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Cold Central Plant Recycling Study: Test Track Construction, Layout, and Instrumentation

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Cold Central Plant Recycling Study: Test Track Construction, Layout, and Instrumentation

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Partnered Pavement Research Center (PPRC) Project Number 4.70 (DRISI Task 3196):
In-Place Recycling Guidance

PREPARED FOR:

California Department of Transportation
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PREPARED BY:

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16. ABSTRACT

This technical memorandum summarizes the construction and instrumentation of a test track to study the behavior of cold central plant recycled (CCPR) layers in a pavement structure. Two recycling agents will be tested including emulsified asphalt from two different producers and foamed asphalt from one binder supplier. The pavement structure includes an aggregate subbase, an aggregate base, the recycled layer, and a gap-graded rubberized hot mix asphalt (RHMA-G) surfacing. The structure was constructed on prepared subgrade. Material properties and construction procedures met all relevant Caltrans specifications. Instrumentation includes multi-depth deflectometers, strain gauges, pressure cells, and moisture sensors. The test track was considered to be representative of a highway project and was approved for Heavy Vehicle Simulator testing.

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PROJECT OBJECTIVES

This study is a continuation of PPRC Project 4.69 (FDR Emulsion and Field). The objective of this project is to update guidance and mechanistic-empirical design procedures for cold pavement recycling. This will be achieved through the following tasks:

- Task 1: An updated literature review on research related to partial-depth recycling (PDR) and cold central plant recycling (CCPR).
- Task 2: Long-term monitoring of existing and new PDR and CCPR field experiments to assess stiffness, cracking, rutting/densification, freeze-thaw, moisture sensitivity, and other observed distresses.
- Task 3: Accelerated pavement testing on a custom test track constructed at the University of California Pavement Research Center. The track will compare cold recycling with emulsified and foamed asphalt, each with appropriate active fillers. Materials will be processed in a cold central plant.
- Task 4: Laboratory testing on test track materials to relate laboratory test results to accelerated wheel load test results, to refine mix design procedures, and to identify suitable criteria for mechanistic-empirical design procedures and performance models.
- Task 5: Development of updated life cycle assessment and life cycle cost assessment parameters for cold recycling projects.
- Task 6: Preparation of research reports and revised guidelines for cold recycling in California.

This technical memorandum covers the construction of the test track under Task 3.

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- Bob Staugaard with Asphalt Pavement and Recycling Technologies
- The UCPRC Heavy Vehicle Simulator and laboratory operations teams

EXECUTIVE SUMMARY

This technical memorandum summarizes the construction and instrumentation of a test track to study the behavior of cold central plant recycled (CCPR) layers in a pavement structure. Two recycling agents will be tested including emulsified asphalt from two different producers and foamed asphalt from one binder supplier. The pavement structure includes an aggregate subbase (0.75 ft. [225 mm]), an aggregate base (0.6 ft. [180 mm]), the recycled layer (0.4 ft. [120 mm]), and a gap-graded rubberized hot mix asphalt (RHMA-G) (0.2 ft. [60 mm]) surfacing. The structure was constructed on prepared subgrade. Material properties and construction procedures met all Caltrans specifications. Instrumentation includes multi-depth deflectometers, strain gauges, pressure cells, and moisture sensors.

The test track was considered to be representative of a highway project and was approved for Heavy Vehicle Simulator testing.

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
Caltrans	California Department of Transportation
CAPM	Capital maintenance
CCP	Cold central plant
CCPR	Cold central plant recycling
ESAL	Equivalent single axle load
FDR	Full-depth recycling
FDR-C	Full-depth recycling with cement
FDR-EA	Full-depth recycling with emulsified asphalt
FDR-FA	Full-depth recycling with foamed asphalt
FDR-N	Full-depth recycling with no stabilizer
FWD	Falling weight deflectometer
HVS	Heavy Vehicle Simulator
IPR	In-place recycling
LCA	Life cycle assessment
LCCA	Life cycle cost analysis
LMP	Laboratory-determined modified Proctor density
LVDT	Linear variable differential transformer
MDD	Multi-depth deflectometer
MaxDD	Maximum dry density
MTD	Maximum theoretical density
NMAS	Nominal maximum aggregate size
OMC	Optimum moisture content
PDR	Partial-depth recycling
PDR-EA	Partial-depth recycling with emulsified asphalt
PDR-FA	Partial-depth recycling with foamed asphalt
PPRC	Partnered Pavement Research Center
RAP	Reclaimed asphalt pavement
RHMA	Rubberized hot mix asphalt
RHMA-G	Gap-graded rubberized hot mix asphalt
RSD	Road surface deflectometer
Std. Dev	Standard deviation
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-µm (No. 200) Sieve in Mineral Aggregates by Washing
T 27 Standard Method of Test for Sieve Analysis of Fine and Coarse Aggregates
T 89 Standard Method of Test for Determining the Liquid Limit of Soils
T 90 Standard Method of Test for Determining the Plastic Limit and Plasticity Index of Soils
T 180 Standard Method of Test for Moisture-Density Relations of Soils Using a 4.54-kg (10-lb) Rammer and a 457-mm (18-in.) Drop
T 209 Standard Method of Test for Theoretical Maximum Specific Gravity (Gmm) and Density of Hot-Mix Asphalt (HMA)

ASTM

D2487 Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)

Caltrans Test

CT 216 Method of Test for Relative Compaction of Untreated and Treated Soils and Aggregates
CT 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 to the Study

Cold recycling of distressed pavements continues to gain interest in the United States and internationally. It provides rapid rehabilitation solutions with minimal disruption to traffic while recycling in-place materials with only limited additional virgin materials. Full-depth recycling (FDR) is typically used on pavements with bottom-up distresses, partial-depth recycling (PDR) is typically used on pavements with top-down distresses, and cold central plant recycling (CCPR) can be used for either recycling strategy, or a combination of strategies, including with lower layer/subgrade stabilization.

The California Department of Transportation (Caltrans) has been using FDR as a rehabilitation strategy since 2001 and PDR as a capital maintenance (CAPM) strategy since 2010. To date, Caltrans has not constructed any projects using CCPR equipment. Most Caltrans FDR projects to date have used a combination of foamed asphalt and portland cement (FDR-FA) as the stabilizing agent. Most PDR projects to date have used a combination of emulsified asphalt and portland cement (PDR-EA) as the recycling agent. The first Caltrans PDR-FA project was constructed in 2018. A number of FDR projects have also been completed where no stabilizing agent has been used, referred to as FDR-N or "pulverization." A limited number of projects using only portland cement (FDR-C) have also been completed. Caltrans currently does not permit the use of emulsified asphalt (FDR-EA) as a stabilizing agent on FDR projects.

Research completed to date by the UCPRC on in-place recycling (IPR) includes the following:

- Phase 1: Background and detailed laboratory and field studies on FDR-FA (2005-2008) *(1)*, including preparation of comprehensive guidelines for FDR-FA *(2)*.
- Phase 2: Test track construction and accelerated wheel load with associated laboratory testing to assess the behavior and performance of FDR-N, FDR-FA, FDR-C, and FDR-EA layers containing recycled rubberized hot mix asphalt (RHMA). Testing under dry conditions was completed in 2014 and testing under wet conditions was completed in 2016 *(3)*. Laboratory testing and analysis to develop preliminary mechanistic parameters for FDR project design and performance modeling was completed in 2017 *(4)*.

- Phase 3: Laboratory and field testing and test road study to assess shrinkage crack mitigation measures for FDR-C projects (2016-2020) *(5-7)*. Preparation of comprehensive guidelines for in-place recycled materials was also completed in this phase *(8).*

Phase 4, which is in progress, includes test track construction to assess CCPR-FA and CCPR-EA in accelerated wheel load, field, and laboratory studies.

1.2 Problem Statements

The following outstanding problem statements related to cold pavement recycling still need to be addressed or require refinement/calibration for California conditions:

- Mechanistic-empirical parameters for cold recycled projects need to be finalized.
- Consistent mix design procedures for all cold recycling strategies need to be developed and laboratory performance testing needs to be undertaken to refine mechanistic-empirical design and performance modeling parameters. Mix design procedures should include raveling tests, given that recycled layers are exposed to traffic for up to 15 days before the asphalt surfacing is placed.
- PDR and CCPR materials produced with only recycled asphalt pavement (RAP) typically have coarse gradations, which leads to compacted layers having relatively high air-void contents. The use of supplemental fines to improve gradations needs to be investigated.
- Time limits for stockpiling of CCPR materials need to be established.
- The effects on construction and performance of RHMA (i.e., more than 25% of the recycled material is RHMA) and fabrics in the recycled layer are not fully understood and need to be evaluated.
- Current PDR construction techniques are not conducive to the application of tack coats between the recycled and underlying layers. Consequently, debonding of these two layers is often observed in cores removed from in-service pavements. Recent developments in spray pavers need to be assessed to see if this equipment can be effectively used in PDR applications to improve long-term performance.
- The long-term performance of deep lift FDR-C projects (i.e., the FDR layer is >1 ft. [300 mm]) has not been quantified. Although this strategy is being used on city and county roads with reported success, to date there are no published studies documenting longer-term performance on roads carrying traffic volumes typical of those on Caltrans roads where FDR-C may be considered. Concerns regarding the compaction of thicker layers on weak/moist subgrades, the potential for cracking resulting from drying shrinkage and/or differential compaction over the thickness of the layer, and the applicability of current shrinkage crack mitigation procedures to these thicker layers need to be investigated.

- The use of rejuvenating agents and other stabilizers (e.g., synthetic polymer emulsions) has not been investigated in cold recycling projects to date.
- Preliminary international research on the use of nano-stabilizers to improve emulsified asphalt performance in recycled layers has shown promising early results and warrants further investigation.
- Preliminary national research on the use of geosynthetics between subgrades and CCPR layers and between recycled layers and asphalt concrete surfacings has also shown positive results. The use of geosynthetics provides a potential alternative to subgrade stabilization, and/or can provide a barrier to prevent fines contaminating the recycled layer. Geosynthetics between an FDR-C layer and the asphalt concrete surface may limit shrinkage cracks in the FDR-C layer from reflecting through the asphalt.

1.3 Project Objectives

This study is a continuation of PPRC Project 4.69 (FDR emulsion and field). The objective of this project is to update guidance and mechanistic-empirical design procedures for cold pavement recycling. This will be achieved through the following tasks:

Task 1: An updated literature review on research related to PDR and CCPR.

Task 2: Long-term monitoring of existing and new PDR and CCPR field experiments to assess stiffness, cracking, rutting/densification, freeze-thaw, moisture sensitivity, and other observed distresses described in the problem statement.

Task 3: Accelerated pavement testing on a custom test track constructed at the UCPRC. The track will compare cold recycling with emulsified and foamed asphalt, each with appropriate active fillers. Materials will be processed in a cold central plant.

Task 4: Laboratory testing on test track materials to relate laboratory test results to accelerated wheel load test results, to refine mix design procedures, and to identify suitable criteria for mechanistic-empirical design procedures and performance models.

Task 5: Development of updated life cycle assessment (LCA) and life cycle cost assessment (LCCA) parameters for cold recycling projects.

Task 6: Preparation of research reports and revised guidelines for cold recycling in California.

This technical memorandum covers the construction of the test track under Task 3.

1.4 Measurement Units

Although Caltrans recently returned to the use of US standard measurement units, metric units have always been used by the UCPRC in the design and layout of Heavy Vehicle Simulator (HVS) test tracks and for laboratory, HVS, and field measurements and data storage. In this report, both US and metric units (provided in parentheses after the US units) are provided in general discussion. In keeping with convention, metric units are used in HVS and laboratory data analyses and reporting, with some US units, where appropriate, to assist the reader. A conversion table is provided on page xiii.

2. TEST TRACK LOCATION AND DESIGN

2.1 Test Track Location

The cold central plant recycling (CCPR) experiment is located on the North Test Track at the University of California Pavement Research Center (UCPRC) facility in Davis, California. An aerial view of the site is shown in Figure 2.1. The track was reconstructed for this project between 01/03/2019 and 05/08/2019. The study described in this report is the fifth research project involving Heavy Vehicle Simulator (HVS) testing undertaken on this test track.

Figure 2.1: Aerial view of the UCPRC research facility.

2.2 Test Track Layout

The North Test Track is 361 ft. (110 m) long and 52.5 ft. (16 m) wide. It has a 2% crossfall in the north-south direction. Four standard-width lanes can be constructed in this space.

The test track layout is shown in Figure 2.2. The gray-shaded area in the figure (Cells A, B and C) covers the three CCPR cells tested in this study. The unshaded area (Cells D through J) covers the four gap-graded rubberized asphalt pavement (RHMA-G) materials (four mixes, three thicknesses constructed on a CCPR-FA layer) tested in another parallel study not discussed in this report *(9)*. All test track measurements and locations discussed in this report are based on this layout.

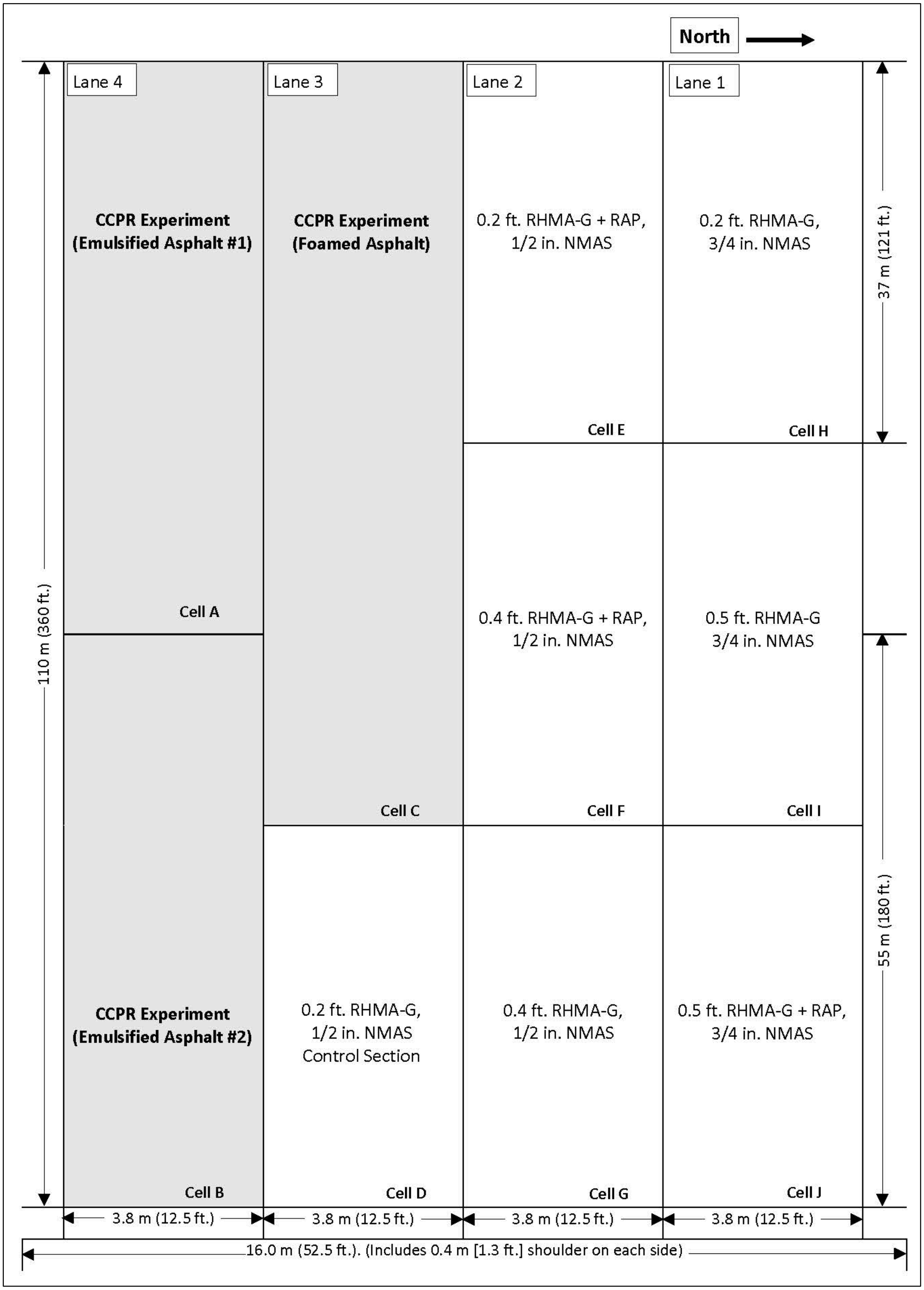

Figure 2.2: Test track layout (shaded area [Cells A, B and C] is the CCPR experiment).

2.3 Test Track Pavement Design

The pavement design for Cells A through C of the test track focused primarily on assessment of the CCPR layers in the structure rather than the RHMA-G surface mix properties. Given that CCPR layers had not been constructed on the Caltrans road network at the time of starting this study, the test track was designed to be consistent with a typical Caltrans partial-depth recycling (PDR) capital maintenance (CAPM) project to understand the behavior and performance of similar pavement materials recycled using cold central plant technology. A relatively thin (0.2 ft. [60 mm]) RHMA-G surfacing was used in the CCPR material study design. All of the mixes in the RHMA-G study (Cells D through J, not discussed in this report) were placed on a CCPR-FA layer.

The pavement design for the test track is shown in Figure 2.3 (CCPR study) and Figure 2.4 (RHMA-G study).

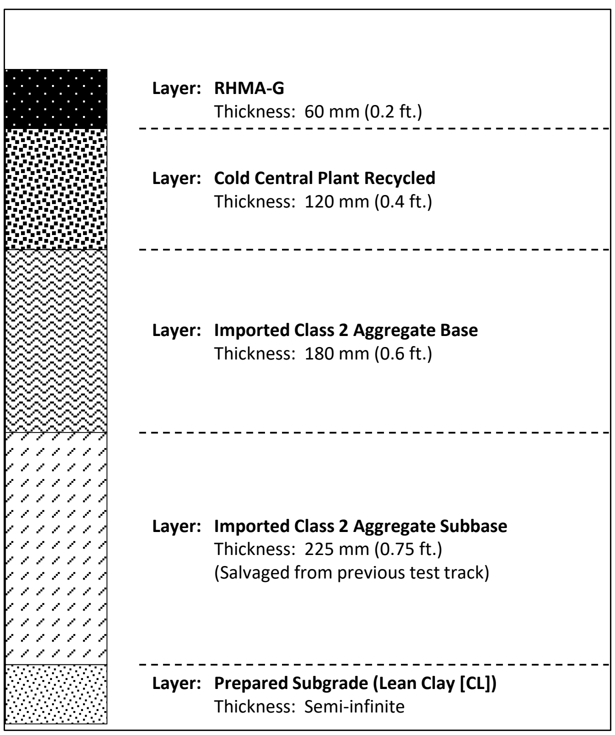

Figure 2.3: Test track design: CCPR experiment.

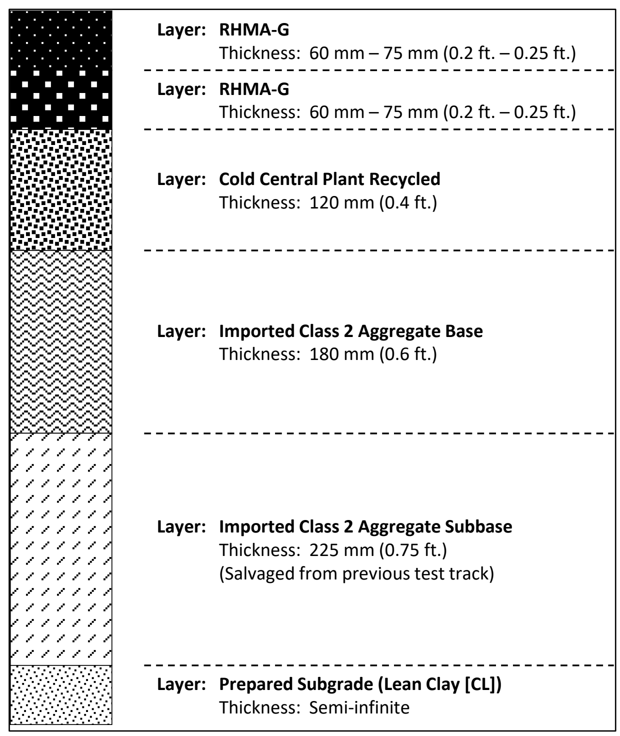

Figure 2.4: Test track design: RHMA-G experiment.

2.4 RHMA-G Mix Design

The RHMA-G mix placed on the CCPR cells was designed and produced by George Reed Inc. Key material design parameters from the job mix formula are summarized in Table 2.1. The mix met all Caltrans standard specification requirements for 1/2 in. nominal maximum aggregate size (NMAS) RHMA-G mixes.

Table 2.1: Mix Design Parameters for RHMA-G

Parameter		1/2 in. NMAS	
		Actual	Compliance
Grading (% passing sieve)	1	100	100
	3/4	100	100
	1/2	97	90–98
	3/8	84	83–87
	#4	39	28–42
	#8	19	14–22
	#200	3.6	0.0–6.0
RAP content by total weight of aggregate (%)		0	N/A
Base asphalt binder performance grade		64-16	N/A
Rubber content (% by weight of binder)		18	18–22
AR binder cone penetration (mm)		3.6	2.5–7.0
AR binder resilience (% rebound)		48	>18
AR binder softening point (°C)		62	52–74
AR binder viscosity (centipoise)		1,600	1,500–4,000
Binder content by total weight of mix (%)		7.8	7.4–8.3
Number of gyrations		150	50–150
Air-void content (%)		3.8	4.0
Voids in mineral aggregate (%)		19.8	18–23
Dust proportion		0.52	N/A
Hamburg (rut depth [mm] at 20,000 passes)		2.2	<12.5
Moisture susceptibility, dry strength (psi)		169	>100
Moisture susceptibility, wet strength (psi)		120	>70

2.5 Cold Central Plant Recycled Material Mix Designs

The mix design for the cold central plant recycled material with foamed asphalt recycling agent (CCPR-FA) was completed by the UCPRC, while the mix designs for the two CCPR material mixes with emulsified asphalt (CCPR-EA) mixes were completed by Pavement Recycling Systems, the contractor who constructed the test track. Designs followed the Caltrans LP-8 procedures that were current at the time. Key design parameters are summarized in Table 2.2. The recycling agent (2.5% residual asphalt) and active filler (1% cement) contents were the same for all three mixes.

Table 2.2: Mix Design Parameters for Cold Central Plant Recycled Materials

Parameter		CCPR-FA	CCPR-EA #1	CCPR-EA #2	Compliance
Grading (% passing sieve)	1	100	100	100	—
	3/4	95	95	95	—
	#4	50	50	50	—
	#30	10	10	10	—
	#200	2	2	2	—
Residual recycling agent content (% of dry aggregate weight)		2.5	2.5	2.5	—
Cement content (% of dry aggregate weight)		1.0	1.0	1.0	—
Water for mixing (% of dry aggregate weight)		5.2	2.0	2.0	—
Maximum theoretical specific gravity		Not tested	2.465	2.499	—
Bulk specific gravity		Not tested	2.131	2.117	—
Density (lb./ft^3)		129	133.1	132.0	—
Air-void content (%)		Not tested	13.5	15.4	10.0–16.0
Indirect tensile strength, dry (psi)		60	Not tested	Not tested	—
Indirect tensile strength, wet (psi)		51	Not tested	Not tested	>35
Tensile strength retained (%)		85	Not tested	Not tested	>70
Marshall stability, dry (lb.)		Not tested	3,525	3,260	>1,250
Marshall stability, wet (lb.)		Not tested	2,720	2,320	—
Marshall retained stability (%)		Not tested	77.2	71.2	>70
Ratio of recycling agent residue to cement		2.5:1	2.5:1	2.5:1	2.5:1
Raveling resistance (% loss)		Not tested	Not tested	Not tested	>95

2.6 Subgrade, Aggregate Subbase, and Aggregate Base Properties

Samples were taken during construction of the subgrade, aggregate subbase, and aggregate base layers for indicator tests. Three samples were taken from the same coordinates on each layer, with sampling locations shown on Figure 2.5. Material properties for each layer are summarized in Table 2.3 through Table 2.5.

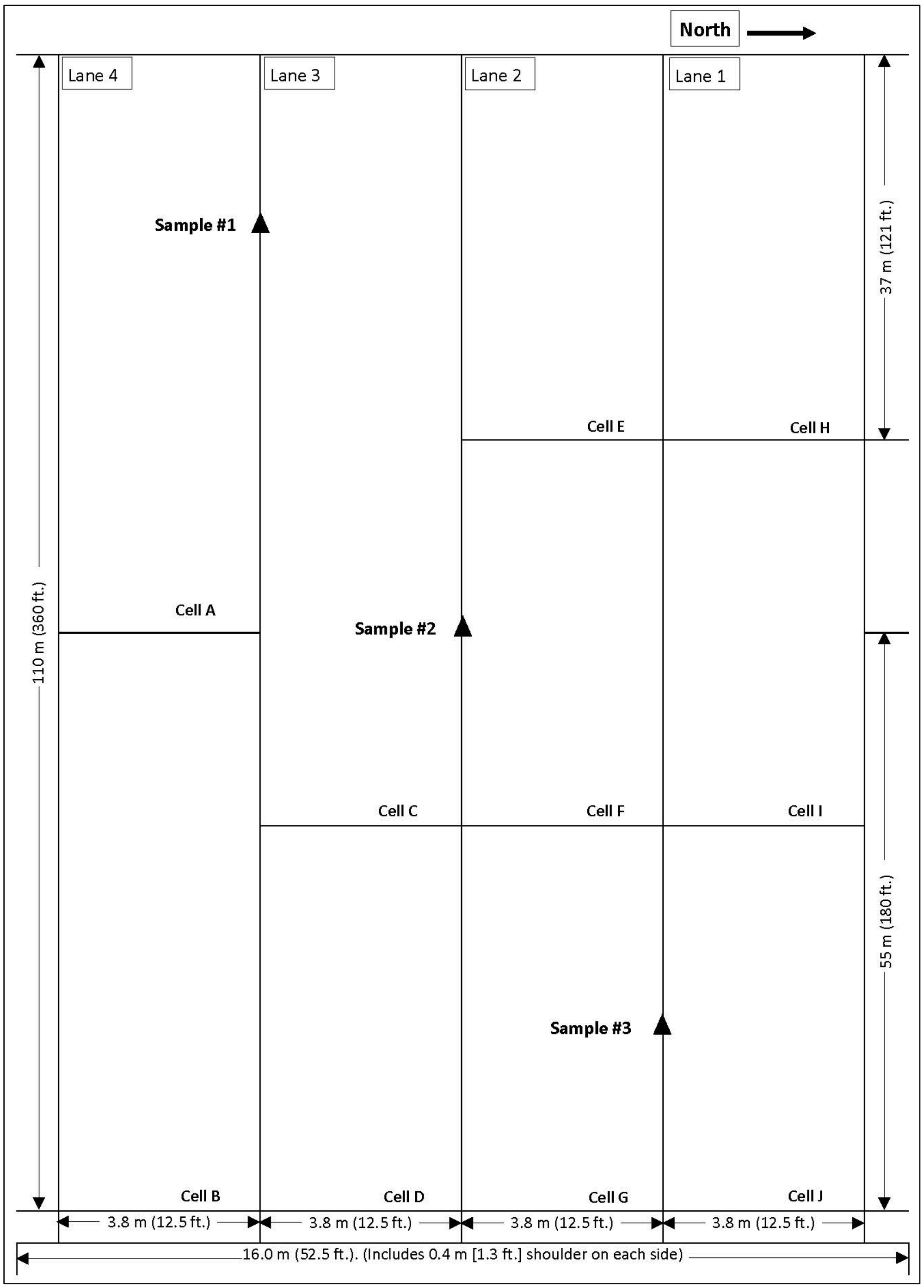

Figure 2.5: Sampling locations.

Table 2.3: Subgrade Material Properties

Property		Result				Operating Range	Contract Compliance
		Sample 1	Sample 2	Sample 3	Average		
Grading:[a]	1" (25 mm)	100	100	100	100	–	–
	3/4" (19 mm)	88	100	98	95	–	–
	1/2" (12.5 mm)	86	98	97	94	–	–
	3/8" (9.5 mm)	84	97	96	92	–	–
	#4 (4.75 mm)	78	95	94	89	–	–
	#8 (2.36 mm)	74	93	91	86	–	–
	#16 (1.18 mm)	71	91	89	84	–	–
	#30 (600 µm)	69	90	88	82	–	–
	#50 (300 µm)	67	87	86	80	–	–
	#100 (150 µm)	63	82	81	75	–	–
	#200 (75 µm)	57	71	73	67	–	–
Atterberg Limits:[b]	Liquid Limit	34	35	37	35	–	–
	Plastic Limit	17	19	16	17	–	–
	Plasticity Index	17	16	21	18	–	–
Max. Dry Density (lb./ft^3)(kg/m^3)[c]		122.5 (1,963)	121.5 (1,946)	122.1 (1,954)	122.0 (1,954)	–	–
Optimum Moisture Content (%)[c]		10.7	11.2	11.0	11.0	–	–
Resilient modulus from DCP (MPa)[d]		66	63	66	65	–	–
Unified Soil Classification[e]		Lean clay (CL)	Lean clay (CL)	Lean clay (CL)	–	–	–

[a] Determined according to AASHTO T 11 and AASHTO T 27
[b] Determined according to AASHTO T 89 and AASHTO T 90
[c] Modified Proctor determined according to AASHTO T 180
[d] Resilient modulus estimated from dynamic cone penetrometer measurements according to Caltrans Site Investigation Guide *(10)*
[e] Unified Soil Classification System according to ASTM D2487

Table 2.4: Aggregate Subbase Material Properties

Property		Result				Operating Range	Contract Compliance
		Sample 1	Sample 2	Sample 3	Average		
Grading:[a]	3" (75 mm)	100	100	100	100	100	100
	2 1/2 (63 mm)					90–100	87–100
	1" (25 mm)	100	100	100	100	–	–
	3/4" (19 mm)	98	99	98	98	–	–
	1/2" (12.5 mm)	86	87	84	86	–	–
	3/8" (9.5 mm)	76	77	72	75	–	–
	#4 (4.75 mm)	56	57	52	55	40–90	35–95
	#8 (2.36 mm)	43	44	41	43	–	–
	#16 (1.18 mm)	35	36	33	35	–	–
	#30 (600 µm)	28	29	27	28	–	–
	#50 (300 µm)	20	21	20	20	–	–
	#100 (150 µm)	15	16	15	15	–	–
	#200 (75 µm)	12	12	12	12	0–25	0–29
Atterberg Limits:[b]	Liquid Limit	Non-plastic	Non-plastic	Non-plastic	Non-plastic	–	–
	Plastic Limit					–	–
	Plasticity Index					–	–
Max. Dry Density (lb./ft^3)(kg/m^3)[c]		142.6 (2,285)	142.0 (2,274)	142.3 (2,280)	142.3 (2279.7)	–	–
Optimum Moisture Content (%)[c]		4.8	5.1	4.9	5	–	–
R-Value		–	79	–	79	–	>50
Sand equivalent		–	30	–	30	>21	>18

[a] Determined according to AASHTO T 11 and AASHTO T 27
[b] Determined according to AASHTO T 89 and AASHTO T 90
[c] Modified Proctor determined according to AASHTO T 180

Table 2.5: Aggregate Base Material Properties

Property		Result				Operating Range	Contract Compliance
		Sample 1	Sample 2	Sample 3	Average		
Grading:[a]	1" (25 mm)	100	100			100	100–100
	3/4" (19 mm)	94	93			93	90–100
	1/2" (12.5 mm)	83	78			78	–
	3/8" (9.5 mm)	76	68			68	–
	#4 (4.75 mm)	56	44			44	35–60
	#8 (2.36 mm)	35	28			28	–
	#16 (1.18 mm)	23	20			20	–
	#30 (600 µm)	16	14			14	10–30
	#50 (300 µm)	10	9			9	–
	#100 (150 µm)	7	6			6	–
	#200 (75 µm)	5	5			5	2–9
Atterberg Limits:[b]	Liquid Limit	Non-plastic	Non-plastic	Non-plastic	Non-plastic	–	–
	Plastic Limit					–	–
	Plasticity Index					–	–
Max. Dry Density (lb./ft^3)(kg/m^3)[c]			140.6 (2,252)			–	–
Optimum Moisture Content (%)[c]			6.0			–	–
R-Value[d]		–	79	–	79	–	>78
Sand equivalent[d]		–	31	–	31	>25	>22
Durability index[d]		–	78	–	78	–	>35

[a] Determined according to AASHTO T 11 and AASHTO T 27
[b] Determined according to AASHTO T 89 and AASHTO T 90
[c] Modified Proctor determined according to AASHTO T 180
[d] Test results provided by aggregate supplier

3. TEST TRACK CONSTRUCTION

3.1 Introduction

Test track reconstruction included the following steps:

1. Remove the old surfacing layers from the previous experiment.
2. Remove the old full-depth recycled layers.
3. Remove and temporarily stockpile the remaining aggregate base layer.
4. Rip and recompact the upper 1 ft. (300 mm) of the subgrade following Caltrans standard specifications. This work was completed on 01/03/2019.
5. Replace the stockpiled old aggregate base materials and shape and compact them to form an aggregate subbase, 0.75 ft. (225 mm) thick, following Caltrans standard specifications. This work was completed on 01/04/2019.
6. Place a new Class 2 aggregate base, 0.6 ft. (180 mm) thick, following Caltrans standard specifications. This work was completed on 01/23/2019.
7. Apply an emulsified asphalt prime coat to the completed base. This work was completed on 03/14/2019.
8. Produce and place a layer of cold central plant recycled (CCPR) material 0.4 ft. (120 mm) thick. The recycling agents included two different emulsified asphalts (CCPR-EA) and one foamed asphalt (CCPR-FA). Residual asphalt contents of 2.5% by weight of the dry aggregate were used for all tests, with 1% portland cement active filler. The provisional Caltrans mix design method and nonstandard specification for partial-depth recycling (PDR) were followed for the mix design and placement of the materials. The CCPR-EA cells were built on 04/23/2019 and the CCPR-FA cells on 04/24/2019.
9. Apply a fog seal to the CCPR layer. This work was completed on 04/25/2019.
10. Apply a tack coat and place the first lift of RHMA-G mix following Caltrans standard specifications. This work was completed on 05/08/2019.
11. On the applicable RHMA-G study cells, apply a tack coat and the second lift of RHMA-G mix following Caltrans standard specifications. This work was also completed on 05/08/2019.

3.2 Existing Track Removal

The cement concrete, asphalt concrete, and full-depth recycled layers from the existing test track were removed and discarded on a waste pile at a nearby asphalt plant. The remaining existing unbound aggregate base was ripped, windrowed, and removed with a scraper. This material was stockpiled on site for later use as the subbase on the new track.

3.3 Subgrade Preparation

The track subgrade was prepared on January 3, 2019. This involved ripping the material with a grader to a depth of approximately 1 ft. (300 mm), mixing and preliminary leveling of the material with the grader, primary compaction with a padfoot roller, finish leveling, and final compaction with a smooth drum roller. The process met the requirements of Section 19 in the Caltrans Specifications. Photographs of the subgrade preparation are shown in Figure 3.1 through Figure 3.5. Levels were determined with a base station. Compaction density was measured with a nuclear density gauge. Moisture gauges were installed in predetermined locations (discussed in Section 4.4).

Figure 3.1: Subgrade: Ripping with a grader.

Figure 3.2: Subgrade: Mixing and shaping.

Figure 3.3: Subgrade: Padfoot roller compaction.

Figure 3.4: Subgrade: Final shaping and compaction.

Figure 3.5: Subgrade: Completed preparation.

3.3.1 Subgrade Quality Control Testing

Compaction Density

Compaction density was measured using a nuclear gauge (CT-231) at four randomly selected locations on each lane on the day of construction. Compaction moisture content was determined by oven drying samples taken in the vicinity of the nuclear gauge measurements. Relative compaction was determined using the moisture-corrected dry nuclear gauge densities and the laboratory-determined modified Proctor density (AASHTO T 180) on materials sampled during material spreading. Although reference wet densities were also determined following CT-216, the modified Proctor results were considered to be a more representative measure of the density and only these results are reported (i.e., the CT-216 results were generally lower than the modified Proctor results, leading to unrealistically high relative compaction numbers). A summary of the results is provided in Table 3.1. The relative compaction achieved exceeded the specification requirements on all lanes.

Table 3.1: Summary of Subgrade Dry Density Measurements

Cell	MaxDD[a] (kg/cm^3)	Nuclear Gauge Density					Moisture Content (%)	
		Average (kg/cm^3)	Std. Dev.[b] (kg/cm^3)	Relative (% of LMP)	Average (pcf)	Std. Dev. (pcf)	OMC[a]	Actual
A	1,954	1,898	62.2	97	118.5	3.9	17.0	15.9
B	1,954	1,898	62.2	97	118.5	3.9	17.0	15.9
C	1,954	1,873	40.2	96	116.9	2.5	17.0	15.8

[a] MaxDD/OMC = Laboratory-determined modified Proctor (LMP) dry density and optimum moisture content (AASHTO T 180)
[b] Std. Dev. = Standard deviation

3.4 Subbase Construction

Subbase construction was completed on January 4, 2019. Stockpiled base material from the FDR test track was distributed onto the prepared subgrade with a scraper, spread with a grader, and compacted with a smooth drum roller at optimum moisture content (additional water was applied with a water tanker when required). The process met the requirements of Section 25 in the Caltrans Specifications. Photographs of the subbase construction are shown in Figure 3.6 through Figure 3.10. Levels and layer thickness were determined with a base station. Compaction density was measured with a nuclear density gauge. Moisture gauges were installed in predetermined locations (discussed in Section 4.4).

Figure 3.6: Subbase: Importing and spreading material with a scraper.

Figure 3.7: Subbase: Spreading and compacting.

Figure 3.8: Subbase: Water spraying.

Figure 3.9: Subbase: Final shaping and compaction.

Figure 3.10: Subbase: Completed preparation.

3.4.1 Subbase Quality Control Testing

Compaction Density

Compaction density measurements on the subbase followed the same procedure as that followed for testing on the subgrade. A summary of the results is provided in Table 3.2. The relative compaction achieved met the specification requirements (95% of laboratory-determined dry density [i.e., modified Proctor, not CT-216]) on all lanes.

Table 3.2: Summary of Subbase Dry Density Measurements

Cell	MaxDD[a] (kg/cm³)	Nuclear Gauge Density					Moisture Content (%)	
		Average (kg/cm³)	Std. Dev.[b] (kg/cm³)	Relative (% of LMP)	Average (pcf)	Std. Dev. (pcf)	OMC[a]	Actual
A	2,281	2,172	32.8	95	135.6	2.0	5.3	4.6
B	2,281	2,172	32.8	95	135.6	2.0	5.3	4.6
C	2,281	2,174	17.9	95	135.7	1.1	5.3	4.4

[a] MaxDD/OMC = Laboratory-determined modified Proctor (LMP) dry density and optimum moisture content (AASHTO T 180)
[b] Std. Dev. = Standard deviation

3.5 Base Construction

The aggregate base was constructed on January 23, 2019. Base material meeting Caltrans specifications for Class 2 aggregate base was trucked from a nearby alluvial quarry in bottom dumps. The aggregates were not crushed, and most were rounded in shape. The material was spread with a grader and compacted with a smooth drum roller. The material was at or close to optimum moisture content at delivery, but additional water was applied with a water tanker when required. The process met the requirements of Section 26 in the Caltrans Specifications. Photographs of the base construction are shown in Figure 3.11 through Figure 3.15.

Figure 3.11: Base: Dumping imported material.

Figure 3.12: Base: Spreading and compacting.

Figure 3.13: Base: Water spraying.

Figure 3.14: Base: Final compaction.

Figure 3.15: Base: Completed preparation.

Levels and layer thickness were determined with a base station. Compaction density was measured with a nuclear density gauge. Moisture gauges and pressure cells were installed in predetermined locations at mid-depth in the layer. Strain gauges were installed on top of the layer (instrumentation is discussed in Section 4.4).

3.5.1 Base Quality Control Testing

Compaction Density

Compaction density measurements on the base followed the same procedure as that followed for testing on the subgrade and subbase. A summary of the results is provided in Table 3.3.

Table 3.3: Summary of Base Dry Density Measurements

Cell	MaxDD[a] (kg/cm^3)	Nuclear Gauge Density					Moisture Content (%)	
		Average (kg/cm^3)	Std. Dev.[b] (kg/cm^3)	Relative (% of LMP)	Average (pcf)	Std. Dev. (pcf)	OMC[a]	Actual
A	2,252	2,206	24.9	98	137.7	1.6	6.2	5.8
B	2,252	2,206	24.9	98	137.7	1.6	6.2	5.8
C	2,252	2,212	6.4	98	138.1	0.4	6.2	5.9

[a] MaxDD/OMC = Laboratory-determined modified Proctor (LMP) dry density and optimum moisture content (AASHTO T 180)
[b] Std. Dev. = Standard deviation

The relative compaction achieved exceeded the specification requirements (95% of laboratory-determined dry density [i.e., modified Proctor, not CT-216]) on both lanes. Although compaction requirements were met, the surface material could be easily dislodged, which was attributed to the rounded nature of the aggregates and consequent poor aggregate interlock. This could result in the material being more susceptible to shearing under traffic loading.

3.5.2 Prime Coat Application on Base

An SS1h prime coat was applied at a rate of 0.25 gal./yd^2 (1.13 L/m^2) on March 14, 2019, approximately six weeks prior to placement of the CCPR layer (delay between construction of the base and CCPR layers was due to different contractors with different availability). The surface was sprayed with water prior to application of the prime coat (Figure 3.16 through Figure 3.18). No vehicle traffic was permitted on the prime-coated track prior to placement of the CCPR layer.

Figure 3.16: Base: Water spray prior to prime coat application.

Figure 3.17: Base: Prime coat application.

Figure 3.18: Base: Completed prime coat application.

3.6 Cold Central Plant Recycled Layer Construction

Materials for the cold central plant recycled layer were crushed on 04/18/2019 and 04/19/2019. The CCPR-EA layer on Lane 4 was constructed on 04/23/2019. The CCPR-FA layers on Lanes 1, 2, and 3 were constructed on 04/24/2019. Material was placed as it was produced, and no treated materials were stockpiled.

3.6.1 Recycled Asphalt Pavement Processing

Recycled asphalt millings were sourced from the CCPR contractor's stockpile in Sacramento. The material was trucked to the site and stockpiled close to the screen and crushing plant. Material was taken from the stockpile and dumped onto a 4 in. (100 mm) static screen. Material that passed this screen was belt fed onto a 1 in. (25 mm) vibrating screen. Oversize material was fed from the screen into an impact crusher and then passed back over the 1 in. screen. All screened material was then belt fed onto a stockpile ready for processing through the cold central plant. The screening and crushing setup and pre-crushed and crushed materials are shown in Figure 3.19 through Figure 3.21.

Figure 3.19: CCPR: Screening and crushing setup.

Figure 3.20: CCPR: RAP millings stockpile.

Figure 3.21: CCPR: Crushed materials.

3.6.2 Cold Central Plant Material Processing

The cold central plant (CCP) was set up next to the crushing plant (Figure 3.22). Recycling agent was fed from a tanker. Active filler (cement) was fed from a super sack directly into the CCP hopper. Compaction and foaming water was sourced from the onboard tank and replenished as required from a water tanker. Processed material was fed from a belt into waiting trucks. Samples for quality control and other testing were sampled from the belt. Issues with foaming water content for the CCPR-FA mix were noted in the early stages of production of this mix (mix placed on Lane 3 on Cell D and then Cell C). This was corrected for the mix placed on Lane 2 and Lane 1.

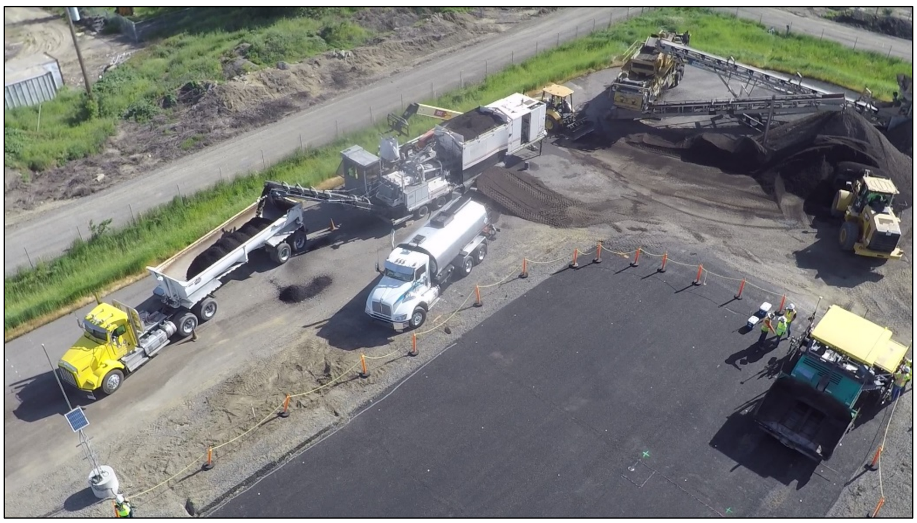

Figure 3.22: CCPR: Central plant setup.

3.6.3 Cold Central Plant Material Placement

Processed material was end-dumped from the truck directly into the paver hopper (Figure 3.23 and Figure 3.24). Long-bed articulated dump trucks were used for the emulsified asphalt mixes, but these proved difficult to maneuver on the track and were switched out for shorter trucks for the foamed asphalt mixes on day 2. Paving and compaction followed conventional procedures consistent with Caltrans partial-depth recycling requirements (Figure 3.25 and Figure 3.26). A rolling pattern was established on each CCPR-EA cell and each CCPR-FA lane. A 10-ton vibrating steel drum roller was used for breakdown compaction, followed by a 20-ton (12 tons with ballast) pneumatic tired roller, and then a 10-ton steel drum roller without vibration for finish rolling. Secondary compaction with the 10-ton steel drum roller was done on the CCPR-EA lane two days after placement.

Figure 3.23: CCPR: Material delivery with long-bed dump truck.

Figure 3.24: CCPR: Material delivery with short-bed dump truck.

Figure 3.25: CCPR: Paving and breakdown compaction.

Figure 3.26: CCPR: Intermediate compaction with pneumatic tired roller.

Placement of both mixes was completed with no major issues that might have influenced later performance of the structure. Some shearing of the recycled layer was observed during compaction with the pneumatic tired roller (Figure 3.27), which was attributed to deflection of the underlying aggregate base under the weight of the roller. Shear cracks were not observed after completion of compaction with the finish roller (Figure 3.28).

Figure 3.27: CCPR: Shear cracks after pneumatic tired roller passes.

Figure 3.28: CCPR: Crack-free surface after final compaction.

3.6.4 Cold Central Plant Layer Quality Control

Compaction Density

Compaction density on the CCPR layers was measured using a nuclear gauge (CT-375) on the day of construction. Measurements were taken at three randomly selected locations on each cell. Relative compaction was determined using the CT-216 method on one sample from each cell. A summary of the density results is provided in Table 3.4. Relative compaction ranged between 98% and 99%. However, these results may be questionable given that the CT-216 method is not always an accurate measure of compaction given the coarse gradation of the material and small specimen size. Relative compaction around 98% was expected.

Table 3.4: Summary of CCPR Layer Density Measurements

Cell	CT-216 (kg/cm^3)	Nuclear Gauge Density					Moisture Content (%)	
		Average (kg/cm^3)	Std. Dev.[a] (kg/cm^3)	Relative (% of 216)	Average (pcf)	Std. Dev.[a] (pcf)	Gauge	Gravimetric
A	2,009	2,021	19	99	126.2	1	16.4	7.8
B	2,009	2,025	26	99	124.8	3	15.8	7.4
C	2,010	2,055	32	98	128.3	2	13.2	6.0

[a] Std. Dev. = Standard deviation

Layer Thickness

Recycled layer thicknesses were determined from a precise leveling survey with measurements taken every 9.8 ft. (3 m) along the centerline of each lane. Measurements were also recorded from cores cut from the centerline 16.4 ft. (5 m) from the start and end of each cell. No cores were taken between these points to ensure that future HVS test sections would not be affected. Measurements were also taken from the density cores and from cores removed to install the multi-depth deflectometers at Station 13 on each HVS section. The results are summarized in Table 3.5 and indicate that the as-built thicknesses were close to the design thicknesses.

Table 3.5: Summary of CCPR Layer Thickness Measurements

Cell	Mix Type	Design Thickness		Average Thickness		Standard Deviation	
		(ft.)	(mm)	(ft.)	(mm)	(ft.)	(mm)
A	Emulsified Asphalt #1	0.4	120	0.40	121	0.03	7.7
B	Emulsified Asphalt #2			0.41	123	0.03	8.1
C	Foamed Asphalt			0.41	123	0.03	8.4

3.6.5 Curing Seal Application

A curing seal using the same emulsified asphalt used in the CCPR-EA layer was applied at a rate of 0.03 $gal./yd^2$ (0.14 L/m^2) after completion of all quality control testing (Figure 3.29 and

Figure 3.30). Given that the test track would not be trafficked until placement of the asphalt concrete surfacing, no sand cover was applied with the curing seal.

Figure 3.29: CCPR: Curing seal application.

Figure 3.30: CCPR: Completed recycled layer after construction.

3.7 RHMA-G Layer Construction

3.7.1 Introduction

The RHMA-G mixes were placed on the four lanes of the test track on 05/08/2019, well within the Caltrans specification allowable 15-day period between construction of PDR and CCPR layers and placement of the asphalt surfacing. All mixes were produced at the George Reed asphalt plant in Clements, California. Mix was transported in end-dumps, and travel time between the plant and the test track was between 75 and 90 minutes depending on traffic.

Production of the mix used for the CCPR cells and as the control for the RHMA-G experiments started at 04:00 hours. This mix was stored in a silo until scheduled for delivery and placement, while the other RHMA-G mixes were produced. The loads used on the CCPR experiment departed from the plant at approximately 11:45, with mix stored in the silo prior to transport for between 3.0 and 5.5 hours.

Tack coat was sprayed onto the CCPR layer approximately 60 minutes prior to starting placement of the RHMA-G mix on each lane. Placement of mix on Lane 3 (CCPR-FA) started at approximately 13:00 and was completed at approximately 14:20. Placement of mix on Lane 4 (CCPR-EA) started at approximately 14:40 and was completed at approximately 15:00.

Ambient air temperature next to the track when placement started at 13:00 was 81°F (27°C). Temperatures increased to a high of 85°F (29°C) at completion of compaction at 15:00. No clouds were observed during the day. Winds were light, with speeds ranging between 0.3 and 3.0 mph

(0.5 and 4.8 km/h) for most of the day, increasing to 6.0 mph (9.6 km/h) in the late afternoon. Relative humidity ranged between a high of 91% at 06:30 and a low of 40% at 16:00.

3.7.2 Tack Coat Application

An SS1h tack coat was applied at a rate of 0.03 gal./yd^2 (0.14 L/m^2) approximately 60 minutes prior to placement of the RHMA-G on each cell (Figure 3.31 and Figure 3.32).

Figure 3.31: RHMA-G: Tack coat application.

Figure 3.32: RHMA-G: Close-up view of tack coat application.

3.7.3 Mix Temperatures

The temperature of the mix in each of five truckloads placed on Cells A, B and C was measured on arrival when the delivery documentation was checked. The average temperature for the mix was 331°F (166°C).

3.7.4 Paving

Given the confined working space on the test track, the short length of the cells, and small quantities of material required, mix was end-dumped directly into the paver (Figure 3.33) rather than dumping into a windrow and then using a material transfer vehicle to load the paver, as specified in the Caltrans specifications. Thereafter, paving and compaction followed conventional procedures consistent with the Caltrans Section 39 RHMA-G specification requirements (Figure 3.34 through Figure 3.37).

3.7.5 RHMA-G Construction Quality Control

Temperature

Temperatures were systematically recorded throughout the placement of the RHMA-G layer using thermocouples (Figure 3.38) and an infrared camera fixed to the paver (Figure 3.39).

Figure 3.33: RHMA-G: Dumping mix into the paver.

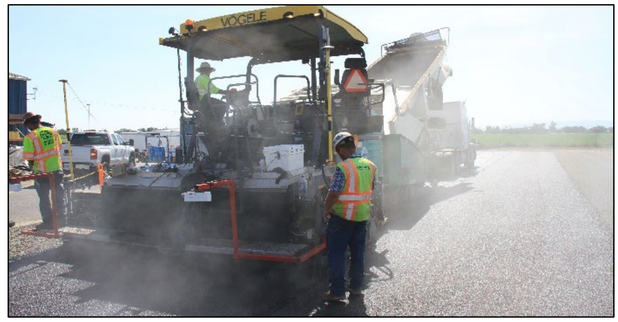

Figure 3.34: RHMA-G: Paving RHMA-G.

Figure 3.35: RHMA-G: Breakdown compaction.

Figure 3.36: RHMA-G: Intermediate (front) and final compaction (back).

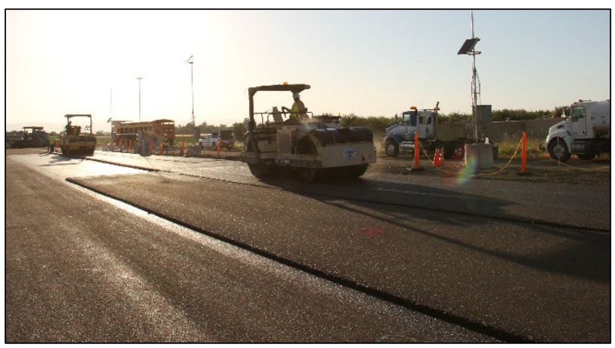

Figure 3.37: RHMA-G: Final compaction.

Figure 3.38: RHMA-G: Temperature measurement with thermocouple.

Figure 3.39: RHMA-G: Temperature measurement with paver-mounted infrared camera.

Average mix temperatures behind the paver screed and at the start and completion of rolling for the mix placed on the CCPR cells are summarized in Table 3.6. These temperatures are consistent with typical temperatures on RHMA-G construction projects.

Table 3.6: Approximate Average Mix Temperatures During Construction

Cell	Mix	Lift	Average Temperature					
			Behind Paver		Start of Compaction		End of Compaction	
			(°F)	(°C)	(°F)	(°C)	(°F)	(°C)
A,B,C	1/2 in. no RAP	1	313	156	304	151	189	87

<u>Compaction Density</u>

Compaction density was measured using a nuclear gauge (CT-375) on the day of construction and on cores removed from each cell on the days following construction. Relative compaction was determined using the theoretical specific gravity values (AASHTO T 209) of samples collected behind the paver on each cell. Nuclear gauge measurements were taken at three randomly selected locations on each cell. A summary of the core density and nuclear gauge density results is provided in Table 3.7. The relative compaction (i.e., percent of maximum theoretical density) achieved on each lift on each cell is plotted in Figure 3.40. Densities measured on cores were in all instances higher than those measured with the nuclear gauge.

Table 3.7: Summary of RHMA-G Layer Density Measurements

Cell	Lift	MTD[a] (g/cm^3)	Core Density			Nuclear Gauge Density		
			Average (g/cm^3)	Std. Dev.[b] (g/cm^3)	Relative (% of MTD)	Average (g/cm^3)	Std. Dev. (g/cm^3)	Relative (% of MTD)
A	1	2.522	2.352	0.016	93.3	2.300	0.013	92.5
B	1	2.522	2.371	0.043	94.0	2.306	0.017	92.8
C	1	2.522	2.357	0.029	93.5	2.315	0.016	93.1

[a] MTD = Maximum theoretical density (determined according to AASHTO T 209)
[b] Std. Dev. = Standard deviation

The results from cores were used for analysis purposes and indicate that all of the cells had satisfactory compaction and met Caltrans specifications (i.e., 91% to 97% of maximum theoretical density). The measurements were consistent across the three cells, with a difference of only 0.7% between lowest and highest relative compaction.

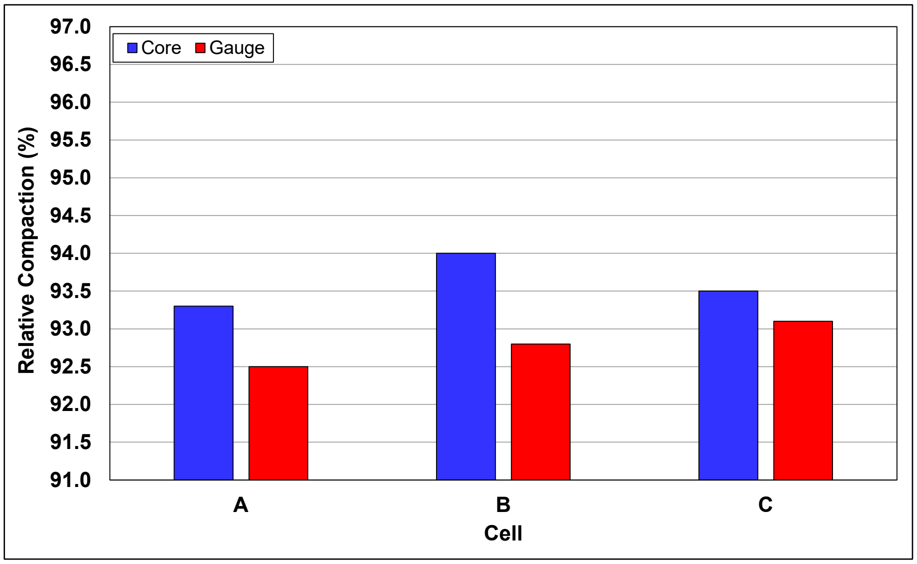

Figure 3.40: Summary of relative density measurements.

<u>As-Built RHMA-G Layer Thicknesses</u>

RHMA-G layer thicknesses were determined from a precise leveling survey with measurements taken every 9.8 ft. (3 m) along the centerline of each lane. Measurements were also recorded from cores cut from the centerline 16.4 ft. (5 m) from the start and end of each cell. No cores were taken between these points to ensure that future HVS test sections would not be affected. However, measurements were also taken from the density cores and later from cores removed to install the multi-depth deflectometers at Station 3 and/or Station 13 on each HVS section. The results are summarized in Table 3.8 and indicate that the as-built thicknesses were close to the design thicknesses.

Table 3.8: Summary of RHMA-G Layer Thickness Measurements

Cell	Mix Type	Design Thickness		Average Thickness		Standard Deviation	
		(ft.)	(mm)	(ft.)	(mm)	(ft.)	(mm)
A	1/2 in. NMAS, no RAP	0.2	60	0.20	59	0.05	15.9
B				0.21	64	0.01	4.1
C				0.22	65	0.01	3.1

3.8 Test Track Approval

The test track was considered to be representative of a highway project and was approved for HVS testing.

4. TRACK LAYOUT, INSTRUMENTATION, AND TEST CRITERIA

4.1 Testing Protocols

The Heavy Vehicle Simulator (HVS) test section layout, test setup, trafficking, and measurements will follow standard University of California Pavement Research Center (UCPRC) protocols *(11)*. Details specific to this project are discussed in the following sections.

4.2 Test Track Layout

The test track layout for this project is shown in Figure 4.1. Two HVS test sections were instrumented during construction in each recycling agent type cell, the first for assessing performance at ambient mid-range temperatures (30°C [86°F]) and the second for assessing performance at relatively high pavement temperature conditions (50°C at 50 mm [122°F at 2 in.] depth). A third cell with post-construction instrumentation was also marked for potential additional testing (e.g., high moisture contents in the CCPR layer). Additional testing, if justified, will be identified and motivated based on the results of the first round of testing and associated laboratory testing.

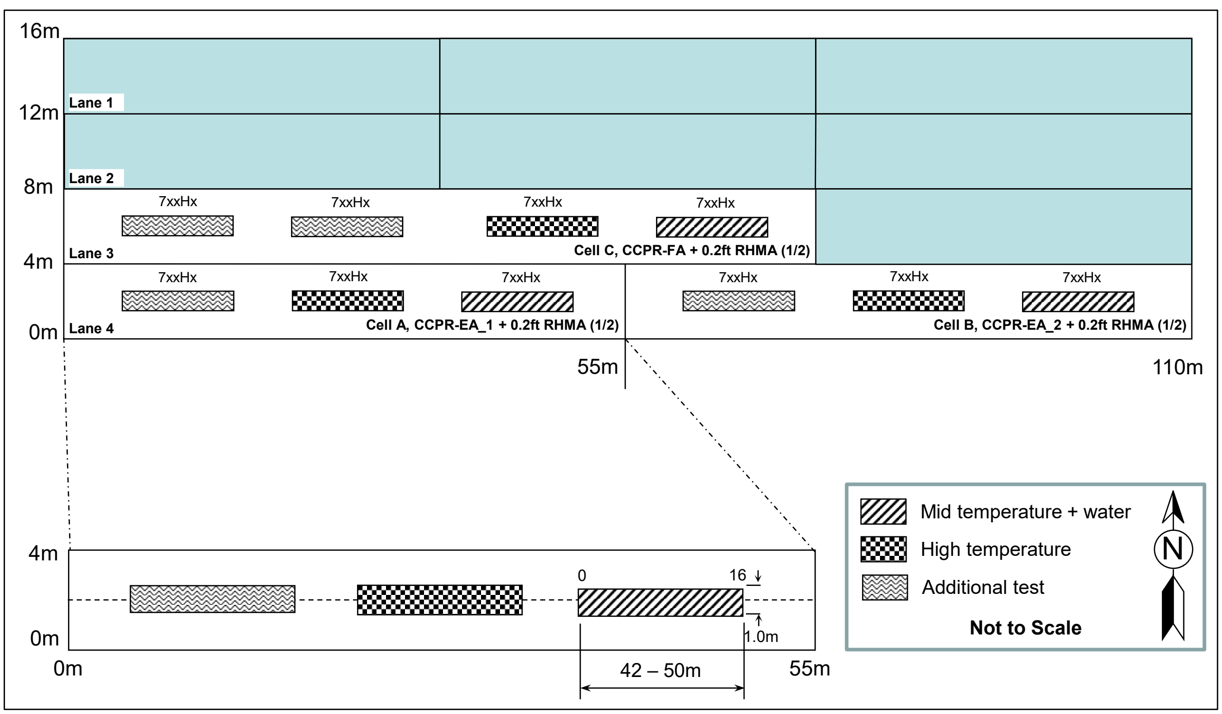

Figure 4.1: Test track layout.

Test section numbers will be allocated in order of location on the test track.

4.3 HVS Test Section Layout

An HVS test section for testing to assess underlying layer performance is 8.0 m (≈26.2 ft.) long and 1.0 m (≈3 ft.) wide. A schematic in Figure 4.2 shows a typical HVS test section along with the stationing and coordinate system. Station numbers (0 to 16) refer to fixed points on the test section and are used for measurements and as a reference for discussing performance. Stations are placed at 0.5 m (≈1.6 ft.) increments. A sensor installed 50 mm below the center of the test section (i.e., Station 8) would have an x-coordinate of 4,000 mm (≈13.1 ft.), a y-coordinate of 500 mm (≈1.6 ft.), and a z-coordinate of 50 mm (≈2.0 in.).

4.4 Test Section Instrumentation

Measurements are taken with the equipment and instruments listed as follows. Typical instrument positions are shown in Figure 4.2.

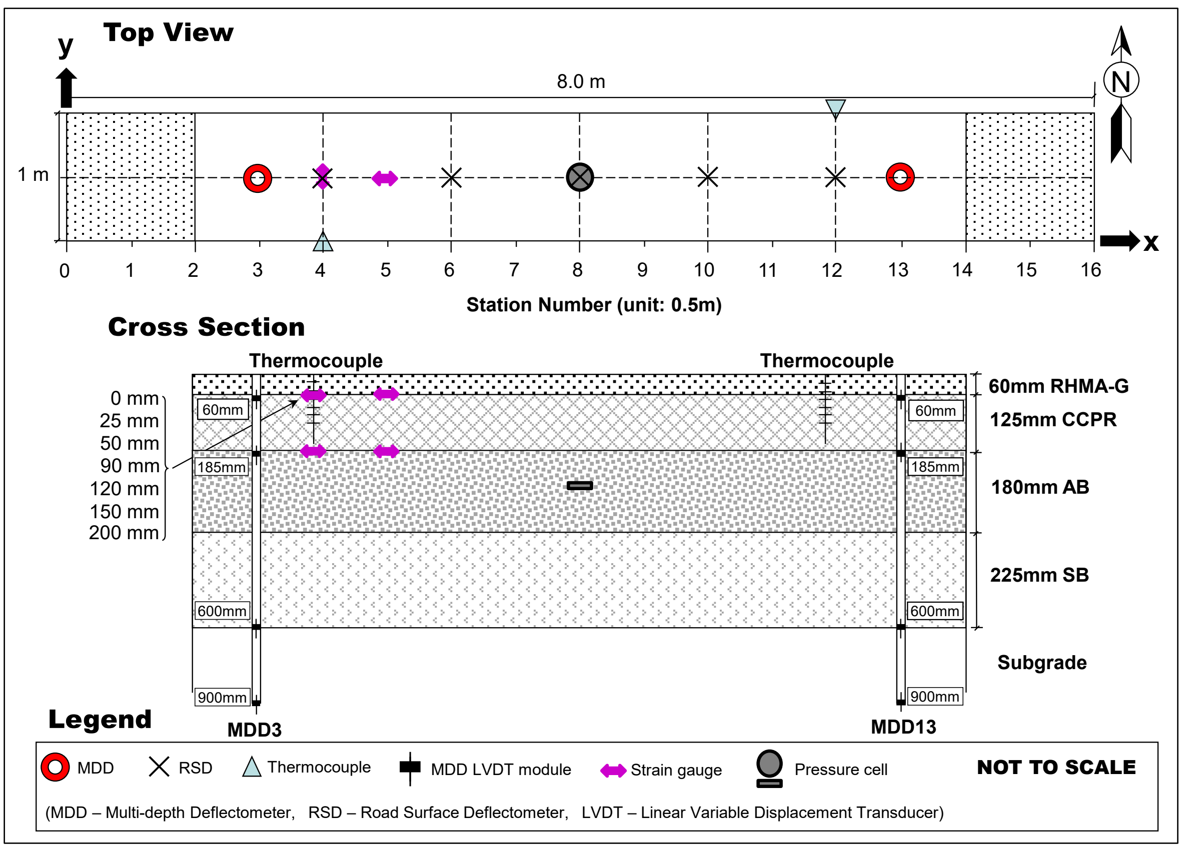

Figure 4.2: Schematic of an HVS test section layout.

- A laser profilometer is used to measure surface profile; measurements are taken at each station.

- A road surface deflectometer (RSD) is used to measure surface deflection during the test. RSD measurements are taken under a creep-speed 40 kN (9,000 lb.) half-axle load at regular intervals. Note that RSD measurements under a creep-speed load (2 km/h [1.2 mph]) would not be the same as those recorded under trafficking speed loads. After load changes, deflections are measured under the new load, as well as under the 40 kN load, which serves as a baseline for assessing damage under the heavier loads. Note that a 40 kN half-axle load on the HVS equates to an 80 kN (18,000 lb.) full axle load on a truck, or one equivalent single axle load (ESAL).
- A falling weight deflectometer (FWD) is used to measure surface deflection on the section before and after HVS testing to evaluate the change in stiffness caused by trafficking. Testing is undertaken on both the trafficked and adjacent untrafficked areas (i.e., 4 m on either end of the 8 m test section) at 500 mm (≈19.7 in.) intervals. Two sets of tests are undertaken on each day to obtain a temperature range for backcalculation of layer stiffnesses.
- Type-T thermocouples are used to measure pavement and air temperatures (both inside and outside the HVS environmental chamber). Seven thermocouples are bundled together to form a "thermocouple tree" for measuring air, pavement surface, and pavement layer temperatures inside the environmental chamber. Pavement layer temperatures are measured at the pavement surface, and at depths of 25, 50, 90, 120, 150, and 200 mm (≈1, 2, 3.5, 4.7, 6, and 8 in.). Air temperatures are measured with thermocouples attached to the outside walls of the environmental chamber, with at least one thermocouple in direct sunlight during any part of the day. Additional air temperatures are recorded at a permanent weather station at the northwest end of the test track.
- A multi-depth deflectometer (MDD) is installed on each test section. An MDD is essentially a stack of linear variable differential transformer (LVDT) modules fixed at different depths in a single borehole. The LVDT modules have non-spring-loaded core slugs that are linked together into one long rod that is anchored at the bottom of a 3.3 m (≈10.8 ft.) borehole. The LVDT modules are fixed to the pavement layer, which allows permanent vertical deformations at various depths to be recorded, in addition to measurement of the elastic deformation caused by the passage of the HVS wheels. The borehole is 38 mm (≈1.5 in.) in diameter. A model MDD with five modules is shown in Figure 4.3. In this project, MDDs will be installed in the middle of the wheelpath, with modules positioned as follows:
    + Station 3: Surface, 10 mm below the top of the aggregate base layer, 10 mm below the top of the aggregate subbase layer, and 10 and 300 mm below the surface of the subgrade.
    + Station 13: 10 mm below the top of the CCPR layer, 10 mm below the top of the aggregate subbase layer, 10 and 300 mm below the top of the subgrade layer.

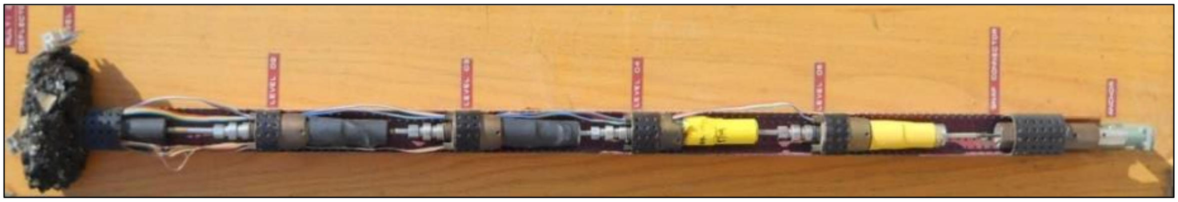

Figure 4.3: A model multi-depth deflectometer (MDD), showing five modules.

- Four strain gauges (*Tokyo Sokki PMFLS-60*) were installed on the centerline of each test section, two at the bottom of the RHMA-G layer, and two at the bottom of the CCPR layer (Figure 4.4). The gauges at Station 4 were positioned to measure transverse strain, and those at Station 5 were positioned to measure longitudinal strain.
- One *RST LPTPC09-S* pressure cell was installed at mid-depth in the aggregate base layer (Figure 4.5) on each test section to measure vertical pressure (stress) under the moving wheel.
- Multiple moisture sensors (*Decogon GS1*) were installed in the subgrade, subbase, and base layers (Figure 4.6), positioned next to and between select sections, as shown in Figure 4.7 and Figure 4.8.

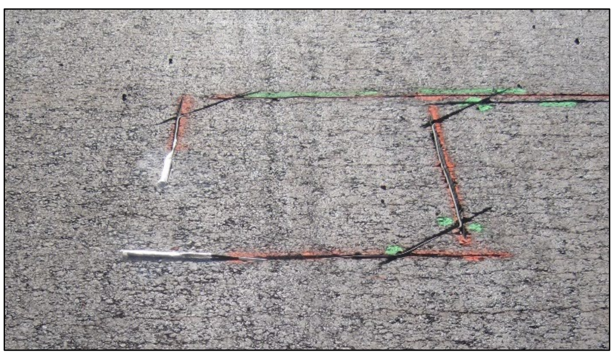

Figure 4.4: Strain gauge installation on top of CCPR layer.

Figure 4.5: Pressure cell installation in the aggregate base.

Figure 4.6: Moisture sensor installation on top of subbase.

Figure 4.7: Moisture sensor locations on top of subbase.

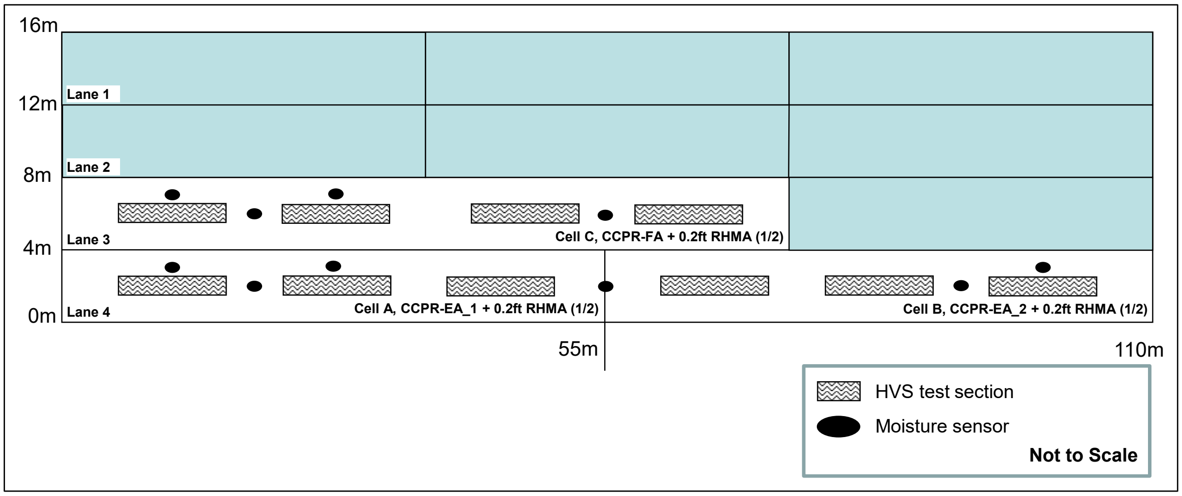

Figure 4.8: Moisture sensor locations.

4.5 Test Section Measurements

4.5.1 Temperature

Pavement temperatures are controlled using an environmental chamber. Both pavement and air (inside and outside the environmental chamber) temperatures are monitored and recorded hourly during the entire trafficking period. In assessing rutting performance, the temperature at the bottom of the asphalt concrete and recycled layers and the temperature gradient from top to bottom of the asphalt concrete and recycled layers are two important controlling temperature parameters that influence the stiffness of these layers and are used to compute plastic strain.

4.5.2 Surface Profile

The following rut parameters are determined from laser profilometer measurements:

- Maximum total rut depth at each station
- Average maximum total rut depth for all stations
- Average deformation for all stations
- Location and magnitude of the maximum rut depth for the section
- Rate of rut development over the duration of the test

The difference between the surface profile after HVS trafficking and the initial surface profile before HVS trafficking is the permanent change in surface profile. Based on the change in surface profile, the maximum total rut is determined for each station, as illustrated for a dual wheel configuration in Figure 4.9. The average maximum total rut for the section is the average of all of the maximum total ruts measured between Stations 3 and 13.

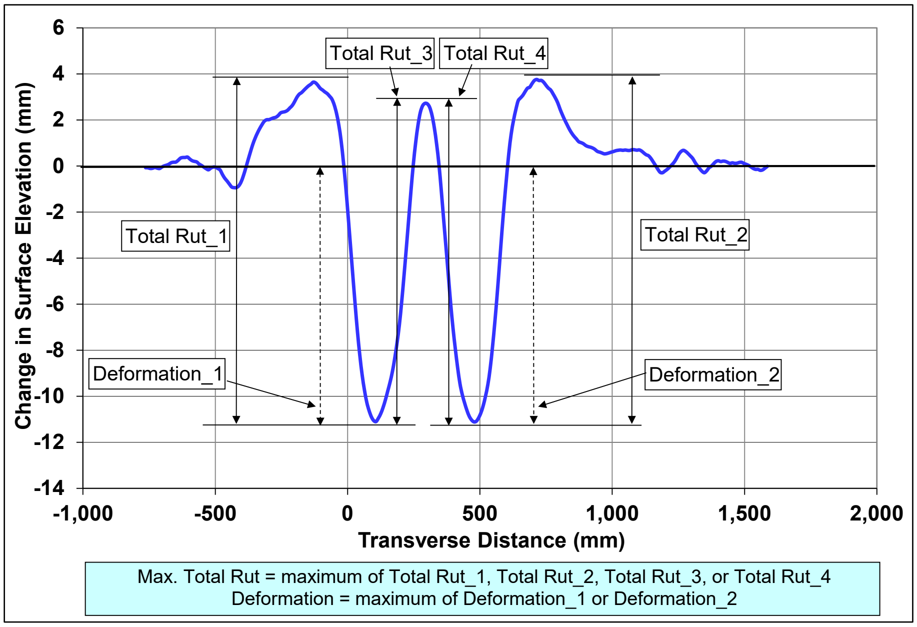

Figure 4.9: Illustration of maximum rut depth and deformation for a leveled profile.

4.5.3 Elastic Vertical Deflection

An example set of MDD data is presented in Figure 4.10, which shows the variation of the elastic vertical deflections measured at different depths versus wheel position as the wheel travels from one end of the test section to the other. The elastic vertical deflection is the difference between the total vertical deflection and the reference value, which is the measurement recorded when the wheel is at the far end of the test section. The peak values are the maximum elastic vertical deflection for each individual MDD module.

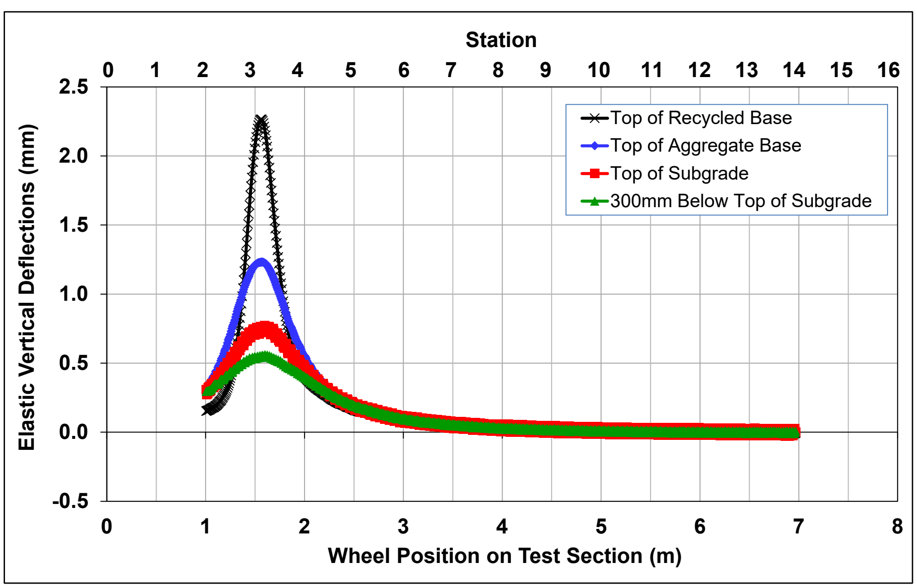

Figure 4.10: Example elastic vertical deflection measured with MDD at Station 3.

4.5.4 Strain

Strain gauges are connected to a *National Instruments NI cDAQ-9237* module. A virtual channel was created for each strain gauge using the *Measurement and Automation Explorer* (*NI-MAX*) software provided by National Instruments. The strain gauge virtual channel readings were determined as:

$$Strain = -\frac{V_r}{GF} = -\frac{V_r}{0.5} = -2V_r \qquad \textbf{(4.1)}$$

Where: Strain = the output of the virtual channel
GF = the gauge factor in the virtual channel setting, and
V_r = the ratio between output and input voltages of the Wheatstone bridge inside the strain gauge.

A gauge factor of 0.5 is used to configure the virtual channel to accommodate the gauge calibration coefficient (C_ε, [average calibration coefficient of 0.830 was provided by the instrument manufacturer]) for each gauge based on the assumption that the voltage ratio is multiplied by 2.0 when converting to strain. The data acquisition software converts the virtual channel reading into microstrain by multiplying it by -0.830x106. The negative sign is necessary to ensure that tensile strain increases with increasing load repetitions.

Strain readings are recorded and loaded into a database where the actual calibration coefficients for each specific strain gauge are stored. When data is extracted from the database, the necessary minor rescaling is built into the query to ensure that the individual gauge factors are used in place of the average value of 0.830. Example strain data recorded from one of the strain gauges is plotted in Figure 4.11, which shows the variation of the strain gauge reading versus wheel position as the wheel travels from one end of the test section to the other. Several quantities are summarized based on the raw readings. Specifically, the reference value is the reading when the wheel is at the far end of the test section. The peak and valley are maximum and minimum values deviating from the reference value, respectively.

4.5.5 Pressure

Example data recorded from a pressure cell is shown in Figure 4.12, which shows the variation of the cell reading versus wheel position as the wheel travels from one end of the test section to the other. Several quantities are summarized based on the raw readings. Specifically, the reference value is the reading when the wheel is at the far end of the test section. The peak and valley are maximum and minimum values deviating from the reference value, respectively.

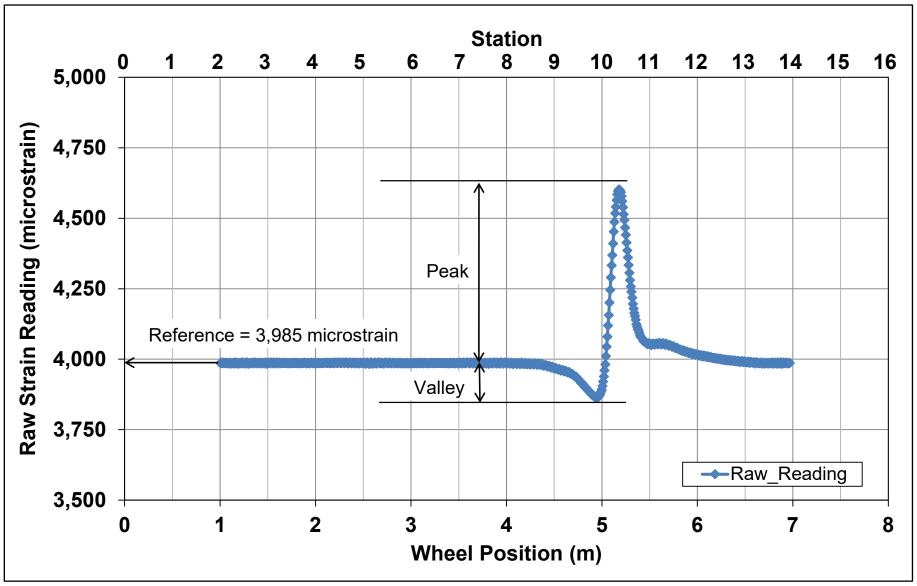

Figure 4.11: Example strain gauge reading and definition of summary quantities.

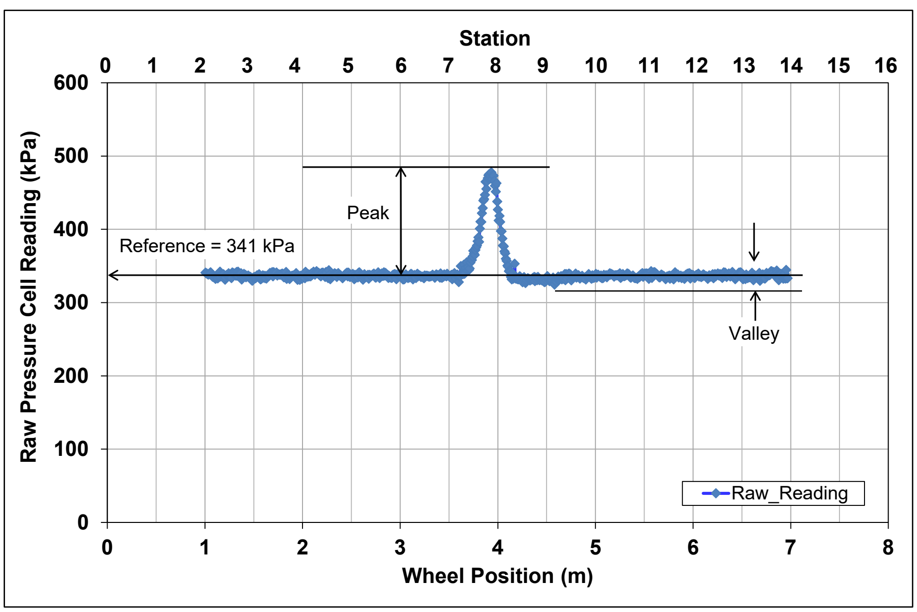

Figure 4.12: Example pressure cell reading and definition of summary quantities.

5. CONCLUSIONS

This technical memorandum summarizes the construction and instrumentation of a test track to study the behavior of cold central plant recycled (CCPR) layers in a pavement structure. Two recycling agents will be tested including emulsified asphalt from two different producers and foamed asphalt from one binder supplier. The pavement structure includes an aggregate subbase (0.75 ft. [225 mm]), an aggregate base (0.6 ft. [180 mm]), the recycled layer (0.4 ft. [120 mm]), and a gap-graded rubberized hot mix asphalt (RHMA-G) (0.2 ft. [60 mm]) surfacing. The structure was constructed on prepared subgrade. Material properties and construction procedures met all Caltrans specifications. Instrumentation includes multi-depth deflectometers, strain gauges, pressure cells, and moisture sensors.

The test track was considered to be representative of a highway project and was approved for Heavy Vehicle Simulator testing.

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