88.3	91.6	81	84.7	85.7	72.7	78.6
0.38	86.2	87.5	78.1	82.2	67.1	73.4	73.0	57.6	66.7
#4	48.6	47.7	48.3	50.2	37.0	43.9	39.2	27.8	38.4
#8	30.5	28.8	30.7	32.1	22.5	27.2	19.1	15.9	24.2
#16	18.6	17.1	18.6	20.3	13.3	17.5	8.6	9.1	14.8
#30	10.4	9.6	10.4	11.6	7.6	10.6	3.7	4.4	7.8
#50	4.5	4.7	5.1	5.7	3.8	5.5	1.5	2.1	2.8
#100	1.8	2.5	2.5	2.9	1.7	2.8	1.1	1.2	0.9
#200	1.0	1.5	1.4	1.7	0.8	1.7	0.6	0.9	0.4

Treated material was also sampled on all sections for report-only purposes to check the coarse portion of the gradations (Figure 4.19). The sieve analyses show that 100% of the material produced by the multi-unit train passed the 1.0 in. sieve, while the single-unit train produced some material that was retained on the 1.25 in sieve. In this gradation range (i.e., #4 to 1.25 in), the multi-unit train generally produced gradations finer than the single-unit train.

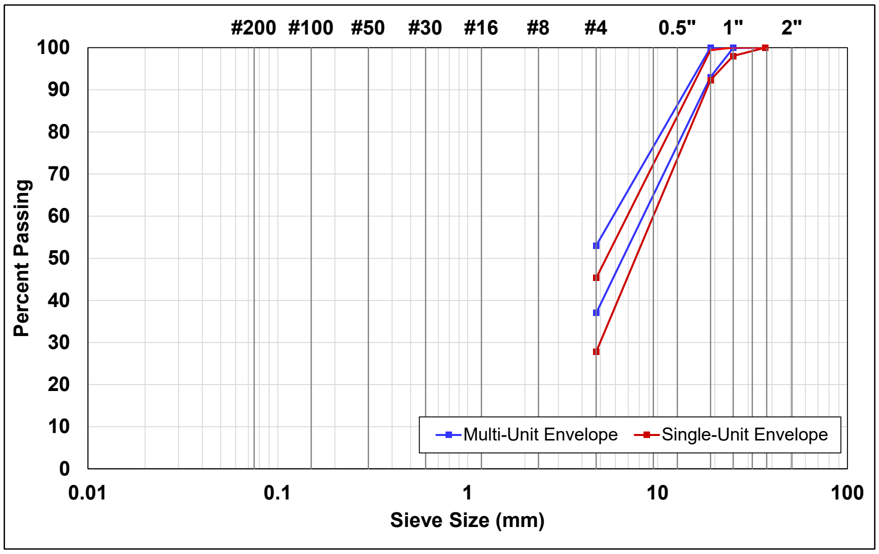

Figure 4.19: SBD-2: Mix gradation envelopes produced with different units and speeds.

4.6.3 Indirect Tensile Strength

Quality Control Test Results

Mix was sampled from the windrow, once per section, to compact specimens for ITS tests. Specimens were not prepared by the contractor for the single-unit train lots with a target MAS of 1.0 in. Gyratory compaction, following AASHTO T 312, was used to compact six specimens. The specimens were transported to a laboratory at the end of the day and placed in a forced draft oven at 104°F (40°C) for 72 hours. Three of the specimens were dry cured for a further 24 hours, and the remaining three were soaked for 24 hours with a water temperature at 77°F (25°C). All specimens were then tested according to AASHTO T 283.

The quality control and mix design ITS results are plotted in Figure 4.20. The specimens produced from the multi-unit train sections generally exceeded the strengths determined during mix design, whereas the specimens from the single-unit train sections did not. No trend between MAS and ITS was apparent, with specimens from the multi-unit train lots with a target MAS of 1.0 in. having higher strengths than those specimens from the multi-unit train lots with target maximum sizes of 0.75 in. and 1.25 in.

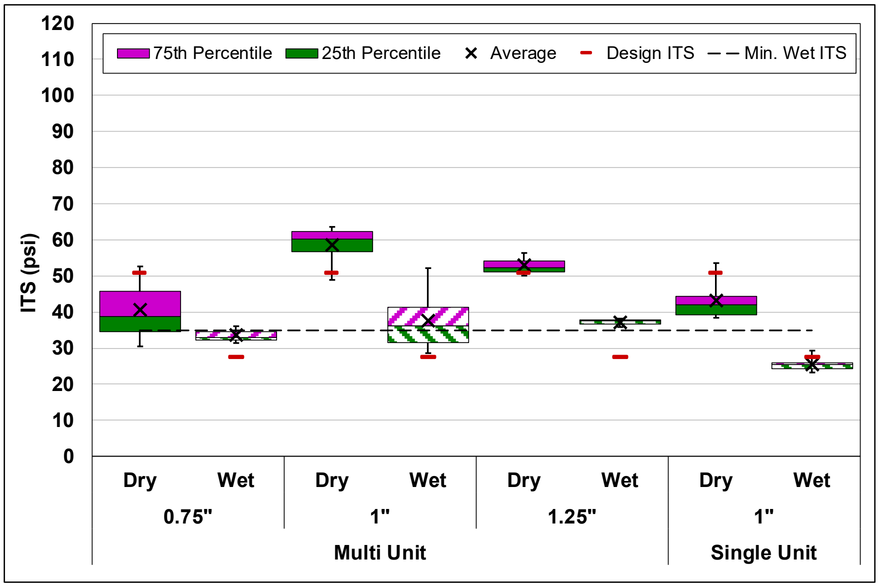

Figure 4.20: SBD-2: Box and whisker plot of indirect tensile strength results.

Box and whisker plots of the quality control ITS specimen bulk densities, the average mix design bulk densities, and average in-place wet and dry densities after rerolling, assuming a moisture content of 6%, are provided in Figure 4.21. The quality control specimens generally had lower densities than the mix design specimens but had higher densities than the in-place dry densities. The difference between the laboratory quality control specimen densities and in-place dry densities, before rerolling, was 12.2 pcf (195 kg/m^3). After rerolling, this difference reduced to 8.2 pcf (131 kg/m^3).

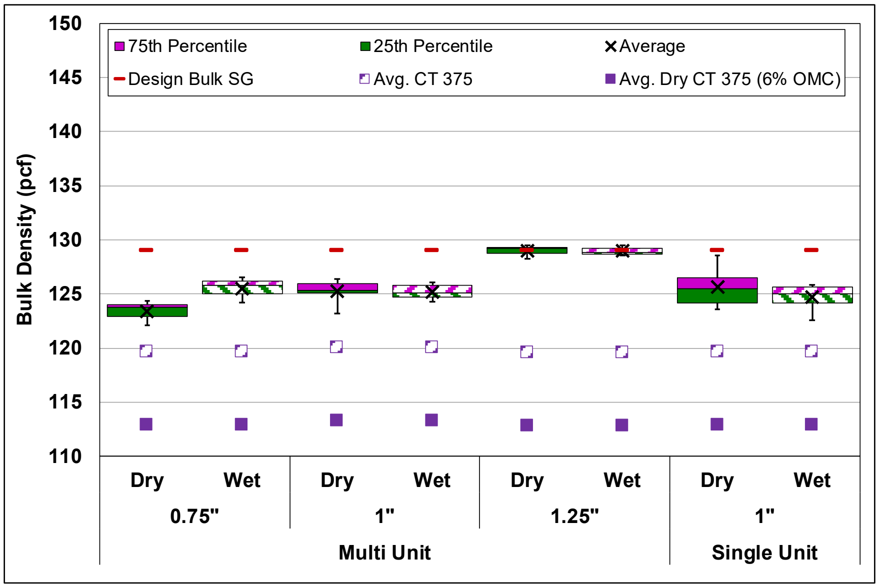

Figure 4.21: SBD-2: Box and whisker plot of indirect tensile strength specimen bulk densities.

Analysis

The ITS data were grouped by dry and wet conditioning to isolate the effects of recycling train and forward speed. The interaction between single-unit train and speed could not be analyzed since ITS testing was not done by the contractor on the sections with a target MAS of 1.25 in. The ANOVA of the dry and wet ITS results are provided in Table 4.9 and Table 4.10, respectively. The ANOVA of the dry ITS results shows that the effect of recycling speed and recycling train were significant. The ANOVA of the wet ITS results shows that the effect of the recycling train type was significant, while speed was not.

Table 4.9: SBD-2: ANOVA of Dry Indirect Tensile Strength Results

Source	Degrees of Freedom	Sum of Squares	Mean of Squares	F-Value	Prob. (>Fcr)	Significant (α = 0.05)?
Train	1	355	355	6.93	0.019	Yes
Speed	1	453	453	8.84	0.009	Yes
Residuals	15	768	51	—	—	—
Total	17	1,575	—	—	—	—

Table 4.10: SBD-2: ANOVA of Wet Indirect Tensile Strength Results

Source	Degrees of Freedom	Sum of Squares	Mean of Squares	F-Value	Prob. (>Fcr)	Significant (α = 0.05)?
Train	1	475	475	16.59	1.00E-03	Yes
Speed	1	31	31	1.07	0.32	No
Residuals	15	430	29	—	—	—
Total	17	935	—	—	—	—

The Tukey's test results in Table 4.11 show the rankings and groupings of the dry and wet ITS results. Observations include the following:

- The multi-unit train lots with a target MAS of 1.0 in. had the highest strengths, followed by the multi-unit train lots with a target MAS of 1.25 in., the single-unit train lots with a target MAS of 1.0 in., and lastly the multi-unit train lots targeting a MAS of 0.75 in.

Table 4.11: SBD-2: Average ITS Results with Different Recycling Trains and Forward Speeds

Factorial	Dry				Wet			
	Average ITS		Sample Size	Groups	Average ITS		Sample Size	Groups
	psi	kPa			psi	kPa		
Multi-Unit_1_EA	58.6	404	3	A	37.6	259	6	A
Multi-Unit_1.25_EA	52.9	365	3	AB	37.2	256	3	A
Single-Unit_1_EA	43.3	299	6	B	25.6	177	6	B
Multi-Unit_0.75_EA	40.7	281	6	B	33.5	231	3	AB

[a] Means with the same letters are not significantly different.

- There was no significant difference as a result of speed for the multi-unit train sections, with the multi-unit train lots with a target MAS of 0.75 in. having the lowest strength and the multi-unit train lots with a MAS of 1.0 in. producing the highest strength.
- The single-unit train lots with a target MAS of 1.0 in. had the lowest strength overall.

Relationship between Indirect Tensile Strength and Density

The relationship between ITS and bulk density for the project is provided in Figure 4.22. A weak correlation exists between strength and density on the project level, attributed in part to the small distribution of specimen densities. When considering the results on a factorial basis (Table 4.12) by reducing the sample size to a single location, the correlation improves for the multi-unit train lots with a target MAS of 0.75 in.

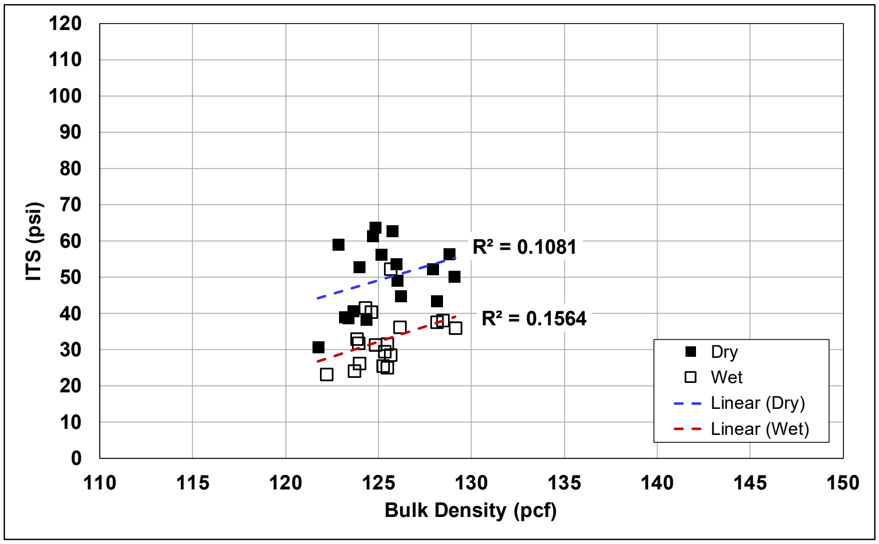

Figure 4.22: SBD-2: Indirect tensile strength and density relationship.

Table 4.12: SBD-2: Effect of Density on Indirect Tensile Strength

Factorial	Condition	Slope (psi/pcf)	R^2
Multi-Unit_0.75_EA	Dry	8.86	0.84
	Wet	0.92	0.21
Multi-Unit_1_EA	Dry	-1.50	0.09
	Wet	2.66	0.05
Multi-Unit_1.25_EA	Dry	-0.10	0.00
	Wet	-1.98	0.72
Single-Unit_1_EA	Dry	1.55	0.26
	Wet	1.12	0.44

4.6.4 Marshall Stability

Quality Control Test Results

Mix was sampled from the windrow to compact specimens for Marshall stability testing. Specimen preparation and testing followed the procedures detailed in Section 3.6.4.

The Marshall stability results for the quality control and mix design specimens are provided in Figure 4.23. The quality control specimens generally exceeded the dry stabilities determined during the mix design but had lower wet stabilities than the mix design. Specimens produced from the single-unit train sections had higher dry and wet stabilities than those from the corresponding multi-unit train sections, which was attributed to the higher densities achieved on the specimens produced from the single-unit train sections.

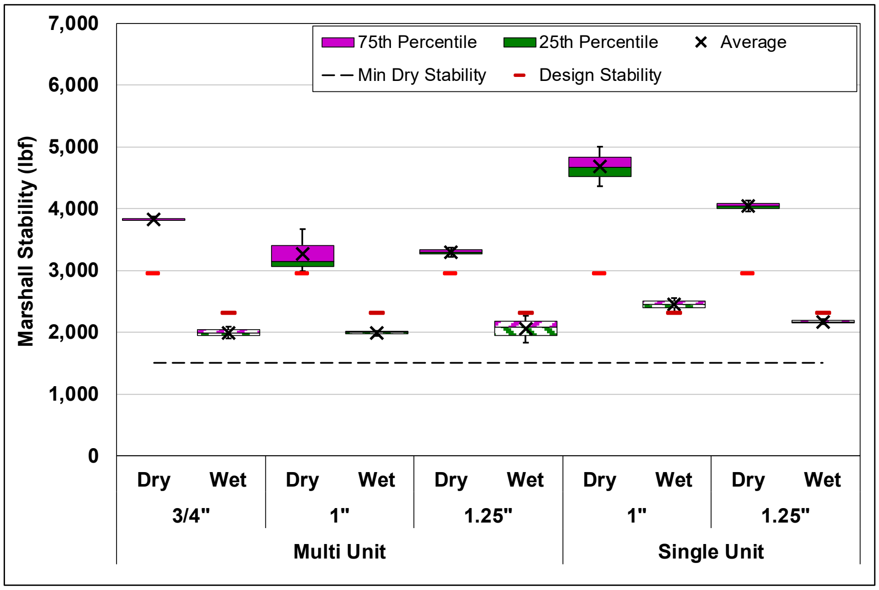

Figure 4.23: SBD-2: Box and whisker plot of Marshall stabilities.

The density results for the quality control specimens, the bulk density of the mix design specimens, and the wet and dry in-place densities, assuming a moisture content of 6%, are plotted in Figure 4.24. The densities of the quality control specimens did not follow the same trend as the ITS quality control specimens. The specimens prepared from the single-unit train lots with a target MAS of 1 in. had higher densities than the rest of the group.

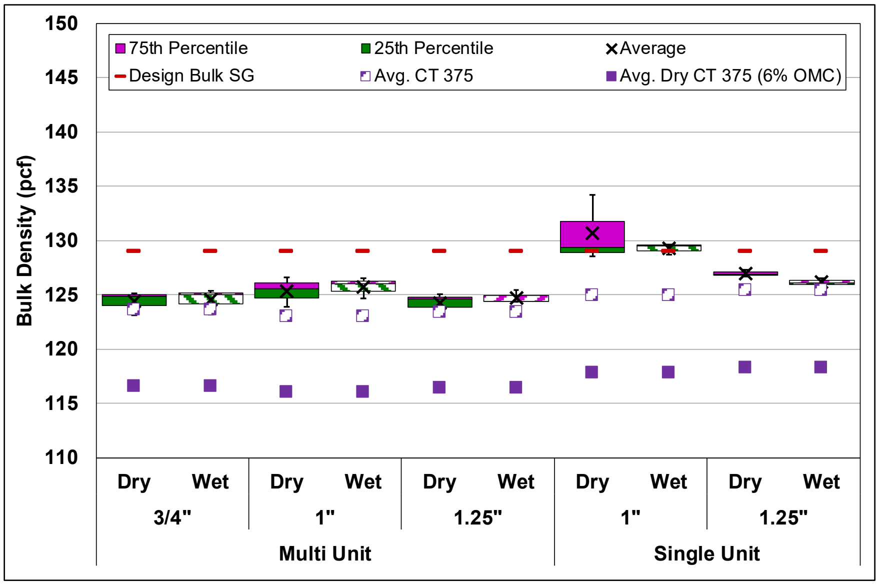

Figure 4.24: SBD-2: Box and whisker plot of Marshall specimen bulk densities.

Analysis

Marshall stability results were grouped by dry and wet conditioning to isolate the effects of recycling train, forward speed, and the difference in forward speed per train on the results. The ANOVAs of the dry and wet stability results are provided in Table 4.13 and Table 4.14, respectively.

Table 4.13: SBD-2: ANOVA of Dry Marshall Stability Results

Source	Degrees of Freedom	Sum of Squares	Mean of Squares	F-Value	Prob. (>Fcr)	Significant (α = 0.05)?
Train	1	2,901,246	2,901,246	61.17	<0.0001	Yes
Speed	1	877,653	877,653	18.51	0.0013	Yes
Train:Speed	1	283,045	283,045	5.97	0.0327	Yes
Residuals	11	521,695	47,427	—	—	—
Total	14	4,583,639	—	—	—	—

Table 4.14: SBD-2: ANOVA of Wet Marshall Stability Results

Source	Degrees of Freedom	Sum of Squares	Mean of Squares	F-Value	Prob. (>Fcr)	Significant (α = 0.05)?
Train	1	311,156	311,156	22.76	5.80E-04	Yes
Speed	1	1,724	1,724	0.13	0.7300	No
Train:Speed	1	118,926	118,926	8.70	0.0132	Yes
Residuals	11	150,374	13,670	—	—	—
Total	14	582,180	—	—	—	—

The ANOVA of the dry stability shows that the effect of recycling speed and recycling train were significant. The ANOVA of the wet stability shows that the effect of recycling train was significant, while speed was not.

The Tukey's test results in Table 4.15 provides the ranking and grouping for the dry and wet Marshall stability results. Observations include the following:

- The dry test results show that the single-unit train lots with a target MAS of 1.0 in. had the highest stability, followed by the single-unit train lots with a target MAS of 1.25 in., the multi-unit train lots with a target MAS of 0.75 in., and lastly the multi-unit train lots with target sizes of 1.25 in. and 1.0 in.
- The wet test results for the single-unit train lots with a target MAS of 1.0 in. were statistically higher than the other sections, all of which had statistically equivalent results.

Table 4.15: SBD-2: Average Marshall Stability Results with Recycling Train and Forward Speed

Factorial	Dry				Wet			
	Average Stability		Sample Size	Groups[a]	Average Stability		Sample Size	Groups[a]
	lbf	kN			lbf	kN		
Single-Unit_1_EA	4,678	20.8	3	A	2,448	10.9	3	A
Single-Unit_1.25_EA	4,046	18.0	3	B	2,168	9.6	3	AB
Multi-Unit_0.75_EA	3,830	17.0	3	BC	1,995	8.9	3	B
Multi-Unit_1.25_EA	3,295	14.6	3	C	2,058	9.1	3	B
Multi-Unit_1_EA	3,267	14.5	3	C	1,988	8.8	3	B

[a] Means with the same letters are not significantly different.

Relationship between Marshall Stability and Density

The relationship between Marshall stability and density, plotted in Figure 4.25, shows a strong relationship between stability and density due to the wide variability in the densities produced during compaction. Reducing the data to the section level (Table 4.16) shows that some sections had a strong negative correlation between stability and density (multi-unit train lots with target MAS of 1.25 in.), while others show no correlation (single-unit train lots with target MAS of 1.25 in.). However, there was a general trend that confirms that higher densities result in higher stabilities, but that factors such as variability inherent with the material and process, and precision and bias of the testing procedures, probably have a greater effect on the stability results than density alone.

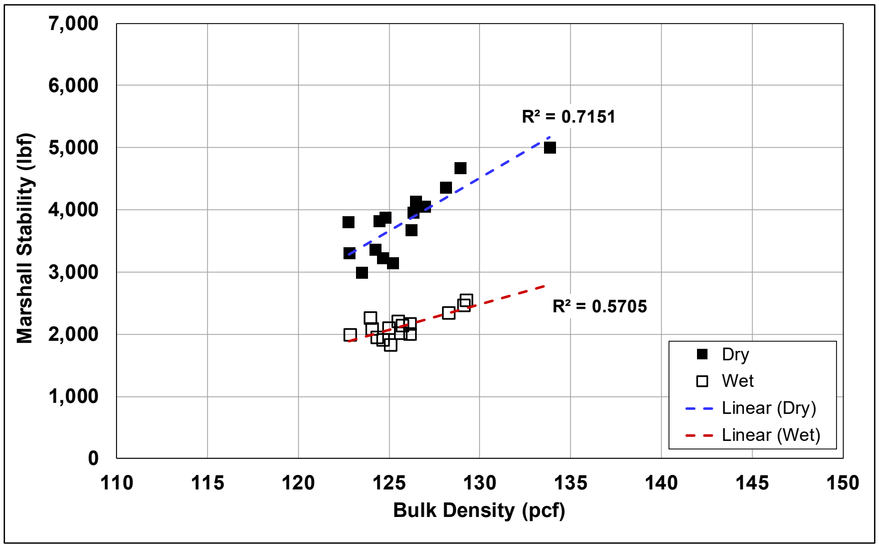

Figure 4.25: SBD-2: Project Marshall stability and density relationship.

Table 4.16: SBD-2: Effect of Density on Marshall Stability

Factorial	Condition	Slope (lbf/pcf)	R^2
Multi-Unit_0.75_EA	Dry	25.9	0.55
	Wet	17.3	0.04
Multi-Unit_1_EA	Dry	232.0	0.81
	Wet	37.3	0.81
Multi-Unit_1.25_EA	Dry	-18.6	0.07
	Wet	-330.4	0.86
Single-Unit_1_EA	Dry	96.7	0.87
	Wet	194.5	0.91
Single-Unit_1.25_EA	Dry	72.1	0.08
	Wet	-49.6	0.18

4.6.5 Summary of Analysis Factors

Possible explanations for the effects of each analysis variable on the material properties include the following:

- Effect of rerolling:
  - \+ On in-place density:
    - Rerolling of the recycled layer resulted in an average increase in in-place wet density of 4.2 pcf (67 kg/m^3).
- Effect of recycling train type:
  - \+ On in-place density:
    - There was no significant difference in in-place density after construction between the sections recycled with the single- and multi-unit trains.
    - There was, however, a difference in density between the sections after rerolling, but this was attributed primarily to the time intervals between primary compaction and

        rerolling. The curing times between construction and rerolling for the single-unit train sections, constructed on the final days of the study, were shorter than the multi-unit train sections, constructed on the first days of the study. Sections with limited curing would likely benefit more from rerolling that sections in a more advanced stage of curing.
    - On indirect tensile strength:
        - The multi-unit train sections generally had higher dry and wet indirect tensile strengths than the single-unit train sections.
    - On Marshall stability:
        - The single-unit train sections generally had higher Marshall stabilities than the multi-unit train sections.
- Effect of forward speed:
    - On gradation:
        - There was no observable effect of speed on overall gradation. However, the multi-unit train did produce a finer gradation than the single-unit train on the coarse portion of the materials (i.e., material passing the 1.0 in. [25 mm] and retained on the #4 [4.75 mm] sieves).
    - On in-place density:
        - Changing the forward speed had no significant effect on in-place density.
    - On indirect tensile strength:
        - There was no observable effect of speed on ITS.
    - On Marshall stability:
        - Forward speed of the single-unit train had a significant effect on the Marshall stability, with slower speeds resulting in higher dry and wet stabilities. The effect of forward speed on the multi-unit train showed no clear trends on Marshall stability, as expected given that gradations are more controlled by the processing unit in the train than by speed.

Observations with regard to gradation were similar to those discussed in Section 3.6.5, with the multi-unit train having more control over the coarse portion of the gradation than the single-unit train. There was no difference between the trains in terms of in-place density after construction and explainable differences after rerolling. Even though the gradation results show that the single-unit produced a coarser gradation, this did not influence in-place density, indicating that the finer portion of the gradation curve has a greater impact on this parameter.

The densities of the ITS and Marshall stability specimens were inconsistent with the densities measured in the field. This was attributed primarily to inconsistencies in the sampling and specimen preparation procedures and not to differences in recycling train type and speed. There is thus no consistent data from this pilot study to indicate that the different recycling trains produce gradations that have significantly different effects on density, ITS, and Marshall stability.

The relationships between density, ITS and Marshall stability have shown that increasing the density can increase strength and stability.

4.7 Conclusions

Observations from this project have shown that:

- Rerolling effectively increased the in-place wet density of the recycled layer.
- Recycling train type had no significant effect on in-place density.
- The multi-unit train generally produced finer gradations in the coarse portion of the grading envelope (i.e., material passing the 1.0 in. [25 mm] and retained on the #4 [4.75 mm] sieves) than the single-unit train, but this did not affect the density and air-void content results. Gradations on the finer portion of the grading envelope (i.e., material passing the #4 sieve) were similar for both trains.
- Recycling train type had no significant effect on indirect tensile strength and Marshall stability.
- Changing forward speed to reduce maximum aggregate size did not influence in-place wet density, and there were no explainable trends in the effects of forward speed on strength and stability results.

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5 CONCLUSIONS AND RECOMMENDATIONS

The three partial-depth recycling (PDR) pilot projects discussed in this report focused on the following:

- The benefits of adding supplemental aggregates
- Comparison of emulsified and foamed asphalt recycling agents in PDR applications
- Comparison of single- and multi-unit recycling trains
- The effect of recycling train forward speed on gradation

5.1 Conclusions

The addition of supplemental aggregates, the choice of recycling train type (i.e., single- or multi-unit), and the effect of recycling unit forward speed are factors that can potentially affect the gradation of PDR materials, which in turn influences compaction density, strength, stability, stiffness, and moisture sensitivity. Results from this study showed that the largest increase in in-place density was measured when supplemental aggregates were added, with densities up to 11 pcf (176 kg/m^3) higher than the control. Changes in recycling train type and forward speed had little to no effect on in-place density.

Improvements to PDR material gradations typically result in higher indirect tensile strengths and Marshall stabilities for the same recycling agent and active filler contents. Reductions in forward speed typically control the maximum aggregate size, but have limited effect on the finer portion of the gradation (i.e., material passing the #4 [4.75 mm] sieve). Multi-unit trains, with appropriate screens on the processing unit, have an extra level of control of maximum aggregate size than single-unit trains, which rely only on forward speed. Results from this study showed that single-unit trains generally produce coarser gradations in the coarse portion of the envelope (i.e., passing the 1.0 in. [25 mm] and retained on the #4 [4.75 mm] sieves) than multi-unit trains, but this did not have a significant effect on in-place density, which is more dependent on the finer fractions that fill voids in the coarser aggregate skeleton. The addition of sufficient supplemental aggregates to fill voids provided the most control over gradation. Pre-milling should not be required to accommodate the supplemental aggregates given that this material is only used to fill voids, which should not increase grade height.

Increases in indirect tensile strength (ITS) with supplemental aggregates were not as significant as the increase in in-place density, especially in terms of wet strength results. These differences could be attributed to variability along the project, specimen dimensions (representative volume element), variability in specimen preparation, material breakdown during Marshall compaction, and precision and bias of the tests. This should be further studied in the laboratory to determine if adding supplemental fines to improve gradation/fill voids alone can increase moisture resistance, or if these improvements are primarily affected by the active filler.

The two recycling agents typically used in PDR, namely foamed asphalt and emulsified asphalt, were also compared in one of the pilot studies. Test results indicated that the sections treated with emulsified asphalt had higher densities than those treated with foamed asphalt, with the same recycling machine and recycling speed. However, there was considerable variability in materials and pavement structure along the length of the project, which likely had an influence on all results.

The quality control test results analyzed in this report provided data on the density, ITS, and Marshall stability determined during construction. The initial findings from the study can be summarized as follows:

- Statistical analyses of quality control results on in-place recycling projects are challenging given the variability in materials and pavement structure along the length of the project. The problem is intensified on pilot projects with multiple experimental sections on which performance is being compared.
- Supplemental aggregates can be used to reliably increase the density and strength of PDR layers without increasing the recycling agent or active filler contents, and by not requiring pre-milling of the road to accommodate the materials without changing grade height.
- There was no discernable difference in the density and strengths of PDR layers produced with the single- and multi-unit recycling trains. The main benefit of the multi-unit train is better control of maximum aggregate size by the on-board screens and crushing unit. The crushing unit does not appear to change or improve the finer portion of the gradation (i.e., material passing the #4 [4.75 mm] sieve), which has a larger influence on compaction density, air-void content reduction, strength, and moisture resistance.
- On coarse gradations, higher foamed asphalt contents were required to achieve the minimum ITS requirement compared to emulsified asphalt. This is attributed in part to the coating action provided by emulsion treatments being more effective than the “spot

welding" action provided by the foam treatments on coarse, high air-void content gradations.

- Marshall compaction (AASHTO T 245) overestimated the in-place density of PDR layers to a greater extent than gyratory compaction (AASHTO T 312).
- Rerolling can result in a small increase in density on PDR-EA layers. The timing of rerolling will influence the extent of this increase.
- The densities recorded on specimens produced for strength and stability tests were not always consistent with the density results measured on the layer in the vicinity of where the samples were taken. This was attributed in part to inherent variability in the materials and pavement structure along the project, sampling and handling procedures, and different specimen preparation procedures used by the contractors.
- Relationships between gradations of field samples and field densities were inconsistent, which was also attributed to inherent variability in the materials which may not be captured in the small samples taken to represent a relatively large area of the layer.

5.2 Recommendations

The three pilot projects should be monitored to evaluate long-term performance to determine if the factors assessed influence this parameter. Monitoring should include, but not be limited to, the following:

- Annual visual surveys to assess rutting, cracking, and any other distresses along with likely causes. The first assessment should include coring, dynamic cone penetrometer (DCP) testing, and subbase/subgrade characterization to characterize the pavement structure and underlying materials.
- Annual or biannual falling weight deflectometer (FWD) testing, which should include a range of temperatures to determine any temperature sensitivity in the material.
- Biannual coring in conjunction with FWD testing to assess strength and stiffness changes in the PDR layer. Additional cores should be taken across any cracks to determine their origin, depth, and likely cause. Results should be used to update *CalME* performance models. If feasible, beams should be cut from the layer after two and five years to measure damage properties of the layer in the laboratory to provide additional performance parameters for *CalME* models.

This study highlighted the following issues and suggested changes within the PDR mix design and quality control procedures followed in these projects (CT 315). These changes have been discussed with the method owner at Caltrans Materials Engineering and Testing Services (METS):

- Different conditioning procedures are specified for testing Marshall stability on emulsified and foamed asphalt specimens. These procedures should be standardized to allow more direct comparisons of the two recycling agents in Marshall stability and ITS test results.
- The two compaction methods, Marshall (AASHTO T 245) and gyratory (AASHTO T 312), both produce specimens with bulk densities that exceed typical dry densities measured on compacted PDR layers. Marshall compaction generally produces specimens with a higher density than gyratory compaction. One specified compaction method should be standardized for mix design and quality control/quality assurance testing.
  - Gyratory compaction is recommended for mix design specimen preparation because the densities of specimens produced with this method are closer to (but still higher) than the densities that will be achieved on the project.
  - Gyratory or vibrating hammer compaction are recommended for specimen preparation for quality control testing, using the breakover densities achieved on the sample lot to determine the quantity of material added to the mold. Although following this procedure should produce strength and stability results that are representative of those on the project, they will typically be lower than the mix design results, given than mix design gyratory-determined densities will be higher than breakover densities, which typically results in higher strengths and stabilities.
- Tensile strength retained should not be used as a mix design or quality control procedure. Instead, minimum wet and minimum dry strengths should be required. The addition of supplemental aggregates tends to have a larger influence on dry strengths than on wet strengths. Although higher wet strengths are typically recorded, the larger difference between dry and wet strengths leads to lower retained strengths, which could result in unnecessarily high recycling agent and active filler contents to meet the retained strength requirements.

REFERENCES

1. Roberts, F.L., Kandhal, P.S., Brown, E.R., Lee, D.Y. and Kennedy, T.W. 1996. *Hot Mix Asphalt Materials, Mixture Design, and Construction*. Lanham, MD: National Asphalt Pavement Association Education Foundation.
2. Al-Qadi, I. and Ozer, H. 2020*. In-Place and Central-Plant Recycling of Asphalt Pavements in Virginia* (FHWA-HIF-19-078). Washington, DC: Federal Highway Administration. fhwa.dot.gov/pavement/sustainability/case_studies/hif19078.pdf.