Cold Asphalt and Hot In-place Asphalt Recycling Technologies

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ABSTRACT

Virtual site visits and interviews of five key State Departments of Transportation (DOTs) plus the two Federal Lands Highway Divisions, along with material producers and paving contractors that served these agencies were conducted to learn more regarding successful use of cold asphalt and hot in-place recycling technologies. Practices investigated were project selection, recycling technology selection, structural pavement design, materials, mixture design, field construction and acceptance, quality control, curing and opening to traffic, lessons learned, pavement performance, contractor perspectives, and agency best practices were collected and synthesized in this report. Some agencies used a single recycling technique while others used multiple. The summary of this information includes practices used by State DOTs to implement cold asphalt and hot in-place asphalt recycling technologies. Examples of positive practices, lessons learned, and challenges from States and Federal Lands Highway Divisions are presented.

Key Words: cold asphalt recycling, hot in-place recycling, cold inplace recycling, cold central plant recycling, full depth reclamation.

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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LIST OF ABBREVIATIONS AND SYMBOLS

Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
ADTT	Average Daily Truck Traffic
AES	Asphalt Emulsion Supplier Program
AGC	Associated General Contractors
APIPRT	Asphalt Pavement In-place Recycling Technologies
ARRA	Asphalt Recycling and Reclaiming Association
ASTM	American Society for Testing and Materials
BIA	Bureau of Indian Affairs
BLM	Bureau of Land Management
BOR	Bureau of Reclamation
CCI	Critical Condition Index
CCPR	Cold Central Plant Recycling
CFL	Central Federal Lands
CIR	Cold-In-place Recycling
CMRB	Cement Modified Recycled Base
CPDM	Comprehensive Pavement Design Manual
DOD	Department of Defense
DOT	Department of Transportation
EFL	Eastern Federal Lands
EPD	Environmental Production Declaration
ESAL	Equivalent Single Axle Load
FDR	Full Depth Reclamation
FHWA	Federal Highway Administration
FLAP	Federal Lands Access Program
FLH	Federal Lands Highway
FLTP	Federal Lands Transportation Program
FOB	Free on Board
FWD	Falling Weight Deflectometer
GPR	Ground Penetrating Radar
HFE	High Float Emulsion
HFMS-2	High float emulsion
HIPR	Hot In-Place Recycling
HMA	Hot Mix Asphalt
HS	Heater Scarifying
HWTT	Hamburg Wheel-Tracking Test
INDOT	Indiana DOT
IRI	International Roughness Index
ITS	Indirect Tensile Strength
JMF	Job Mix Formula
JTT	Just in Time Training
LADA	Liquid Asphalt Distributor Association
LCA	Life Cycle Assessment

LCCA	Life Cycle Cost Analysis
LWD	Light Weight Deflectometer
MDD	Maximum Dry Density
ME	mechanistic-empirical
MEPDG	Mechanistic-Empirical Pavement Design Guide
MMP	Materials Management Plan
MOI	Materials Manual of Instructions
MOT	Management of Traffic
NAPA	National Asphalt Pavement Association
NCAT	National Center for Asphalt Technology
NCHRP	National Cooperative Highway Research Program
NHI	National Highway Institute
NMDOT	New Mexico DOT
NPS	National Park Service
OGS	Office of General Services
PCAR	Pavement Condition Assessment Reports
PCC	Portland Cement Concrete
PCCP	Portland Cement Concrete Pavement
PCR	Pavement Condition Rating
PDDM	Project Design and Development Manual
PE	Professional Engineer
PG	Performance Grade
PMS	Pavement Management System
PTD	Project Target Density
QA	Quality Assurance
QC	Quality Control
QPL	Qualified Products List
RA	Recycling Agent
RAP	Reclaimed Asphalt Pavement
RMS	Retained Marshall Stability
SBS	Styrene-Butadiene -Styrene
SCDOT	South Carolina DOT
TFHRC	Turner-Fairbank Highway Research Center
TSR	tensile strength ratio
U.S.	United States
UCS	Unconfined Compressive Strength
USACE	U.S. Army Corps of Engineers
USCS	Unified Soil Classification System
USDOT	US Department of Transportation
USFWS	U.S. Fish and Wildlife Service
USP	Unique Special Provision
VDOT	Virginia DOT
VE	Value Engineering
VPP	Vendor Placed Paving
VTM	Virginia Test Method
VTRC	Virginia Transportation Research Council

WFL	Western Federal Lands
WMA	Warm Mix Asphalt

Symbols

ITS_{Dry}	dry indirect tensile strength
a_i	layer coefficient

CHAPTER 1 INTRODUCTION

INTRODUCTION

State Departments of Transportation (DOT) and other agencies are faced with increasing material costs today coupled with a greater desire to consciously integrate principles of sustainability into pavement construction. [1] The asphalt industry has been a leader in recycling for decades with over 99 percent of reclaimed asphalt pavement (RAP) being put back to use. [2] RAP is the number one recycled material in the U.S. Historically, the majority of RAP has been recycled back into hot mix asphalt (HMA), with the majority of it being used in State DOT pavements. Initially this was driven by the desire for cost-effective alternatives to virgin asphalt binder. However, in some areas (typically urban areas) the available supply of RAP exceeds the demand resulting in stockpiles of excess RAP. [3] Conversely, in rural areas the available supply of RAP can be less than the demand and to haul excess RAP in urban areas to rural areas can lead to less sustainable pavement construction. This challenge can be addressed using a portable cold central recycling plant or cold in-place or hot in-place recycling techniques. These same technologies can also be used in urban areas to increase recycling rates. Finally, in a National Asphalt Pavement Association (NAPA) 2019 construction season survey, 28 companies collectively indicated that they used over 4.2 million tons of RAP while performing in-place recycling processes during the 2019 construction season. [2]

This effort focuses on the following sustainable asphalt recycling techniques: cold in-place recycling (CIR), full depth reclamation (FDR), cold central plant recycling (CCPR), and hot in-place recycling (HIPR). The Asphalt Recycling and Reclaiming Association (ARRA) defines cold recycling as, "*Cold recycling is a method of reconstructing any flexible pavement where the need arises from structural failures*." [4] Muench et al., defined CIR, FDR and HIPR as follows: *"CIR - A pavement rehabilitation method in which some fraction of the existing pavement thickness (up to about 4 inches) is milled up, crushed and screened, then mixed with asphalt cement (or emulsified/foamed asphalt) and replaced to serve as a high-quality base material upon which to pave. FDR - A pavement rehabilitation method in which the existing full pavement thickness and some portion of the underlying material is pulverized, blended, and stabilized (with cement, lime, foamed/emulsified asphalt, etc.) to provide a high-quality base material upon which to pave. HIPR - A pavement rehabilitation method in which the existing asphalt pavement surface (usually ¾–2 inches deep) is heated and softened, scarified or milled, supplemented with aggregate and/or additives (if required), mixed, then replaced."* [1] Apeagyei and Diefenderfer defined "*CCPR is a process in which the recycled material is milled from a roadway and brought to a centrally located recycling plant that in-corporates the recycling agents into the material."* (5). State DOTs and industry commonly use these terms, but individual State DOTs will sometimes have more detailed definitions or descriptions in specifications or design documents. Figure 1 through Figure 4 illustrate the sustainable asphalt recycling techniques.

When compared with other rehabilitation or reconstruction techniques that mitigate or completely eliminate distresses in an existing pavement, the sustainable recycling techniques listed above offer many potential benefits such as: [4]

- Reduced cost, energy consumption/carbon footprint, use of natural resources, construction duration, and road user delays.

- Pavement geometry (profile and cross-slope) may be corrected while preserving overhead clearances and improving pavement structural capacity and pavement performance.
- Reuse of some or all of the existing pavement materials.

Figure 1. Picture. Cold In-place Recycling.

Figure 2. Picture. Full Depth Reclamation.

Figure 3. Picture. Cold Central Plant Recycling.

Figure 4. Picture. Hot In-Place Recycling.

Sustainability encompasses economic, environmental and societal aspects. Life Cycle Cost Analysis (LCCA) has been used to quantify the economic aspect of pavement construction, rehabilitation and maintenance alternatives for years. More recently Life Cycle Assessment (LCA) has been used to quantify the environmental aspects of pavements. Harvey et al. defined LCA as follows, "*LCA provides a comprehensive approach to evaluating the total environmental burden of a particular product (such as a ton of aggregate) or more complex systems of products or processes (such as a transportation facility or network), examining all the inputs and outputs over its life cycle, from raw material production to the end of the product's life."* in an FHWA Technical Brief. [(6)]. Robinette and Epps successfully used LCCA and LCA to illustrate and quantify economic and environmental aspects of in-place asphalt recycling techniques. The LCCA showed cost saving and the LCA showed reduced environment impacts, when compared to traditional reconstruction techniques. [(7)]

This background information and other recent activities identified a need to: 1) learn more regarding the details of positive practices implemented by State DOTs; 2) collect and communicate experiences, lessons learned and performance information; and 3) identify gaps for creation of research needs statements for the Turner Fairbanks Highway Research Center (TFHRC) and/or the National Cooperative Highway Research Program (NCHRP) on CIR, CCPR, FDR and HIPR techniques.

OBJECTIVE AND SCOPE

The primary objective of this overall effort was to identify and put forth positive practices implemented by State DOTs for successful cold asphalt and hot in-place asphalt recycling. This effort will compliment: FHWA HIF-17-042; ARRA Basic Recycling Manual; AASTHO Provisional Standards MP 31-17 and MP 38-18; AASHTO Provisional Practices PP 86-17 and PP 94-18; and ARRA Guidelines CR101, CR102, CR201, CR202, CR301, FDR101, FDR102, FDR103, FDR201A, FDR202, FDR301 and FDR302 which provide agencies and contractors with guidelines for the use of CIR, FDR, and CCPR. [4, 8 – 24] It is worth noting that there are currently two National Cooperative Highway Research Program (NCHRP) sponsored projects related to this effort on-going. Specifically, NCHRP Project 14-43, Construction Guide Specifications for Cold Central Plant Recycling and Cold In-Place Recycling and NCHRP Project 09-62 Phase IV, Rapid Tests and Specifications for Construction of Asphalt-Treated Cold Recycled Pavements. [25]

To accomplish this objective, the information will be collected through virtual site visits and other means with five key State DOTs. With the COVID-19 Pandemic, it was not possible to have State DOT field visits. The Western and Central Federal Lands Highway Offices (FLH) graciously agreed to host a virtual visit. The five other participating agencies include Indiana DOT (INDOT), New Mexico DOT(NMDOT), New York State DOT (NYDOT), South Carolina DOT (SCDOT) and Virginia DOT (VDOT).

STATE DOTS VIRTUAL SITE VISITS

The scope of each virtual visit included: a pre-visit kickoff web meeting and review of agency documents (policy, specifications, research reports, etc.) and two or three-day virtual visits to obtain a detailed understanding of agency processes, positive practices, lessons learned and pavement performance. The outcomes of each visit were to include a brief report to each FHWA Division Office, and DOT visited on the observations and any recommendations identified. Reviews from all DOTs will be compiled into a summary document of positive practices and considerations for using CIR, FDR, CCPR, and HIPR in the form of a Technical Brief with an accompanying PowerPoint presentation; and depending on observations, draft standard practices in the American Association of State Highway and Transportation Officials (AASHTO) format may be developed along with research need statements for consideration. This document is a brief report on the observations and recommendations identified through the field visits conducted for all the different agencies stated previously.

ORGANIZATION OF THE REPORT

This report is organized into seven chapters as described below:

- Chapter 1 presents the introduction along with the objective and scope of the virtual site visits with the FLH and the five key State DOTs.
- Chapters 2 through 7 summarize the findings and observations from each of the seven site visits that were completed. Each chapter includes the State DOT's recycling criteria, structural pavement design adopted, the materials characteristics, the mixture design requirements, the field construction acceptance criteria, the pavement performance and cost, the contractor perspectives, the lessons learned and best practices as well as research activities and needs.

CHAPTER 2 VIRTUAL SITE VISIT: FLH

INTRODUCTION

The Office of Federal Lands Highway (FLH), of the US Department of Transportation (USDOT), Federal Highway Administration (FHWA), is a unique entity with unique responsibilities providing project delivery services in the 50 US states, District of Columbia, Puerto Rico, and US Territories. FLH provides transportation engineering and financial resources for public roads servicing transportation needs of Federal and Tribal lands. FLH administers many different programs and funds to enable transportation improvements for Federal Land Management Agency Partners. Partners include: the Bureau of Indian Affairs (BIA); Bureau of Land Management (BLM); Bureau of Reclamation (BOR); Department of Defense (DOD); National Park Service (NPS); Tribal Governments; U.S. Army Corps of Engineers (USACE); USDA Forest Service (Forest Service); and the U.S. Fish and Wildlife Service (USFWS). FLH has Western, Central and Eastern Federal Lands Highway Division offices located in Vancouver, WA, Lakewood, CO, and Ashburn, VA, respectively.

The FLH project delivery services are associated with the Federal Lands Transportation Program (FLTP) roadway networks of the Federal Land Management Agencies mentioned in the paragraph above. The FLTP networks include about 138,050 miles of roads and 5,155 parking lots. Through the Federal Lands Access Program (FLAP), FLH also provides project delivery services to cities, counties, and State DOTs. The FLAP program was established to improve roadways that provide access to, are adjacent to, or are located within Federal lands. The FLAP program prioritizes funding on routes that serve high-use recreation sites and economic generators. The FLTP program represents about 60 percent of the project delivery services FLH provides and the FLAP program the remaining 40 percent. A high majority of the roads that FLH rehabilitates or reconstructs are either asphalt or aggregate surfaced, with the remainder being Portland cement concrete pavement. The information in this report will focus on cold asphalt recycling techniques and applications implemented by CFL and WFL. Cold recycled asphalt techniques employed by CFL and WFL include CIR, CCPR, FDR, and RAP millings base.

CIR is produced with conventional or engineered emulsions and typically placed in a structural layer with a thickness of three to four inches. The thickness may be adjusted to make sure that cold milling machine tracks do not penetrate the in-place structure. Fortunately, in many of the locations where CIR is used granular subbases are present due to mountainous regions. CIR is typically surfaced with at least two inches, and commonly three to four inches, of HMA. However, a small percentage of CIR is surfaced with double application chip seals in the arid southwest US.

CCPR is normally produced with engineered emulsions and is typically placed in thicknesses of three to five inches. The entire roadway is included, providing the opportunity to address grade and cross slope issues if needed. Multiple CCPR structural layers may be used and to prevent challenges with compaction normally lift thickness does not exceed four inches. CCPR is normally surfaced with three to four inches of HMA.

FDR is produced with emulsion, foamed asphalt, or Portland cement. Mechanically stabilized FDR (no stabilizing agent) is also used by FLH. FDR is typically placed in thicknesses from six to ten inches. If the thickness reaches 10 inches or greater there is a potential for inadequate compaction.

Recycling contractors must demonstrate the ability to achieve density in order to proceed at this thickness. If density specifications cannot be met, then a maximum thickness of six inches is allowed. Pre-milling is performed to address grade raise concerns for geometric considerations. Sometimes pre-milling is three to four inches. FDR is typically surfaced with at least two inches, and most commonly three to four inches, of HMA. However, a small percentage of FDR is surfaced with double application chip seals in the arid southwest US.

RAP millings base is a cold recycled asphalt technique also used by FLH. It is placed in thickness from three to 10 inches. No more than six inches is placed at a time to avoid compaction issues. Because the RAP is removed and stockpiled, it can easily be brought back to the roadway and placed in multiple lifts. RAP millings base is typically surfaced with HMA or double application chip seals.

CIR accounts for five to 10 percent of all FLH lane miles annually. Typically, only 1 or 2 projects are built with CIR annually with greater than 100,000 square yards (yd^2) placed. CCPR is only used in WFL for construction in Yellowstone National Park and other locations. FDR makes up the largest portions of the WFL and CFL programs, with about 50 percent of all annual lane miles employing this technique. RAP millings base is used for about 20 percent of the WFL annual program. It is important to note that projects may have multiple scopes using multiple cold asphalt recycling techniques. There is often a mix and match of different techniques used in spot locations.

The use of cold asphalt recycling techniques is up from past. WFL has increased use of them lately due to the need to reuse materials in remote locations because of reduced ability to access new aggregate sources. FDR is common and has increased to take over some CIR work. Use of CIR has decreased, partially due to limited contractor availability and partially due to required geometric design improvements on many of the routes undergoing rehabilitation. However, decreased use of CIR is not related to performance as FLH has experienced outstanding long-term performance on CIR projects. FDR reclaimer contractors are readily available. Common project conditions are also conducive to FDR due to steep terrain and environmental conditions. Unlike with State DOTs, RAP supply and demand is different for FLH due to many remote project locations. RAP is allowed in HMA by contractor's choice. About fifty percent of CFL and WFL mix designs contain RAP and the maximum amount allowed is 20 percent.

The in-place recycling culture is well established in FLH, and use of recycling techniques is prioritized overusing virgin materials when possible. The Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects (FP-14) contain sections for most of the recycling techniques used by FLH. Section 304 is FDR Mechanical, Section 305 is FDR Cement, 306 is FDR Asphalt, 310 is CIR Asphalt Base. [(26)] There are also some special provisions used, for example for CCPR. Much of the roads CFL and WFL have responsibility for supporting carry low traffic, and thus are good candidates for applying cold recycling techniques. FDR is most commonly used by FLH and mill and overlay is avoided if possible. Table 1 presents as summary of statistics on cold recycled techniques use by FLH.

Table 1. Summary of Cold Asphalt Recycling Techniques use by FLH.

Recycling Technique	Cold			
	CIR	**FDR**	**CCPR**	**RAP millings base**
Projects per Year	1 or 2	20+	1 or 2	1+
Use (% of total use)	5%	80%	5%	10%
Square Yards (million)[1]	-	-	-	-
Cost per Square Yard[2]	$10.00	Cement $7.00	-	-
Districts Using	CFL, WFL	CFL, WFL	WFL	CFL, WFL
Years of Experience	≈ 50	≈ 40	≈ 15	≈ 50

[1]Area is not tracked.
[2]Average costs reported, costs may vary significantly from state to state across FLH Divisions.

PROJECT/RECYCLING TECHNOLOGY SELECTION CRITERIA

The FLH has a Project Design and Development Manual (PDDM) that provides detailed guidance on selection of projects for using recycling technologies. (27) Chapter 11 of the PDDM includes multiple criteria. Section 11.1.5.2 contains guidance on preliminary pavements recommendations and requires briefly summarizing the following data and information:

- Field investigation, including pavement, base, and subgrade conditions and quality.
- Material testing results.
- Design criteria used.
- Design alternatives considered and evaluated.
- Design alternative recommended.
- Recommended follow-up testing or additional information gathering.

Section 11.1.5.3 provides guidance on final pavements recommendations and requires comprehensive documenting to support design recommendations, to a level commensurate with the project scope and risk, with the following:

- General project information
- Approval sheet (i.e., Quality Control (QC)/Quality Assurance (QA) documentation)
- Procedures and results
- Summary of the performance history of the pavement as documented in the Pavements Project Start-Up Information deliverable above.
    - Pavement distress data.
    - Traffic load and growth projection evaluation with estimated percentages of
    - vehicle classifications.
    - Relevant geometric site conditions (e.g., pavement and bench width, steep
    - grades, etc.).
    - Relevant climatic and environmental info (e.g., frost depth, annual rainfall, etc.).
    - Pavement drainage characteristics.
    - Tabular summary of sampling and testing (e.g., boring / coring logs, test pit

information, material source quality, FWD (Falling Weight Deflectometer) results, DCP results, lab test results,
visual descriptions, etc.).
    - Values or inputs determined by engineering judgment.
- Analysis
    - Pavement design methodology and inputs.
    - Economic evaluation (e.g., comparative cost analysis of alternatives, LCCA, etc.).
- Pavement Design and Materials Recommendations
    - Structural section including material type.
    - Pavement rehabilitation method, if applicable.
    - Needed sub excavation, patching, crack sealing, underdrains, or other application that will resolve problems with wet and/or weak subgrade soils.
    - Auxiliary pavement items including, as applicable, prime/tack coat, asphalt binder grade, emulsified asphalt grade, stabilizing/recycling agents, antistrip additive type, cement type, gradations for base and surfacing material, and any other information that is needed to assure that the appropriate material type and quantity is used.
    - Address special construction issues related to pavements including but not limited to material haul distance, the need for special contract revisions, lift thickness, curing time, traffic control, and steep grades.
- Support Information. Include the following when applicable and appropriate (generally as attachments or appendices):
    - Site map(s) with sampling and testing locations.
    - Material testing reports.
    - Field notes, logs, FWD data, etc.
    - Calculations and/or design software reports.
    - Photos (photographically document and represent typical and atypical project condition, features, and materials).

Section 11.2.5 provides guidance on roadway surfacing type selection and reference sections of the FP-14. [26]

In summary, criteria used to identify or select cold asphalt recycling techniques include the:

- Scope or type of project (3R or 4R)
- Pavement investigation for data-based decisions
- Existing distress
- Existing type of pavement (chip seal)
- Subgrade type and condition (i.e., clay)
- Traffic profile to allow for curing or not
- Pavement layer thicknesses
- Grade for overlay and concerns with grade increases for side slopes
- Safety considerations and need to widen roads, as some are only 18-feet wide and need to be widened to 24-feet wide

Contractor capability and experience/equipment availability are also considered during selection of cold asphalt recycling techniques. For example, CIR equipment is not available in Alaska and mainly FDR foamed asphalt equipment is available.

STRUCTURAL PAVEMENT DESIGN

FLH uses the AASHTO Guide for Design of Pavement Structures 1993 for designing pavements. The following layer coefficients (a_i) are used: HMA = 0.40 to 0.44; 0.28 to 0.30 for CIR and CCPR (WFL); FDR (mechanical) = 0.10 to 0.12; FDR (cement) = 0.15 to 0.22 (depending on cement content); FDR (asphalt) = 0.20 to 0.25; and RAP Millings Base = 1:1 as aggregate base = 0.12 to 0.14. Other inputs (e.g., terminal serviceability, reliability, etc.) are not changed. Dynamic modulus was used to develop several layer coefficients or confirm/validate layer coefficients. [28] Light weight deflectometer (LWD) was used for validation of FDR (mechanical) and FDR (cement) layer coefficients. The LWD showed substantial increase for FDR (cement).

MATERIALS

Table 2 is a high-level summary of materials used in each recycling technique. Raw and composite materials information follows.

Table 2. Summary of Materials Allowed Used in Recycling Techniques.

Material Parameters	Recycling Technique		
	Cold		
	CIR	FDR	CCPR
Binders	Engineered Emulsion	Portland cement, other cementitious materials, Foamed, Emulsion	Engineered Emulsion
Virgin Aggregate	Allowed[1]	Allowed[1]	N/A
Active Fillers	Lime slurry or Portland cement	Portland cement (with Foamed applications)	Lime slurry or Portland cement
Processed Recycled Material Top Size	< 1.5”	< 2.0”	< 1.5”
Other Gradation Requirements	During mix design	During mix design	During mix design
Other Aggregate Requirements	N/A	N/A	N/A

[1]It is important to note the virgin aggregates are primarily used for isolated geometric adjustment of roadway profiles.

Binders

For CIR and CCPR both WFL and CFL call out engineered emulsions with some minimum requirements but are flexible allowing the contractor select binders that are required to meet the mix design engineering property requirements 70 psi Indirect Tensile Strength (ITS). For FDR emulsion, which is the least frequently used treatment, CSS-1 emulsion is specified. With FDR foam the neat Performance Grade (PG) binder specified for the geographic area is specified.

Active Fillers

Lime slurry or Portland cement are allowed in CIR and CCPR. With FDR cement, lime is sometimes used to help break up heavy clay and lime kiln dust has been used due to availability. For FDR emulsion and foamed asphalt up to 2 percent cement has been used, though one percent is typically used.

Processed Material Gradations

RAP used for CCPR is typically from the project the CCPR is being placed on. The only gradation requirement is 100 percent pass the 1.5-inch sieve. A RAP QC plan is not required, but total water content has to be within 2 percent of the mix design water content. It was noted that it is important to be sure adequate staging area is available for the CCPR plant and the RAP stockpile to be used when specifying CCPR.

MIXTURE DESIGN

FLH requires the contractor to complete mix designs and submit for approval. CIR mix designs are typically per FLH T 524 and FDR mix designs are per FLH T 522. [30,31] FLH Divisions may also have special provisions. Sampling for CIR and CCPR mixture designs may include a minimum of 350 pounds of material obtained from cores or millings. Additional cores may be taken to define consistency. For FDR cement cores or materials from test pits or from a reclaimer (not often) are used for mix designs. For FDR emulsion or FDR foamed asphalt cores, auger borings, or test pit samples may be used.

CIR mix designs require 150 mm diameter samples prepared at three emulsion contents using a gyratory compactor applying 35 gyrations to meet the requirements of FP-14 Section 310. [26 – 30] WFL uses a performance-based mix design procedure for CIR and CCPR. A specified set of gradation tolerances is used for mix with 100 percent passing the 1.5-inch sieve. Samples are cured at 140°F (60°C) to constant weight for no less than 16 hours and no more than 48 hours. Typical values air voids are 8-16 percent or more. A design air void level is not used. Table 3 is a summary of CIR and CCPR emulsion mix design requirements.

Table 3. Cold In-Place Recycled Asphalt Base Mix Design Requirements.

Material or Property	Requirement
Indirect tensile strength, AASHTO T 283 [1] Tensile strength dry Tensile strength ratio (TSR)	 70 psi (480 kPa) minimum 70% minimum
Raveling test, American Society for Testing and Materials ASTM D7196, 4-hour cure at 50 °F (10 °C), 50% humidity [2] Average mass loss	 5% maximum

[1] Follow the modified AASHTO T 283 procedures as indicated in FLH T 524. Vacuum saturation of 55 to 75 percent, no freeze cycle, 24-hour soak in water bath at 77°F (25°C)
[2] Use the listed testing conditions for the raveling test, unless otherwise directed by the CO.

FDR emulsion and foamed asphalt mix designs are per FLH T 522, with 150 mm diameter samples prepared at three emulsion or three asphalt content plus water contents using a gyratory compactor applying 35 gyrations to meet the requirements of FP-14 Section 306. [26 – 31] A specified set of gradation tolerances is used for mix design with 100 percent passing the 1.5-inch sieve. Samples are cured at 140°F (60°C) to constant weight for no less than 16 hours and no more than 48 hours. Typical values air voids are 8-16 percent or more. A design air void level is not used.

Table 4 and Table 5 summarizes FDR emulsion and foamed asphalt mix design requirements.

Table 4. FDR Emulsion and Foamed Asphalt Recycled Asphalt Base Mix Design Requirements.

Binder type	Material or Property	Requirement
Emulsified asphalt and foamed asphalt	Indirect tensile strength, AASHTO T 283 [1]	
	Tensile strength wet	25 psi (170 kPa) minimum
	Tensile strength ratio (TSR)	60% minimum

[1] Follow the modified AASHTO T 283 procedures as indicated in FLH T 522.

Table 5. FDR Emulsion and Foamed Asphalt Recycled Asphalt Base Mix Design Requirements.

Property	Requirement
Foamed asphalt expansion characteristics at 320, 338, & 356 °F [1]	
Asphalt expansion ratio	10 minimum
Half-life of foamed expansion	6 seconds minimum

[1] See FLH T 522 for test procedures.

FDR cement mix designs are performance based and need to conform to FP-14 Section 305. [26] Specimens are prepared at three cement doses (estimated optimum and 2 percent above and below this). The optimum moisture content and maximum density using standard Proctor compaction is determined and the mix design properties in Table 6 must be met at the selected cement dose.

Table 6. FDR Cement Mix Design Requirements.

Material or Property	Requirement
Unconfined compressive strength, ASTM D1633, Method A [1] Average strength (3 specimens) Maximum strength of a single specimen break	 200 psi (1.4 MPa) min. 400 psi (2.8 MPa) or less
Loss in mass, AASHTO T 135 & AASHTO T 136, 12 cycles	14% max.

[1] At 7-day cure at 70 °F (21 °C) according to ASTM D1632.

FLH uses some index-based performance tests for designing cold recycled asphalt mixtures. Table 7 presents a summary of index-based performance tests used based on potential pavement distress mechanisms.

Table 7.Index-based Performance Tests Included in FLH Cold Recycled Asphalt Mix Designs.

Pavement Performance	Recycling Technique		
	Cold		
	CIR	FDR	CCPR
Rutting	N/A	Cement unconfined compressive strength (UCS) Asphalt ITS	N/A
Cracking	ITS	Cement UCS Asphalt TSR	ITS
Moisture Damage	TSR	Asphalt T 283	TSR
Raveling	D7196	N/A	D7196

FIELD CONSTRUCTION & ACCEPTANCE

Mix Design Changes During Construction

Some agencies and contractors have faced challenges with making the transition from laboratory mix design to field production. To address these challenges FLH requires control strips be constructed on the first day of production and that the required mix properties, in-place compaction and thickness are verified. Contractors may request to be allowed to continue production at risk.

Test Sections

As part of production startup, control strips must be constructed. For CIR and CCPR a 1500-foot-long control strip, one-lane wide, and at the designated lift thickness has to be constructed. For FDR asphalt and FDR cement, on the first day of production a 1000-foot-long control strip is stabilized, one-lane wide, and at the designated lift thickness. Verification of the mix design and accomplishment of the required density and thickness have to be observed.

Quality Control and Acceptance

Cold Recycled Asphalt

The FLH specifications include rigorous equipment requirements that help assure planned quantities of materials are provided during construction. The CIR specification states, *Provide the following for pugmill and proportioning equipment: (1) Capable of continuously mixing the milled material with emulsified asphalt, water, lime, and other additives to produce a uniform and homogenous mixture; (2) Belt scale for continuous weighing of milled and sized material with an interlocked computer controlled liquid metering device capable of automatically adjusting the flow of asphalt emulsion to the mass of milled material coming into the mixer; (3) Proportioning equipment capable of applying emulsified asphalt and water to within plus or minus 0.2 percent of the required quantity by mass of milled material; (4) Proportioning equipment with a digital meter for monitoring the flow rate and total milled material, emulsified asphalt, and water applied. When lime is required at the milling head or in the pugmill, incorporate lime slurry to within plus or minus 10 percent of the approved application rate. Produce the lime slurry using quicklime or hydrated lime and water in a slurry production unit equipped with scales and meters accurate to within 0.5 percent by mass.*

The CCPR specification states, *for central plant mixing, use equipment capable of continuous mixing of the milled materials with emulsified asphalt, water, and any additional additives to produce a uniform and homogenous mixture. Provide a mixer with a belt scale for continuous weighing of the milled and sized material and equipped with an interlocked computer controlled liquid metering device capable of automatically adjusting the flow of asphalt emulsion to the weight of milled material coming into the mixer. Provide proportioning equipment capable of applying emulsified asphalt and water to within plus or minus 0.2 percent of the required amount by weight of milled material. Provide proportioning equipment with a digital meter for monitoring the flow rate and total amount of milled material, emulsified asphalt, and water applied.*

The FDR Asphalt specification states, *automatically adjust the asphalt and water flow based the reclaimer speed and recycled material mass for the approved mix design. Maintain the asphalt temperature within the range recommended by the supplier. Complete pulverizing and mixing operations in continuous one lane-width segments up to ½ mile (0.8 kilometers) in length. Mix the pulverized roadway material with emulsified asphalt binder, other additives, and the necessary mixing water for optimum dispersion. If two passes are used, shape and compact the reclaimed material with a steel drum roller after the first pass to provide depth control for the second pass of the reclaimer. Add the required quantity of emulsified or foamed asphalt during the final pass of the reclaimer. Verify that the emulsified or foamed asphalt is evenly dispersed and coating the pulverized material. Dig test pits within the mix at least every ¼ mile (0.4 kilometers) and observe the distribution of the emulsified or foamed asphalt in each pit.*

FLH has very clear material testing and inspection requirements broken down by source, design, production startup (control strip), production and finished product in tabular form with responsibilities and how the results are used. They can be found in Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects FP-14 at the end of each material specification section as well as in Appendix A of this report. [26] Appendix A Table A. 1 is for CIR; Appendix A Table A. 2 is for FDR Cement and Appendix A Table A. 3 is for FDR Asphalt. The specification also requires pre-recycling preparatory meeting at least 7 days prior to starting recycling operations. The reader is referred to the tables for details and the subsequent discussion will focus primarily on compaction requirements and production startup.

For CIR and CCPR quality control and acceptance requirements similar. Compaction has to begin within 30 minutes of spreading. Pneumatic-tire rollers are used until displacement subsides. Then steel-wheel rollers are operated in either static or low-amplitude vibratory mode to remove pneumatic tire marks and achieve final density. The standard specifications include Type A and Type B compaction options. CFL specifies Type A compaction, while WFL typically specified Type B compaction. The compaction types are:

(1) *Type A compaction. Use roller patterns established during the control strip. Compact the recycled mix to obtain a minimum density of 97 percent of the control strip density. Measure in place density according to ASTM D2950. If an area fails to meet required density, rework and recompact the area. If applications rates of the emulsified asphalt from the approved mix design are changed by more than ±0.2 percent by mass of milled material, or if other material conditions distinctly change, reestablish roller pattern.*

(2) Type B compaction. Compact the recycled mix using the following equipment, sequence, and number of rollers passes:

> *(a) Four to six roller passes with a double drum, vibratory roller having a minimum mass of 5.5 tons (5 metric tons) and equipped with frequency and amplitude controls.*
>
> *(b) Four to six roller passes with a pneumatic-tire roller having a minimum mass of 2000 pounds (910 kilograms) per wheel and a contact pressure of 80 pounds per square inch (550 kilopascals).*
>
> *(c) Two to four roller passes with a static steel-wheel roller with a minimum pressure of 250 pounds per square inch (1730 kilopascals).*

During the production startup control strip three samples of millings are taken after the material has passed through the crusher and prior to adding emulsion for Type A compaction to verify that 100 percent passes the 1½-inch sieve. Density readings are taken after each roller pass to establish a roller pattern for achieving the maximum in-place density defined as the break point of the plot of roller passed versus compaction per ASTM D2950. The mix design bulk specific gravity is used to determine the maximum in-place density observed.

Once in production, for acceptance density, depth, gradation, indirect tensile strength, emulsion application rate, and surface tolerances are monitored. Tensile strength is not used for acceptance but is used for process control (once every four days of production). Appendix A Table A. 1 include details.

For FDR Cement the control strip is constructed using the equipment and procedures that the contractor plans on using for the entire project. After each pass of the roller nuclear gauge density readings are taken to establish the roller pattern needed to obtain compaction specification requirements. The compaction and finishing requirements are:

Compact the processed material uniformly to at least 95 percent of maximum density as determined from AASHTO T 134. Furnish rollers sized and configured to achieve the required compaction and finishing. Operate rollers according to the manufacturer's recommendations. Compact the processed material full width by rolling from the sides to the center, parallel to the centerline of the road. Along curbs, headers, walls, and places not accessible to the roller, compact the material with approved tampers or compactors. During compaction and final grading maintain the moisture content of the mixture to within 2 percent of optimum. Do not leave areas of stabilized material uncompacted or undisturbed for more than 30 minutes. Complete compaction within 1 hour after mixing.

FDR Cement acceptance requirements include gradation, moisture content, density and UCS. See Appendix A Table A. 2 for details.

For FDR Asphalt the control strip is constructed using the equipment and procedures that the contractor plans on using for the entire project. Once a 100-foot length of reclaimer pulverized and mixed is completed, but prior to compaction, a test pit is excavated to assess the effectiveness of mixing and asphalt distribution. If it is not homogeneous, the process is repeated until it is. Three loose mix samples are taken from the control strip to verify 100 percent of the reclaimed material passes a 2-inch sieve. The compaction equipment requirements are: *Use at least three rollers: primary, secondary, and finish rollers sized and configured to achieve the required compaction and finish. Operate rollers according to the manufacturer's recommendations. Compact the processed material full width by rolling the material between the reclaimer wheel paths first then from the sides to the center, parallel to the centerline of the road.* After each pass of the roller nuclear gauge density readings are taken to establish the roller pattern needed to obtain at least 97 percent of the maximum wet density per AASHTO T180 on material from behind the reclaimer. For FDR Asphalt acceptance requirements include Gradation, Moisture content, Density, half-life & expansion ratio, and ITS. See Appendix A Table A. 3 for details.

Curing and Opening to Traffic

FLH specifications include cold recycled asphalt curing and maintenance provision that are unique to the recycling technique.

For CIR and CCPR, keep traffic and construction equipment off of the recycled asphalt base for at least 2 hours after completing compaction and until it is sufficiently stable to withstand raveling, marring, and permanent deformation. Route hauling and other construction equipment uniformly over the full width of the recycled asphalt base to minimize non-uniform compaction. Maintain the recycled asphalt base to the correct line, grade, and cross-section. Provide additional rolling with a steel wheel roller to recompact and maintain a dense surface. Use a power broom to remove loose particles. If the recycled asphalt base loses stability, density, or finish, reprocess and recompact as necessary to restore the strength of the damaged material. Place the next course or final surface when the moisture content of the recycled asphalt base is reduced to 2.5 percent or less according to AASHTO T 255, but within 14 days after recycling regardless of moisture content.

For FDR Cement cure the layer at least 1 day before placing the next course by one of the methods:

1. Water method - Keep the surface continuously moist by applying water through a spray bar equipped with nozzles producing a fine, uniform spray. During the first 24 hours of curing, use a water truck with side spray to avoid driving on the newly stabilized layer.
2. Prime coat method - Seal the surface by placing an inverted prime coat according to Subsection 411.06(b). Provide and maintain a continuous film over the surface.

For FDR Emulsified asphalt keep traffic and equipment off the stabilized base for at least 1 hour after completing compaction. Do not allow traffic and construction equipment on the stabilized base until it is sufficiently stable to withstand marring and permanent deformation. For FDR Foamed asphalt before opening the stabilized base to traffic and after completing compaction, moisten the surface and roll with a pneumatic-tire roller to create a tight and closed surface. Continue to keep the surface moist until placement of the next course or final surface. Place a fog seal on the surface of the stabilized base after final compaction and overlay the stabilized base material within 14 days after compacting.

Weather limitations are important to consider with cold recycled asphalt techniques. FLH specifications include weather limitations. *For CIR and CCPR the weather limitations are: Place the cold recycled asphalt base on a dry, unfrozen surface when the air temperature in the shade is above 50ºF and the pavement surface temperature is above 40ºF. Do not place cold recycled asphalt base when fog, showers, rain, frost, or temperatures below 35ºF are anticipated within 24 hours following the placement of the mix. For FDR Cement weather limitations are: Do not add cement when the underlying surface is frozen, muddy, or when conditions allow for excessive loss to eroding or blowing. Begin cement application when the air temperature is above 40°F and is expected to stay above 40°F for 48 hours. For FDR Asphalt weather limitations are: Do not use foamed asphalt with an application temperature below 320°F. Apply emulsified or foamed asphalt when the surface and air temperatures in the shade are at least 50ºF. Do not begin applying emulsified asphalt during periods of fog, rain, or when temperatures below 35°F are anticipated within 48 hours.*

Lessons Learned

The extensive FLH experience with cold recycled asphalt techniques has revealed several important lessons learned. They include the following:

- Consider geometric constraints (underpasses, drainage inlets, guardrail height, etc.) as recycled pavement fluff (increase in total thickness post-recycling) occurs.
- Perform adequate project subsurface investigation to understand variability and allow for appropriate recycling type selection and material designs.
- When performing CIR leave adequate pavement structure in-place to support the recycling equipment.
- Limit cold asphalt recycled layer thicknesses such that adequate compaction can be achieved.

- When performing CCPR take advantage of the opportunity to address grade and cross slope issues.
- Schedule is an important part of the design process, plan CIR and CCPR project construction for summer for best success.
- Recognize that CCPR requires adequate space for processing.
- Do not include aggregate base in CIR.
- When active filler is used in high wind situations a slurry helps contain the material to the roadway.
- Allow CIR and CCPR material to begin to cure prior to compaction giving consideration to temperature, humidity, and shading.
- With CIR and CCPR keep rollers back from paver, unlike with HMA, to allow for initial curing.
- Under high temperatures and low humidity, the fog seal can be placed more quickly to prevent raveling without concern for trapping moisture.
- Under cooler, more humid conditions the timing of the fog seal is based on visual observations.
- Micro cracking may occur in CIR or CCPR that will knead back together trafficking.
- With FDR Cement, using an inverted prime coat as the cure method will significantly reduce raveling of the FDR Cement layer due to traffic prior to placement of HMA riding surface.

PAVEMENT PERFORMANCE AND COST

There are many options available for rehabilitating a pavement and selection of the most appropriate and cost-effective alternative is an important engineering decision during the project development phase. CFL and WFL have established through life-cycle cost analysis that cold recycled asphalt techniques have lower costs than conventional construction methods when local materials and contractors are available. This analysis is also supported by their pavement management system models. This information is used with client agencies to explain the risks associated with initial cost, pavement performance, and overall life-cycle cost. Cold recycled asphalt techniques are commonly justified and often selected as part of the preferred treatment.

FLH reported overall good performance with the cold asphalt recycling techniques. Techniques used to assess performance include visual observations, pavement management data and LWD. Direct comparisons of conventional rehabilitation and recycling rehabilitation are difficult to find. A reasonable sample size for comparison simply is not available. In generally, recycled sections are performing well.

It was indicated that there are several benefits with cold asphalt recycling including:

- Recycling conserves nature resources and reduces the carbon footprint associated with obtaining them.
- Recycling reduces overall project costs.
- LCA should be used to illustrate the reduced carbon footprint associated with cold asphalt recycling in remote and sensitive locations.

CONTRACTOR PERSPECTIVES

Contractor interviews did not take place as part of the FLH virtual site visit.

FLH BEST PRACTICES

Throughout the visit, several FLH best practices were identified that included the following:

1. FLH is using recycling techniques to minimize impacts on some of the most precious land in the world.
2. FLH prioritizes cold asphalt recycling technologies when designing projects and selecting materials, which is rational especially based on the fact that many projects are constructed in remote locations.
3. Application of multiple cold asphalt recycling techniques regardless of traffic level, although it is low on many roads.
4. The FLH Project Development and Design Manual provides good direction and criteria for project selection, materials selection and pavements.
5. Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects," FP-14 includes straightforward specifications for CIR, CCPR, FDR cement, FDR emulsion and foamed asphalt, as well as several other recycled base materials.
6. FLH has documented cold recycled asphalt mix design procedures for CIR, CCPR, FDR cement, FDR emulsion and foamed asphalt, as well as other recycle base methods.
7. FLH has been an early adopter of recycling technologies having over 50 years of experience using CIR and RAP millings base coupled with over 25 years of experience using CCPR and FDR.
8. Requiring mix designs be developed by the contractor.
9. Mix designs are consistent with many other agencies.
10. Mix design material submission details are in specifications.
11. Requiring mix design material submissions 30 days prior to planned construction
12. Requiring a preparatory phase meeting at least 7 days before control strip.
13. Requiring control strips (1500 feet long and 1 lane wide at the designated lift thickness) with maximum in-place density determined as the break point of compaction curve (passes vs. density).
14. Specifications having very clear material testing and inspection requirements broken down by source, design, production startup (control strip), production and finished product in tabular form with responsibilities and how the results are used.
15. Sponsoring research to make sure mix design and structural design are relevant with today's materials technologies.

ALTERNATIVE USES OF RAP

FLH prioritizes recycling over the use of virgin materials when possible. This is particularly important because many of FLH projects are in remote locations. The cost of getting virgin materials to project locations can be significant and it is likely the carbon footprint is significantly greater than if materials are recycled in-place. Accordingly, FLH uses CIR, CCPR and FDR, as well as other forms of recycling base courses.

RESEARCH ACTIVITIES AND RESEARCH NEEDS

Recent research sponsored by FLH was focused on the development of cold recycled asphalt mix design procedures and structural layer coefficients for the AASHTO Guide for Design of Pavement Structures 1993. Details can be found in Reference 28.

A potential research need identified is documenting the performance of the recycling techniques used over their expected performance lives.

CLOSING REMARKS

FLH is actively and successfully using sustainable cold asphalt recycling techniques. Specifically, FLH uses CIR, CCPR and FDR, as well as other forms of recycling base courses. The support of FLH and FLH staff that participated in this effort is greatly appreciated. The input provided revealed several positive practices that will be of significant value to other agencies.

CHAPTER 3 VIRTUAL SITE VISIT: INDOT

INTRODUCTION

The INDOT roadway system includes 29,800 lane miles with 11,200 center line miles total. About 90 percent of the pavements are flexible and about 10 percent are rigid. There is some composite pavement in the state also. INDOT is a leader in the use of cold asphalt recycling technologies using CIR, CCPR and FDR methods. It has up to 10 years of successful experience using these techniques, though well-defined specifications and a design document were completed in 2017 that institutionalized use of them. Pilot projects date back to 2010 and since 2014, 30 cold recycle projects have been constructed in Indiana. CIR and CCPR are constructed with emulsions while FDR is constructed with emulsion or cement. The recycling techniques have been primarily used in rural areas on minor roads. This trend will likely continue until more performance information is available (10 to 15 years), after which the techniques will likely be used on higher volume roads.

Table 8 presents a summary of asphalt recycling techniques in use by INDOT. The breakdown of the cold asphalt recycling techniques used by INDOT in the recent past has been approximately 38 percent CIR, 12 percent CCPR, 38 percent FDR Cement, and 12 percent FDR Emulsion. The use of the recycling techniques has been steadily increasing and will likely continue to grow in the future as it has been a cost-effective solution that performs well when the right material is used in the right locations. When CIR is used the depth of recycling is 3 to 4 inches and the CIR does not go into the aggregate base. Cracked pavements which are structurally sound and have well-drained bases were identified as good CIR candidates. FDR is typically 10 inches but can be combined with CCPR if greater depths are required. One project has been constructed with an FDR plus CCPR combination that was reported to be successful. CIR may be surfaced with a chip seal on low volume roads, though it is normally surfaced with at least one lift of HMA. CCPR is surfaced with HMA.

Table 8.Summary of Cold Asphalt and Hot In-place Recycling Techniques use since 2017.

Recycling Technique	**Cold**				**Hot**
	CIR	**FDR Cement**	**FDR Emulsion**	**CCPR**	
Use (percent of total use)	38	38	12	12	
Square Yards	1,102,540	1,101,387	357,986	347,651	**N/A**
Cost per Square Yard	$4.37	$3.74	$3.97	$5.50	
Districts Using	All have used recycling technologies				
Years of Experience[1]	In earnest since 2017				

[1]Up to 10 years

PROJECT/RECYCLING TECHNOLOGY SELECTION CRITERIA

Chapter 602 of the INDOT Design Manual includes descriptions of each recycling technology, types of distresses they address, and typical application depths or layer thicknesses. [32] Chapter 602 also illustrates how to use the existing pavement type, composite versus full depth asphalt, and pavement distresses to identify potential cold recycling techniques to use for specific projects. The document also includes descriptions of each recycling technology, typical applications and depths or layer thicknesses. The following descriptions of FDR, CIR and CCPR are quoted from the manual:

<u>Full Depth Pavement Reclamation</u>: *The INDOT Geotechnical Services must investigate, evaluate, and make recommendations on the soil moisture content, and organic content to determine the suitability of the pavement subbase and subgrade materials for FDR. FWD is also required to determine subbase and subgrade strength. Pavements that have extensive subgrade or drainage problems are candidates for FDR only when additional work is undertaken to correct the deficiencies. In areas where the required treatment is too deep for single pass FDR or due to vertical constraints adjustments in the construction process can be made to address the constraints, such as a two-pass technique. Full depth reclamation projects are rehabilitation projects that should be designed geometrically as structural overlays. Pavement distresses which can be treated by FDR include:*

1. *all forms of cracking including age, fatigue, edge, slippage, block, longitudinal, reflection, or discontinuity;*
2. *reduced ride quality due to swells, bumps, sags, patches, or depressions;*
3. *permanent deformations in the form of rutting, corrugations, or shoving;*
4. *loss of bonding between pavement layers;*
5. *moisture damage (stripping);*
6. *loss of surface integrity due to raveling, potholes or bleeding;*
7. *excessive shoulder drop off; or*
8. *inadequate structural capacity,*

The expected design life, performance requirements during the design life, and acceptable future maintenance requirements are related to treatment depth of the FDR, types and amount of stabilizer used, subgrade type and conditions. For FDR projects, an existing roadway assessment, structural capacity assessment, materials properties assessment, geometric assessment of the existing and proposed sections, traffic assessment, constructability assessment, and an economic assessment needs to be conducted. A flow chart has been developed to aid in the selection of the correct treatment for pavement recycling projects. See Figure 602-1A (Figure 5)*, Pavement Recycling Treatment Selection Flowchart for determining an appropriate recycling treatment. The expected service lives of the various FDR rehabilitation techniques, when undertaking a pavement life-cycle economic analysis, generally fall within the following ranges:*

*1. FDR with single-lift HMA overlay ....7 - 15 years**

*2. FDR with two-lift HMA overlay ....12 - 20 years**

** Mechanistic-Empirical Pavement Design Guide (MEPDG) design analysis is necessary to determine the exact design life.*

Cold In-Place Recycling: Cold In-place recycling is the process of reusing the existing asphalt pavement by milling to a depth of 3 to 4 in. (75-100 mm), mixing the millings with a recycling agent (asphalt emulsion) and paving and compacting the cold-recycled mix. CIR has been successfully used on pavements with a higher degree of cracking that would normally require removal of the cracked surface and a thick overlay. Instead, the top portion of the existing pavement is recycled, and a thin overlay is applied over the cold recycled asphalt pavement. CIR is applicable for urban or rural roadways with high or low volumes of traffic. CIR can be used as a preventive maintenance treatment to address most types of pavement distresses. Cracked pavements which are structurally sound and have well-drained bases are the best candidates. The CIR process destroys existing crack patterns and produces a crack-free layer for the new surface course such as an HMA or an asphalt surface treatment. For CIR to be effective in mitigating cracking, as much of the existing asphalt pavement layer should be treated as possible. For a CIR project, assessments of the existing roadway, structural capacity, material properties, geometry of the existing and proposed cross sections, traffic, constructability, as well as an economic assessment must be conducted. See INDOT Standard Specifications section 416 for Cold In-Place Recycling.

Cold Central Plant Recycling: Cold Central Plant Recycling (CCPR) is a proven pavement rehabilitation method that utilizes recycled materials. CCPR involves stockpiling Reclaimed Asphalt Materials (RAP), crushing RAP to a specific gradation, mixing RAP with a recycling agent, adding additives to the RAP mixture if needed, transporting the CCPR mixture to the project site, laying down the CCPR mixture, paving the recycled CCPR mix, and compacting the recycled CCPR mixture for use as a temporary riding surface. A final surface layer will be provided on the prepared CCPR material. CCPR is most frequently used as part of the rehabilitation of an existing roadway, where the existing pavement cannot be in-place recycled or must be removed to allow treatment of underlying materials. However, CCPR can also be used in new construction where an existing separate source of RAP is available. CCPR in conjunction with an asphalt overlay is generally used with high frequency and high-severity, non-load associated distresses. It can also be used to address load related stress when used in conjunction with a multiple lift asphalt overlay to increase the pavement's structural capacity. The expected design life and performance during the design life are related to the depth of treatment and the type and thickness of the asphalt overlay course(s).

INDOT and local governments historically used Portland Cement Concrete (PCC) pavements, so the potential presence of the old PCC pavements needs to be considered when starting the process of selecting rehabilitation/recycling techniques. INDOT considers multiple items when selecting candidate projects and recycling techniques that they may be used on them. Figure 5 is an excerpt from the INDOT Design Manual, Chapter 602, that provides guidance for designers in the selection of CIR, FDR, and CCPR pavement recycling treatments. [32] This is a very detailed and clear recycling treatment selection flowchart.

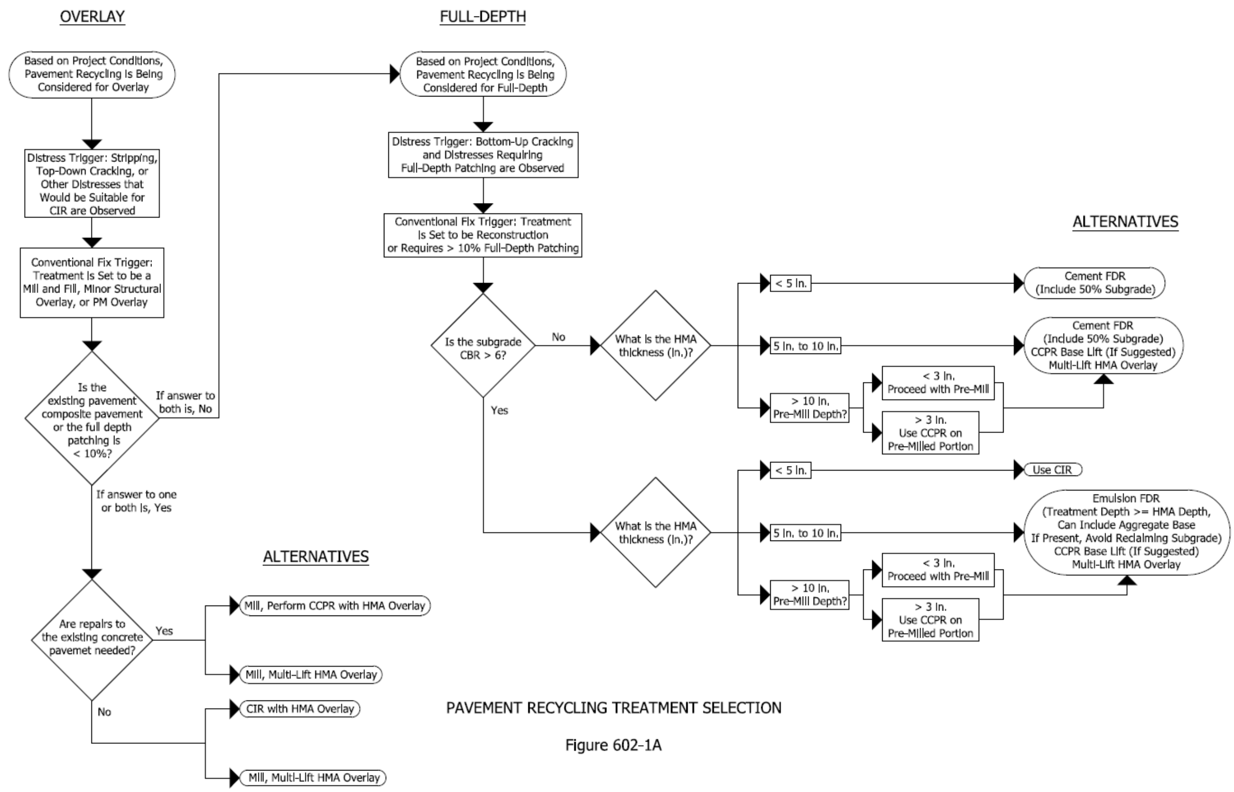

Figure 5. Chart. INDOT Pavement Recycling Treatment Selection Flowchart [26]

INDOT staff indicated that in general use of recycling technologies is on a case-by-case basis and that good information on pavement condition is needed for project selection. When a recycling technology fits the project selection guidelines, they use recycling technique identified. The staff also indicated that FWD testing is frequently performed. If really bad subgrade (in failure) is identified, then a project is seen as a candidate for FDR. FWD is sometimes used as a justification for using recycling.

In summary, existing pavement type, roadway classification/traffic level, required patching, and for FDR subgrade CBR are criteria used to identify and select recycling technologies for use. INDOT indicated that there is not much variation in geographic or climatic conditions across the state, thus they do not impact recycling technology selection and the selection is centrally managed (not made at the district level). Additionally, INDOT indicated that experienced contractors work in Indiana, so a lack of experience is not a consideration.

STRUCTURAL PAVEMENT DESIGN

The INDOT pavement design procedure is based on the AASHTO Mechanistic Empirical Pavement Design Method, and the AASHTOWare Pavement Mechanistic Empirical (ME) Design software is used, all of which is detailed in Chapter 601 of the INDOT Design Manual. [32] The manual indicates that the designer needs to obtain specific PG grade and mixture type inputs for each District, and it provides direction on where to obtain them. The Pavement ME software does not directly handle recycled materials and the Pavement ME User Group does not currently have a recommendation for handling them, though it is a topic being discussed. Thus, INDOT uses a resilient modulus in the range of 75 to 100 Ksi for CIR and FDR based on research.

MATERIALS

Table 9 is a high-level summary of materials used in each recycling technique. Details can be found in References 33, Sections 307 (FDR Cement), 308 (FDR Emulsion), 416 (CIR), 417 (CCPR). [33]

Table 9. Summary of Materials Used in each Recycling Technique.

<table>
<tr><th rowspan="3">Material Parameters</th><th colspan="5">Recycling Technique</th></tr>
<tr><th colspan="4">Cold</th><th>Hot</th></tr>
<tr><th>CIR</th><th>FDR Cement</th><th>FDR Emulsion</th><th>CCPR</th><th rowspan="7">N/A</th></tr>
<tr><td>Binders</td><td>Emulsions</td><td>Type I Cement</td><td>Emulsions</td><td>Emulsions</td></tr>
<tr><td>Virgin Aggregate</td><td>Allowed</td><td>Allowed</td><td>Allowed</td><td>Allowed</td></tr>
<tr><td>Active Fillers</td><td>Portland Cement
Allowed</td><td>–</td><td>Portland Cement
Allowed</td><td>Portland Cement
Allowed</td></tr>
<tr><td>Processed Recycled Material Top Size</td><td>< 1.5”</td><td>< 2.0”</td><td>< 2.0”</td><td>< 1.5”</td></tr>
<tr><td>Other Gradation Requirements</td><td>95-100 p1”
≥55% #4,
2-20%p200</td><td>≥ 35% p#4,
≤ 20% p200</td><td>≥ 35% p#4,
≤ 20% p200</td><td>95-100 p1”
≥55% #4,
2-20%p200</td></tr>
<tr><td>Other Aggregate Requirements</td><td>–</td><td>–</td><td>–</td><td>–</td></tr>
</table>

Binders

Emulsions are used for CIR, FDR Emulsion and CCPR. Type 1 Cement is used for FDR Cement. INDOT uses an Asphalt Emulsion Supplier Program (AES) and has a Qualified Products List (QPL) provision. [34] Requirements include a supplier quality control plan and monthly reporting requirements, as well as AASHTO Re:Source laboratory accreditation. INDOT performs department audits.

Active Fillers

Type I Portland cement is allowed in CIR, CCPR, and FDR Emulsion if needed to fulfill mix design requirements at a maximum dose of 1 percent and emulsion to cement ratio of 3:1.

MIXTURE DESIGN

INDOT requires that contractors have mix designs performed in AASHTO Re:Source accredited laboratories. For CIR/CCPR pavement samples from cores, test pits, milled RAP, or stockpile samples of RAP. Pavement samples are to be cut in laboratory to the appropriate depth to represent the planned field treatment. Additional aggregates may be sampled. A minimum of 350 pounds of sample is required. For FDR a minimum of 1/lane mile from cores, test pits, or milled rap to include in-place pavements, base, corrective aggregates, subbase, additional aggregates or additional RAP. Samples of the existing pavement collected as cores, test pits or milled RAP to represent the entire depth of the treatment including underlying materials and layers.

CIR/CCPR mix designs are performed per INDOT ITM 592. (35) FDR Emulsion and FDR Cement mix designs are performed per INDOT ITM 594 and ITM 595, respectively. (36, 37) Table 10 is a high-level summary of mix design requirements for each recycling technique. Details can be found in References 34 through Reference 37. Gyratory compaction (AASHTO T312) is used for CIR/CCPR with 100 mm diameter molds. The CIR/CCPR mix designs must meet the requirements listed in Table 11. The only difference in CIR and CCPR mix designs is an additional curing period is used for CCPR. Gyratory compaction (AASHTO T312) is used for FDR Emulsion with 150 mm diameter molds the FDR Emulsion mix designs must meet the requirements listed in. AASHTO T180 is used for compaction of FDR Cement and the mix must meet the project UCS requirement. The minimum UCS is based on the total HMA overlay spread rate and ranges from 300 to 500 psi.

Table 10. Mix Design Summary Information.

<table>
<tr><th rowspan="3">Material Parameters</th><th colspan="5">Recycling Technique</th></tr>
<tr><th colspan="4">Cold</th><th>Hot</th></tr>
<tr><th>CIR</th><th>FDR Cement</th><th>FDR Emulsion</th><th>CCPR</th><td rowspan="11">N/A</td></tr>
<tr><td>Compaction method</td><td>Gyratory (100mm)</td><td>Modified Proctor</td><td>Gyratory (150mm)</td><td>Gyratory (100mm)</td></tr>
<tr><td>Gyrations / Blows</td><td>30 for Marshall Stability, 20 for Raveling Test</td><td>T180</td><td>30</td><td>30 for Marshall Stability, 20 for Raveling Test</td></tr>
<tr><td>Curing</td><td>Stability 16-48hr @ 140F, Raveling 4hr @50F</td><td>7-day, moist cure</td><td>24-72hr @104F</td><td>Stability 16-48hr @ 140F, Raveling 4hr @50F</td></tr>
<tr><td>Binder dose selection</td><td>Meeting Design Criteria</td><td>Meeting Design Criteria</td><td>Meeting Design Criteria</td><td>Meeting Design Criteria</td></tr>
<tr><td>Coating</td><td>N/A</td><td>N/A</td><td>N/A</td><td>N/A</td></tr>
<tr><td>Raveling Test</td><td>D7196</td><td>N/A</td><td>N/A</td><td>D7196</td></tr>
<tr><td>Moisture Density Relationship</td><td>N/A</td><td>T180</td><td>N/A</td><td>N/A</td></tr>
<tr><td>Moisture Sensitivity Test</td><td>Retained Stability</td><td>N/A</td><td>IDT (wet)</td><td>Retained Stability</td></tr>
<tr><td>Rutting Test</td><td>Marshall Stability</td><td>UCS</td><td>N/A</td><td>Marshall Stability</td></tr>
<tr><td>Cracking Test</td><td>N/A</td><td>N/A</td><td>IDT (dry)</td><td>N/A</td></tr>
</table>

Table 11. CR with Asphalt Emulsion Mix Design Requirements.

CR Test	Passing Criteria
Marshall Stability, lbs. (kg), AASHTO T 245	1250 lbs. (567 kg) minimum
Retained Stability, %	70% minimum
Raveling Test, 50˚ F (10˚ C), %, ASTM D7196	2.0% maximum
Additional Additive(s) Cement, %	1.0% maximum
Emulsion to Cement Content Ratio	3:1 minimum

Table 12. FDR Emulsion Mix Design Requirements.

CR Test	Passing Criteria
Indirect Tensile Strength, AASHTO T 283, psi	40 psi minimum
Conditioned Indirect Tensile Strength, AASHTO T283, psi	25 psi minimum
Additional Additive(s) Cement, %	1.0% maximum
Emulsion to Cement Content Ratio	3:1 minimum

FIELD CONSTRUCTION & ACCEPTANCE

Mix Design Changes During Construction

Some State DOTs and contractors have faced challenges with making mix design changes during construction. The INDOT specifications rely on QC testing during construction to determine if changes are needed. Mix designs can be adjusted during production at the discretion of the Engineer. These decisions are made at the field level.

Equipment

The equipment requirements in INDOT specifications are very clear and relate to the latest recycling technologies. They include requirements for weighing, measuring and metering to help ensure INDOT receives the appropriate doses of materials (water, cement, emulsion) within clearly defined tolerances that are interlocked with controls and the quantities that have to be reported.

Control Strips

Control Strips are required by INDOT for all cold recycling techniques on the first day of production. For compaction, the contractor has minimum compactor type requirements and uses them to determine the maximum density that can be obtained, and the rolling pattern used is documented.

Quality Control and Acceptance

INDOT requires the following quality control plans for all recycling technologies. For CIR and CCPR there are QC requirements around gradation, moisture content, emulsion content, in-place density, field moisture content, and optimum field density. For CIR depth of pulverization is also included. Acceptance for CIR and CCPR is based on gradation (100% passing 1.5” sieve) and in-place density of 97 to 102 percent of control strip maximum density monitored with a nuclear gauge. If outside this a new control strip is performed. CCPR Acceptance also includes smoothness requirements.

For FDR there are QC requirements around depth of pulverization, gradation, moisture content, emulsion application rate, in-place density and proof rolling. The proof rolling is performed with a tandem or tri-axle dump truck loaded to legal limit with less than ½ inch deformation/rutting criteria. FDR Cement acceptance is based on gradation (100 percent passing 2” sieve and greater than 55 percent passing the #4 sieve), in-place density within 95% of Maximum Dry Density (MDD) per T180 monitored with nuclear direct transmission gauges to 95% of control strip MDD, unconfined compress strength, and proof rolling. FDR Emulsion acceptance is based on gradation (100 percent passing 2” sieve and greater than 55 percent passing the #4 sieve), in-place density within 95% of MDD per T180 monitored with Nuclear direct transmission gauges to 95% of control strip MDD and proof rolling.

Curing and Opening to Traffic

INDOT has curing and preparation requirements for all cold recycling technologies. For CIR and CCPR curing is for a minimum of 3 days and one of the following has to be met: less than 3% moisture content or mixture has cured a minimum of 10 consecutive days without rainfall. The entire CIR or CCPR surface shall be scarified prior to placing the overlay. Tack coat is required on the CIR or CCPR prior to placing HMA. For FDR Cement curing is per the QCP and the surface course must be placed within 2 weeks. FDR must cure a minimum of 3 days and cured to minimize moisture loss for the time period necessary to achieve the required minimum 7-day UCS. Tack coat is required on the FDR prior to placing HMA. For FDR Emulsion curing is for a minimum of 3 days and must meet one of the following: less than 3% moisture content; in-place moisture has remained constant at 50% or less of the design optimum moisture content for 5 days. Tack coat is required on the FDR prior to placing HMA.

Lessons Learned

INDOT indicated several lessons learned with it experience in using cold recycling technologies. The included:

- Using alternate bidding was helpful in getting the recycling program going, but INDOT learned that it needed to define the specific stabilizer for FDR.
- FDR can be combined with CCPR to treat thicker pavements.
- With FDR, structural capacity is improved, as defined by surface deflection from FWD.
- If there are significant changes in roadway cross section (subgrade, moisture, pavement thickness), a project may require more than one mix design.
- Importance of rational and effective project selection guidance: what are the correct criteria?
- Importance of appropriate project design: selection of stabilizing agent and pre-project testing requirements.

- When a recycling technique is used in a new location, construction and inspection staff need to be properly trained on the process.
- It is important to realize that pulverizers only mix materials longitudinally, not transversely.
- When using FDR, it is important that it be constructed a minimum of 1 foot wider than the finished surface edge of pavement for structural support.
- Proof rolling may reveal that FDR Emulsion requires cement to obtain adequate strength if localized high levels of moisture are encountered.
- Cement may be needed as part of an FDR Emulsion, CIR, or CCPR mix design to account for moisture, but it will only be known after the mix design process begins (a change order may be required).
- Making sure geometry is considered and that grade and cross slope corrections do not lead to insufficient recycled layer depth. Do not use milling to establish cross slope.
- Full surveys of profiles are a good design practice to provide reliable finished profile grades.
- It is important to assure adequate drainage when using cold recycling technologies. At times it may require that additional right of way be acquired to provide proper ditches or address other needs.

PAVEMENT PERFORMANCE AND COST

INDOT reported overall good performance with cold asphalt recycling techniques and noted that pilot projects from over 10 years ago are beginning to be rehabilitated now with longitudinal and transverse cracking being the common distresses being observed. A few projects were identified that challenges existed on that were lessons learned. They included a project that had peat and organic materials in the subgrade, one with numerous utilities and poor drainage, and one with some HMA slippage due to excess moisture in the recycled base.

Rutting and cracking performance data is being collected in the INDOT Pavement Management System (PMS). There is a plan in place to assess the structural performance of recycled asphalt pavements. INDOT is considering a network level FWD testing program in the next couple of years that would cover the entire system with FWD every 3 or 4 years to help with decisions on when and where to do projects. Coring is done with FWD testing and saved in database for development of deterioration curves. INDOT is obtaining a 3-D Ground Penetrating Radar (GPR). It will be included with project level testing and in the future network level GPR will be available. LWD testing is being explored during and post-construction.

Direct comparisons of pavements with and without recycling techniques are not available for comparison, which is common. Several benefits to using recycling techniques compared to conventional treatments were identified. They included reduction in:

- Construction time.
- Development time of plan preparation and getting them to bid.
- Process and right-of-way time.
- Time of environmental reviews.

There are many options available for rehabilitating a pavement in need. Selection of the most appropriate and cost-effective alternative is an important engineering decision. INDOT does a preliminary life-cycle cost analysis to compare the cost of in-place recycling versus the pavement life. In-place recycling is commonly justified and often selected as the preferred treatment. An analysis of the structural performance and cost associated with FDR compared to conventional rehabilitation was performed by INDOT. [38] Figure 6 is a comparison of subgrade and surface deflection data showing significant improvements in structural capacity with the FDR construction. Figure 7 shows the estimated cost savings on FDR projects compared to replacement and Figure 8 that the FDR cost is saving range from 40 to 70 percent compared to replacement. Replacement would be more likely to buy right-of-way and make other improvements like replacement ditches, wider shoulders, etc. Any right of way procured for would be significantly less than for a replacement project. The roads selected for FDR would never be candidates for replacement. A key point is FDR projects provide a new structural foundation that should provide better long-term performance for the investment.

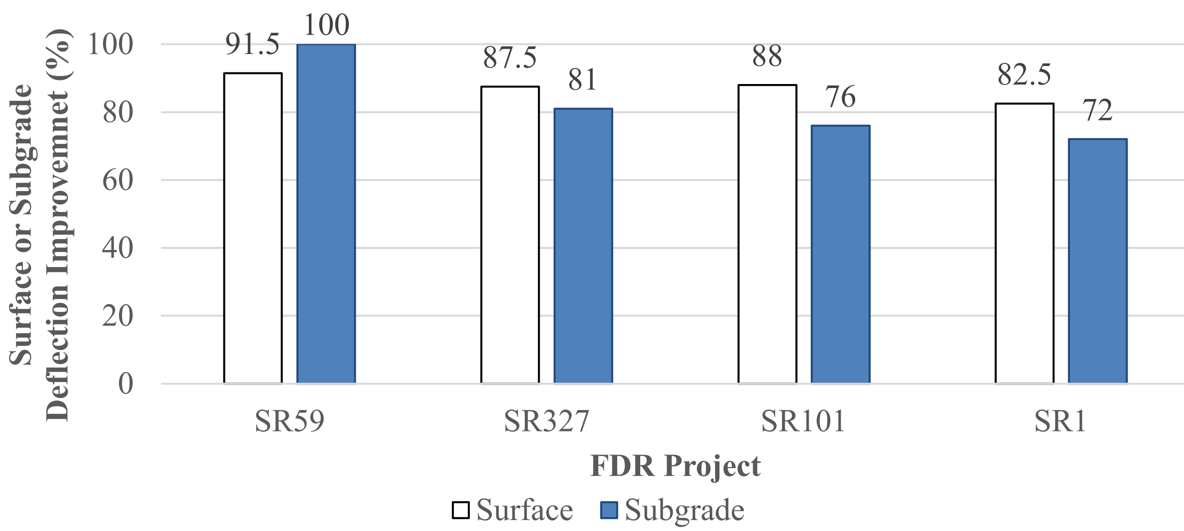

Figure 6. Chart. INDOT Observed Improvements in Surface and Subgrade Deflections with FDR.

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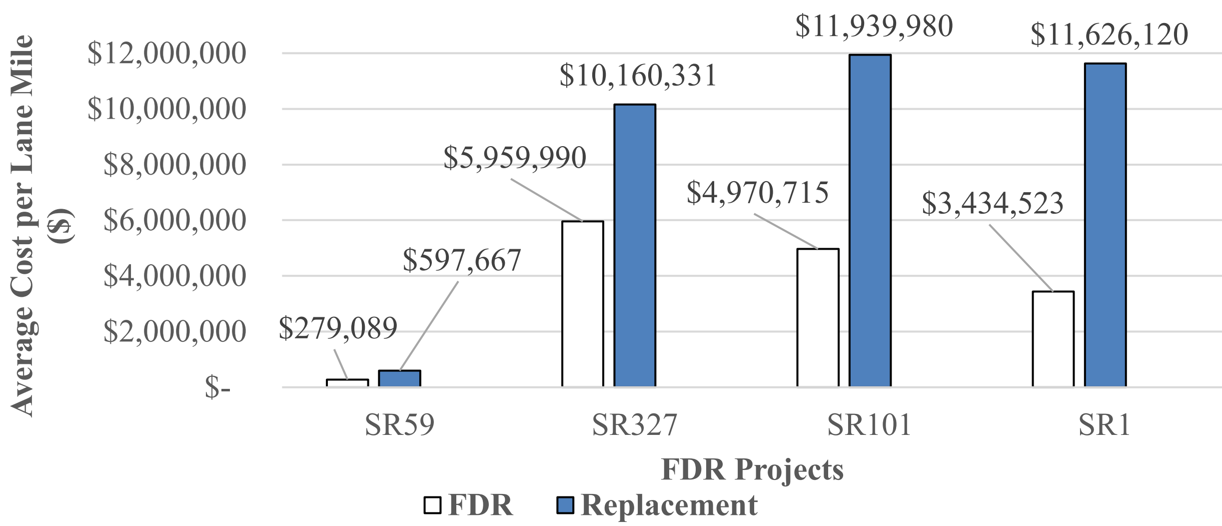

Figure 7. Chart. INDOT Average Cost per Lane Mile Comparison FDR versus Replacement.

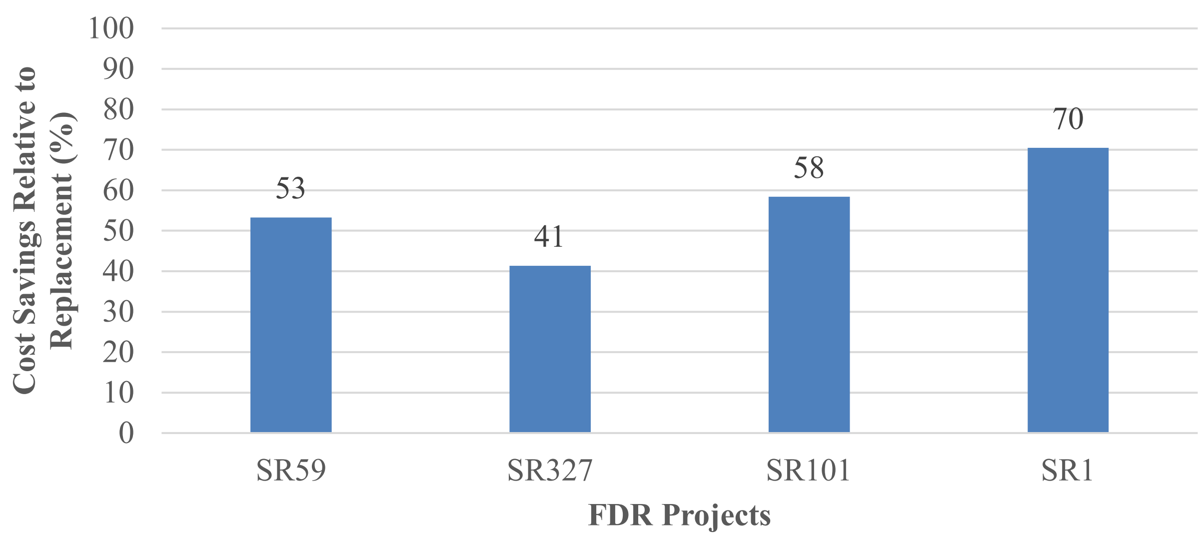

Figure 8. Chart. INDOT Percent Cost Savings per Lane Mile for FDR versus Replacement.

CONTRACTOR PERSPECTIVES

With the COVID-19 Pandemic leading to virtual site visits, it was not possible to visit INDOT construction projects. INDOT arranged for a virtual interview with a limited number of contractors to obtain their perspective on cold asphalt recycling experiences in Indiana. A set of seven open end questions were asked and each contractor had the opportunity to respond to each question. The questions and summary of response follow:

1. **<u>Is the number of recycling projects let in the State each year well balanced with number of recycling contractors operating in the State?</u>**

There are many projects going to bid and there are multiple bidders (i.e., 2-3 recycling subcontractors) on each project. The recycler is often a sub-contractor. For CIR recycling contractors are mobilizing from out-of-state as the program develops. The general contractors are getting multiple quotes. There are both INDOT and local agency projects with the distribution of them being about one-half INDOT and one-half local agencies. The square yards of recycling is much larger for INDOT projects since the projects are larger. The number of projects is increasing, but still not double digits in terms of number of projects. Once INDOT developed specifications, local agencies were able to improve implementation of recycling techniques

2. **<u>Is there less bidding competition on DOT projects with recycling techniques than on other conventional paving projects?</u>**

   Recycling contractors work as subcontractors for prime contractors. There are typically 2 to 3 local recycling contractors that bid on each DOT project. There was a local market initially. FDR has a strong market for soil stabilization, so general contractors knew who to reach out to for FDR subcontractors. Takes a couple of projects to get local contractors started. First CIR project was an alternate bid which was unique. The project was originally planned as a conventional mill and fill with a lot of patching (included a bridge). A Unique Special Provision (USP) was used that had a lot of revisions from then until now. FDR grew the same way. SR-1 in the Greenfield District was an alternate bid with emulsion or cement for a project going into a landfill with heavy traffic. SR-14 had cement. A few local, central Indiana engineers championed the effort. One took the risk and put it on a project. A city/county championed it to get started.

   Using alternate bidding was helpful in get the recycling program going. After initial projects, INDOT learned that it needs to define the specific stabilizer. Original intent with INDOT specifications was to write an FDR specification and let contractors decide. This would lead to challenges in the bidding process (tons of cement vs. gallons of emulsion). After experimenting, two different specifications with different pay items were created and designer were trained to select right the stabilizer for each project. Training took place on them, and the recycling committee created a flow chart for treatments (in place prior to 2015) / materials / and project selection. The flow chart makes sure projects are good candidate for the recycling technique specified (FDR vs. CIR vs. etc.). Each road is examined individually based on project goals and there is not really a geographical trend on use of specific recycling technologies. One project had a section that did not pass proof rolling (amount of moisture), so cement had to be use. There was not a cement item in the plans so that created a headache in the change order.

3. **<u>Do challenges or risks exist when transitioning from lab mix design to production start-up in the field or during production?</u>**

   Initial coring and design do not capture everything. The initial design is typically good for about 90 percent of a project, but there are changes sometimes. How the state deals with that is a challenge and raises the question of what is the proper modifier? There may need to be adjustments made along a project when unanticipated changes in the existing pavement are encountered such as asphalt thickness, base thickness, repairs with stone, and peat. Change orders are used when this happens. INDOT and industry have a good relationship, and this provides an avenue through which troubleshooting can occur so rational changes are made.

Just in time training is included in specifications. During the training it is helpful to share mix design data, what it means, and pictures of what could be encountered on the project. This gets collaboration going early before issues may arise. It also helps identify what inspectors should be looking for. The Heritage Group is studying the differences in mix design field produced material properties and their relationship to field performance. Samples have been being collected from the field for three years and compared to lab mix designs. The data is indicating that the consistency of a project being rehabilitated is a big factor. The data analyzed shows that about 80 to 150 percent of design values are being achieved in the field.

4. **Are there examples of techniques or production best practices used by contractors or DOT staff to make mixture adjustments during production that are not in DOT specifications, but could be to allow for rapidly acceptable changes to improve mixture quality?**

   The specifications are pretty thorough. If a contractor believes a stabilization rate needs to be changed the engineer must approve it if the change is more than ±0.5 percent. Contractors have flexibility with lower dose changes. This seems to have been effective and working well for both parties.

5. **Are there recommended best practices for answering the question, "How does an agency know it is getting the proper proportions of mixture components in recycled mixture?"**

   One method is to have a separate pay item for stabilizer; thus, the DOT pays for what is being used. With earlier specifications the stabilizer was incidental to the recycling bid item. There was one project with an issue with a meter that got caught by QC. Technology and equipment are improving. It is important for contractors to keep equipment and technology up to date. Contractors consider what is required elsewhere in neighboring states. The CIR equipment is used in multiple states (single unit or long train), and it is important to keep up with equipment manufacturers. Illinois looking to have meters calibrated annually.

6. **Is there a mechanism(s) in place that allow for training/knowledge transfer, review of lessons learned, and partnering on improvements with DOT and contractor stakeholders participating?**

   There is a recycling committee which plays a big part in education. Industry, suppliers, and INDOT are all involved. Just in time training is important for training and partnering, that helps develop good working relations. Gap between design and boots on ground is closed with it because the just in time training connects design and construction. The model used by INDOT has been recommended in other states because it works. Exposure through the Purdue Road School helps with education and knowledge transfer also. The Purdue Road School includes participants from municipalities and industry.

7. **What are some of future activities that could help support successful use of recycling technologies?**

One struggle with recycling is figuring out how to get recycling options in front of designers, materials, pavement designers, and construction folks. There could be more focus on designers at scoping in terms of messaging recycling as a successful option. INDOT solidified this in its design manual and recycling is considered a standard option to be considered during scoping and design. College pavement programs need to include more content on recycling. ARRA could prepare a college course that could be supplied to universities. This would parallel NAPA's professor training program offered at National Center for Asphalt Technology (NCAT) that includes a textbook. Having a funding mechanism for cold recycling when a reduced carbon footprint will occur, such grants to get credit for using these technologies. There is industry resistance to cold recycling. What may have been an 8-inch overlay is now a 3-inch overlay on FDR. The resistance needs to be overcome. INDOT is choosing this to "force" the decision. Local agencies struggle more with pressure from local asphalt aggregate producers. Potential solutions include:

- Education
- Paving contractors starting to self-perform recycling
- A "marriage" between ARRA and NAPA would help but may not occur in the near future.

Key information provided by recycling contractors working in Indiana included:

- There is an established recycling program at INDOT and in other agencies, coupled with an adequate number of contractors to competitively bid and build the work.
- Just in time training is valuable for INDOT and contractors and minimizes issues that could arise on projects.

There are needs for education on recycling technologies for all stakeholders. There are several online National Highway Institute (NHI) Asphalt Pavement In-place Recycling Technologies (APIPRT) training courses available:

- NHI 131140 Hot In-place Recycling (web-based training)
- NHI 131142 Full Depth Reclamation (FDR) (web-based training)
- NHI 131050 Asphalt Pavement In-place Recycling Techniques
- Inspector Training for Cold In-place Recycling (web-based training)

INDOT BEST PRACTICES

Throughout the visit, several INDOT best practices were identified that included the following:

1. Having clearly defined recycling techniques and potential applications of each.
2. Very detailed pavement recycling treatment selection process flowchart Figure 5 very well done.
3. Recently updated specifications and test methods related to FDR, CIR and CCPR.
4. Asphalt Emulsion Supplier Program (AES) with QCP, monthly reporting, department audits, AASHTO ReSource requirement and QPL provision.
5. Requiring all mix designs be developed in an AASHTO ReSource accredited lab.
6. Clear direction on pavement design using AASHTOWare Pavement ME Design software in Chapter 604 of the INDOT Design Manual.

7. INDOT Design Manual Chapter 604 on getting District specific material inputs for PG and mix types. Also, selection of mix types to prevent inadequate ratio of lift thickness to mixture nominal maximum aggregate size.
8. Just in Time Training is required within 14 days of recycling construction with that operations and inspection personnel participating.
9. FDR requires QCP with depth of pulverization, gradation moisture content, cement application rate, in-place density and proof rolling.
10. CIR and CCPR require QCPs with depth of pulverization, gradation, moisture content, emulsion content, in-place density, field moisture content, and optimum field density.
11. FDR (cement) specification (SS 307) has subgrade soil sulfate content ≤ 1000ppm requirement.
12. Control strips are required on first day of all recycling construction.
13. Equipment section of the CIR, CCPR and FDR specifications include provision to make it possible for INDOT know the correct quantities of materials are being used.
14. Have a pay item for the stabilizer helps insure the property dose is used.
15. Proof rolling is a requirement in all the specifications.
16. INDOT is collecting cost and performance data as a function of time that can be used to communicate the successful use of recycling, as well as the sustainable benefits (cost savings, reduced environmental impacts and positive societal aspects).
17. INDOT has identified some alternative uses of RAP to maximize the recycling or reuse of it.
18. Learning from past experiences and integrating changes into design procedures and specifications for continuous improvement. This includes post-project team meetings to discuss challenges and identify solutions, as well as annual statewide meetings as needed.
19. Having a venue at which all stakeholders (recycling committee) can provide input on potential improvements, as well as an educational venue (Purdue Road School) have helped promote the use of recycling technologies.

ALTERNATIVE USES OF RAP

INDOT staff identified several alternative uses of RAP that include:

- Use in HMA.
- Some Districts have been using RAP to fill in edge drop-offs as the binder in RAP helps hold the material in-place.
- District maintenance units have requested to keep a certain percentage of RAP generated from a project for their needs.
- Use of RAP in embankment has started recently.
- RAP in parking lots for local projects.

RESEARCH ACTIVITIES AND RESEARCH NEEDS

Currently INDOT does not have any on-going research projects specific to cold asphalt recycling technologies. INDOT is committed to monitoring the performance and cost-effectiveness as projects age. It is also committed regularly review the effectiveness of specifications and updating them for improvement. INDOT is considering potential implementation of the NCHRP Project 09-62 shear and raveling tests.

INDOT identified the following research needs:

- Adequate long-term performance data to identify keys to success and what can be done to increase performance lives.
- Determination of what are the best surfaces to use with cold recycled technologies including chip seals, micro surfacing, HMA and white topping.
- The ability to more effectively integrate cold recycling technologies in the PavementME Software.
- Education of the benefits of recycling and application of the technologies for project engineers.
- Having a funding mechanism for cold recycling when a reduced carbon footprint will occur, such grants to get credit for using these technologies.

CLOSING REMARKS

INDOT is actively and successfully using multiple sustainable cold asphalt recycling techniques. Specifically, INDOT uses CIR, FDR Emulsion, FDR Cement, and CCPR and the rate of use is increasing. The support of INDOT and INDOT staff that participated in this effort is greatly appreciated. The input provided revealed several positive practices that will be of significant value to other agencies.

CHAPTER 4 VIRTUAL SITE VISIT: NMDOT

INTRODUCTION

The NMDOT owns and maintains over 30,000 lane miles of roads, with approximately 25, 062 being highway lane miles. About ninety-nine percent of the roads are flexible pavement surfaced with asphalt materials. Less than one percent is rigid pavement. Cold asphalt recycling and hot in-place recycling techniques used by NMDOT include CIR, FDR, CCPR, and HIPR. Two types of HIPR are used, remixing and repaving. CIR, FDR, and CCPR are used on construction projects, while HIPR is only used for maintenance projects and is always surfaced with virgin HMA or a chip seal. Beginning in 1984, NMDOT became a national leader in the use of CIR completing 130 projects over a 12-year period. (39) However, poor performance on a very limited number of projects led the NMDOT to stop using CIR for period of time. It was suggested that CIR was being so successfully used that it eventually got used on a limited number of projects that were not ideal CIR candidates.

Table 13 presents as summary of asphalt recycling techniques use by NMDOT. The breakdown of the cold asphalt recycling techniques use by NMDOT in the recent past has been approximately 60 percent FDR, 32 percent CCPR and eight percent CIR. The total quantities of each and units cost for the time period 2010 to present. When CIR is used the depth of recycling is maintained in the asphalt layer 1 to 2 inches above the aggregate base course. For FDR the depth is maintained in the aggregate base layer typically penetrating about two to four inches into it, with a typical FDR compacted thickness of 8 inches. Use varies across Districts for cold recycling techniques, while all Districts utilize HIPR.

It was noted that RAP supply has exceeded demand in some areas of the state, as large stockpiles can be observed. This coupled with it not being economical to transport the RAP to other markets, with less supply than demand, has led to NMDOT more recently placing focus on the use of CCPR.

Table 13. Summary of Cold Asphalt and Hot In-place Recycling Techniques use by NMDOT.

Recycling Technique	Cold			Hot	
	CIR - Emulsion	FDR - Foamed	CCPR - Foamed	HIPR Remixing	HIPR Repaving
Use (percent of total use)	10	50	40	N/A	N/A
Square Yards	267,300	1,910,349	1,015,870	N/A	N/A
Cost per Square Yard	$6.91	$14.28	$10.62	N/A	N/A
Districts Using	2 of 6	5 of 6	3 of 6	6 of 6	6 of 6
Years of Experience	3[1]	9	8	> 20	> 20

[1]Began to use CIR again.

PROJECT/RECYCLING TECHNOLOGY SELECTION CRITERIA

NMDOT considers multiple items when selecting candidate projects and recycling techniques that they may be used on them. The New Mexico Department of Transportation Design Manual was updated in 2020 and provides direction with procedures related to project planning, design, construction, and assessment stages. [40] Preliminary investigation, site investigation, surfacing materials and pavement design, as well as design documentation requirements are clearly defined in the manual. The manual has field investigation, FWD and laboratory testing requirements that support the flexible pavement design procedure policy.

NMDOT staff indicated that thorough site investigation to understand site variability and engineering analysis is an important step in selecting projects that will include cold recycling techniques. At least four borings, three to four feet in depth below existing pavement materials, are performed per mile in each direction to determine types and thicknesses of existing materials, cross section consistency (are mainlines and shoulders similar, etc.) and to collect samples for laboratory testing. FWD testing is also performed and used to back calculate moduli of in-place materials, evaluate consistency, and identify any particularly soft areas that may require special design and construction considerations. Intact cores are evaluated for stripping, layer delamination, excess binder, presence of paving fabric and used in the project determination process.

In general, NMDOT use of cold asphalt recycling and HIPR techniques is consistent with the guidelines presented in the ARRA Basic Asphalt Recycling Manual and the FHWA TechBrief on Project Selection Guidelines for Cold In-place and Cold Central Plant Pavement Recycling as illustrated in Figure 5.[4,8] The NMDOT Pavement and Design Bureau develops Pavement Condition Assessment Reports (PCAR) that include preliminary treatment recommendations (e.g., minor rehabilitation, major rehabilitation, etc.) based on investigations that include distress surveys, FWD testing, and construction histories with details of a Pavement Condition Rating (PCR), as well as individual distress plots as a function of location. The NMDOT Districts make project selection decisions with input from General Office such as the PCAR.

Recommendations in the PCAR are not specifically based on roadway classification, traffic level, geographic location or climatic region. Recycling techniques have been used on Interstate pavements Interstate 25 (I-25) and Interstate 40 (I-40). However, the NMDOT pavement design method does integrate reliability that is a function of traffic level. Climatic region is not a criterion because the recycling techniques used are surfaced with new HMA or Warm Mix Asphalt (WMA) designed in accordance the NMDOT Standard Specification for Highway and Bridge Construction which requires that the asphalt binder PG of the surface is appropriate for project specific climatic conditions.[41] Contractor experience is not considered when selecting recycling techniques and there have been limited cases where there was only one bidder. Industry has suggested that NMDOT should have a consistent “recycling program” so that investment can be made for recycling equipment by New Mexico based contractors.

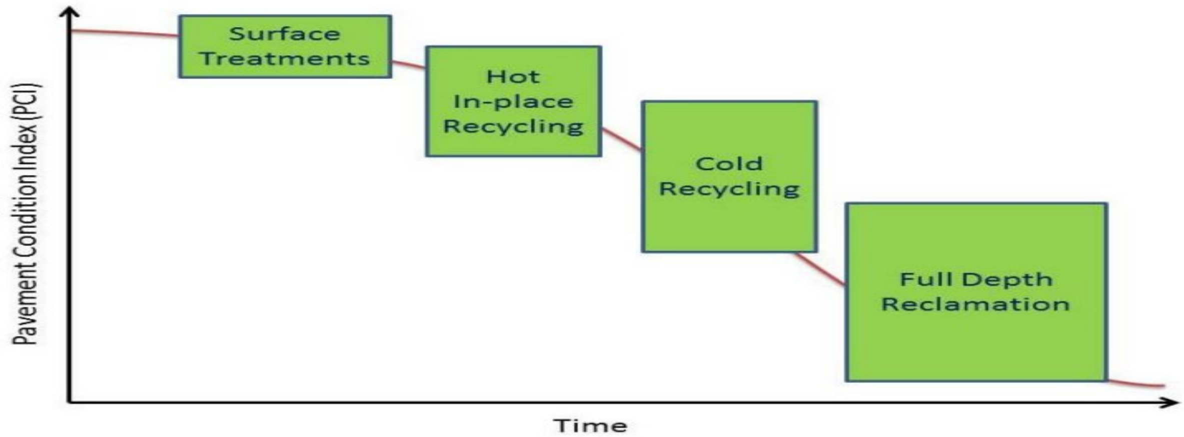

Figure 9. Chart. Asphalt Recycling Strategies Based on Pavement Condition. [8]

STRUCTURAL PAVEMENT DESIGN

The NMDOT pavement design procedure is based on the AASHTO Guide for Design of Pavement Structures 1993 and documented in the recently updated New Mexico Department of Transportation Design Manual. [40] The NMDOT pavement design procedure includes structural layer coefficients for each cold asphalt recycling and HIPR technique that were developed based on indirect tensile strength (ITS) tests and verified with FWD back calculation. The layer coefficients are summarized in Table 14.

Table 14. NMDOT Structural Layer Coefficient Values.

Material	Layer Coefficient Minimum
Rubberized/Open Graded Friction Course (R/OGFC)	0.00
New HMA	0.44
New Stone Matrix Asphalt (SMA)	0.44
New Hot Recycled HMA	0.44
New Hot-In-Situ Recycled HMA	***0.30***
PCCP Crack and Seat	0.30
New Cold In-Situ Recycled HMA	***0.35***
New Cold Central Plant Recycling –Foamed Asphalt	***0.35***
New Full Depth Reclamation – Foamed Asphalt	***0.30***
Asphalt Treated Aggregate Base Course	0.25
Cold-Mixed Asphalt Pavement	0.15
New Treated Open Graded Aggregate Base Course	0.15
New Untreated Aggregate Base Course	0.15
Existing Untreated Aggregate Base Course	0.08
New Lime or Cement Stabilized Subgrade	-

The design method also integrates reliability that is a function of traffic level and subgrade soil properties. The reliability level used is applied based on roadway classification such the higher reliability is used for roadway classifications with the higher traffic.

MATERIALS

Table 15 is a high-level summary of materials used in each recycling technique. Details can be found in References 41 through Reference 47.

Table 15. Summary of Materials Used in each Recycling Technique.

Material Parameters	Recycling Technique				
	Cold			Hot	
	CIR	FDR	CCPR	HIPR Remixing	HIPR Repaving
Binders	Emulsions, Engineered Emulsions	Foamed Asphalt	Foamed Asphalt	Recycling Agent	Recycling Agent
Active Fillers	Portland Cement or Hydrated Lime Slurry	Portland Cement	Portland Cement	N/A	N/A
Processed Recycled Material Top Size	1.25”	3”	1”	N/A	N/A
Other Gradation Requirements	N/A	N/A	See Table 4	N/A	N/A
Other Aggregate Requirements	Deleterious Material	Plasticity Index	Plasticity Index	N/A	N/A

Binders

NMDOT has historically used high float emulsion (HFE) for CIR. The base binder in emulsions used in CIR has historically been PG64-22 and has to meet the creep stiffness and m-value requirements of AASHTO T 320, *Standard Specification for Performance-Graded Asphalt Binder* [48] as well as the requirements of AASHTO T 59, *Standard Method of Test for Emulsified Asphalt* [49]. However, the use of engineered emulsions is becoming more common in so that CIR mixture performance test requirements can be satisfied. For FDR and CCPR PG64-22 is typically used, must meet AASHTO T320 requirements for the project location and there are half-life of foamed expansion and expansion ratio criteria. For HIPR only ARA-1P recycling agent is used and must contain at least 1.5 percent Styrene-Butadiene-Styrene (SBS) polymer. The dose must restore the aged binder to meet the PG binder grade requirement for the project specific location per AASHTO T 320, when blended per Appendix A of AASHTO M 323 *Standard Specification for Superpave Mix Design*. (50)

Active Fillers

Either hydrated lime slurry or Portland cement can be used as active filler in CIR, though the current trend is moving more towards cement. Lime slurry has to contain a minimum of 30 percent solids. Up to 1.5 percent Portland cement can be used and the residual asphalt binder to Portland cement ratio must be greater than or equal to three. For FDR and CCPR only Portland cement can be used as active filler. Up to 1.5 percent Portland cement can be used and the residual asphalt binder to Portland cement ratio must be greater than or equal to three.

Processed Material Gradations

For CIR only the top size is specified as passing the 1.25-inch sieve. Similarly, for FDR only the top size is specified as passing the 3-inch sieve. For CCPR much tighter gradation controls are specified as shown in Table 16. Additionally, CCPR may be supplemented with virgin aggregates and ½ inch Crushed RAP. The crushed RAP has to be processed per a special provision that includes QC plan requirements. (51)

Table 16. CCPR Gradation Requirements.

Sieve Size	Percent Passing
1.5 inch	100
1.0 inch	85 - 100
¾ inch	70 - 100
No. 4	40 - 68
No. 10	25 - 55
No. 200	4 - 20

MIXTURE DESIGN

NMDOT requires that mix designs be performed in AASHTO Re:Source accredited laboratories. Table 17 is a high-level summary of mix design requirements for each recycling technique. Details can be found in References 41 through Reference 47. Gyratory compaction is used for CIR and HIPR mix designs using 30 gyrations, while Marshall compaction is used for FDR and CCPR mix designs applying 75 blows per face. The CIR mix design includes coating, raveling, ITS, moisture sensitivity and rutting and cracking test requirements. In the CIR mix design specimens are prepared at three emulsion contents anticipated to surround the optimum which is selected based on ITS. The CCPR is similar to FDR with more rigorous mix design requirements. For example, better gradation control and a little higher TSR requirement for the CCPR. Both FDR and CCPR designs require that moisture density relationships be developed. The HIPR is essentially designed like a regular HMA or WMA with the same mix design requirements found in the NMDOT Standard Specifications for Highway and Bridge Construction. (41) The mix designs associated with all of the cold asphalt recycling and HIPR techniques include rutting, cracking and moisture sensitivity testing. The rutting test used for CIR, FDR and CCPR is Marshall Stability, while the

Hamburg Wheel Track Test (HWTT) is used for HIPR. The ITS cracking test used for all of the recycling techniques. To evaluate the moisture sensitivity of the cold asphalt recycling techniques a form of the TSR test is used while the HWTT is used for the HIPR mixtures.

Table 17. Mix Design Summary Information.

Mixture Design Parameters	**Recycling Technique**				
	Cold			**Hot**	
	CIR	**FDR**	**CCPR**	**HIPR Remixing**	**HIPR Repaving**
Compactor	Gyratory	Marshall	Marshall	Gyratory	Gyratory
Gyrations / Blows	30	75	75	30	30
Curing	15-48hr @ 140°F to ≤0.05% MC change/2hrs, 12-24hr @ room temperature	72hr @ 104°F	15-48hr @ 104°F	T283 dry set only	T283 dry set only
Compaction Temperature (°F)	25	25	25	–	–
Binder dose selection	Minimum Dry and Wet ITS	Minimum Dry and Wet ITS	Minimum Dry and TSR	@ 4% Air Voids	@ 4% Air Voids
Coating	T 59	N/A	N/A	N/A	N/A
Raveling Test	D7196	N/A	N/A	N/A	N/A
Moisture Density Relationship	N/A	T180	T180	N/A	N/A
Moisture Sensitivity Test	T 283[1]	T 283[1]	T 283[1]	T 324 HWTT	T 324 HWTT
Rutting Test	Marshall Stability	Marshall Stability	Marshall Stability	HWTT	HWTT
Cracking Test	ITS	ITS	ITS	ITS	ITS

[1]The curing, conditioning and criteria differ among these materials.

FIELD CONSTRUCTION & ACCEPTANCE

MIX DESIGN CHANGES DURING CONSTRUCTION

Some State DOTs and contractors have faced challenges with making mix design changes during construction. NMDOT indicated that "in the old days" decisions were made on-the-fly by the contractor and project engineer. Examples of changes that could lead to better finished recycled material are add water adjustments, active filler dose, binder (RA, emulsion, or foamed asphalt) dose, etc. NMDOT indicated that with FDR and CCPR it is not common to have to make changes during production, though it can be more common with CIR, and it is common with HIPR techniques as there can be changes in the surface mix which are reflected in the recycled mix if adjustments are not made. Therefore, NMDOT has made several changes to minimize the need for mix design changes during production. Changes NMDOT has made include the following:

- More thorough site investigations that better defines variability of existing pavements and requiring a PCAR be developed.
- Specifying that the same cold milling equipment be used to obtain RAP samples for CIR mix design samples that will be used during construction.
- Requiring eight hours of pre-construction training for contractor and DOT staff at least seven days prior to commencement of CIR construction.
- Requiring the contractor to provide a CIR Emulsion supplier technician with at least five (5) years of experience in CIR operations that is approved by the State Asphalt Engineer through the Project Manager. The technician has to be on the project site at the start of the CIR operation to monitor the characteristics and performance of the CIR emulsion, as well as be available throughout the CIR operation to evaluate the CIR mix and make adjustments to the CIR emulsion formulation as required.

Test Strips

NMDOT requires test strips for all the cold asphalt and HIPR techniques it specifies. This is an opportunity to evaluate the recycling process, materials, ability to achieve compaction, and demonstrate a rolling pattern.

Quality Control and Acceptance

NMDOT requires quality control plans for all the cold asphalt and HIPR techniques it specifies. The specification for each recycling technique includes an appendix with a single table detailing all material testing and inspection requirements; sampling locations; the parties responsible for performing the sampling, testing and inspections; and the frequency for materials selection/mix design, test strip, and production/construction. The reader is referred the specifications for details found in Reference 41 through 47. The quality control requirements are extensive. In some cases, both NMDOT and the contractor are performing the same tests, on the same materials at the same time as go/no-go tests.

Acceptance and payment are based on density for the cold asphalt recycling techniques. Payment is made per the schedule shown in Table 18 and each day's production and full lane width is considered a lot, unless the paving length is less than 2000 feet. If the production is less than 2,000 linear feet, the results are combined with the previous day's production.

Table 18. Cold Asphalt Recycling Techniques Payment Schedule for Lot Densities.

Percent of Average Density from Prior Days' Moisture-Density Relationship	Percent of Payment as Applied to the recycling technique SY
> 97.0	100
≤ 96.0 to < 97.0	95
≤ 95.0 to < 96.0	90
< 95.0	75

Lessons Learned

NMDOT indicated that post-construction project team meetings to discuss challenges and identify solutions to them or changes that could prevent future issues are held on some projects. The goal is to learn from past experiences and integrating changes into design procedures and specifications for continuous improvement. Three examples of lessons learned with FDR and one with CIR were shared. For FDR, one lesson learned was that using excess Portland cement can lead to microcracking of FDR. One may think that more cement would increase FDR strength, but it can also cause shrinkage of the FDR and micro cracking. NMDOT recognized the importance of limiting the amount of cement used to no more than 1.5 percent by dry weight of reclaimed material. A second lesson learned with FDR was the importance of applying tack coat on sealed FDR prior to placing HMA or WMA on it to prevent slippage failures of the HMA or WMA. The third lesson learned with FDR was that a Rex compactor designed for compaction of refuse in landfills, which is not a vibratory compactor but can be operated at a faster pace than a sheepsfoot roller, could be successfully used to compact an 8-inch layer of FDR successfully when a sheep's foot roller could not. Figure 10 is a picture of the compactor. A lesson learned on a CIR and CCPR project was that it is important to verify that the thickness of the existing HMA is adequate if geometric (grade and slope) changes or corrections are planned.

Figure 10. Picture. Rex compactor.

PAVEMENT PERFORMANCE AND COST

NMDOT reported overall good performance with cold asphalt recycling and HIPR techniques. Two Districts indicated that maintenance activities, timing, and frequency for recycled pavements are similar to control mixes. NMDOT is collecting cost and performance data as a function of time that can be used to communicate the successful use of recycling, as well as the sustainable benefits (cost savings, reduced environmental impacts and positive societal aspects) in the future. FDR was reported to cost about $100,000 per mile (with no overlay) while reconstruction is about $1,000,000$^+$ per mile. And for Interstate pavements reconstruction is about $2,000,000$^+$ per mile. The time of construction for FDR was reported to be reduced significantly when compared to reconstruction reducing user impacts and safety risks.

The NMDOT standards for the PCR, Highway Performance Monitoring System (HPMS) Cracking Percent, Roughness (IRI), and Rutting follow. The PCR is an index that was developed specifically for New Mexico. The PCR is a composite measure of overall distress and roughness related to a pavement section. PCR is based on 80 percent of the pavement distress (Overall Condition Index) and on 20 percent of the Roughness Index calculated from the measured International Roughness Index (IRI). PCR is described using a 0-100 scale, where 0 is the worst condition and 100 is the best condition, in presenting the current roadway condition. The pavement condition is usually broken into 6 categories based on the PCR value as shown in Table 7 with the suggested treatment associated with each condition.

Table 19. NMDOT PCR Ranges, Pavement Conditions and Suggested Treatments.

PCR Range	Condition	Suggested Treatment
86-100	Very Good	Monitor – none to minor preservation, fog seals or other surface coats.
66-85	Good	Major preservation, overlays – to minor rehabilitation, thin mill and inlay.
51-65	Fair	Minor to major rehabilitation – mill and inlay between 2.5 and 5 inches
46-50	At Risk	Minor to major rehabilitation
26-45	Poor	Major rehabilitation 5 inches deep to PPC, FDR
0-25	Very Poor	Reconstruction

New FHWA guidelines under 23 CFR Part 490 set thresholds for determining pavement condition using Roughness, Rutting, and Cracking Percent (Fatigue) values, as shown in the following Table 20.

Table 20. New FHWA Guidelines.

Pavement Condition	Roughness (IRI)[1] (inches/mile)	Rutting[2] (inches)	Cracking Percent[3] (%)
Good	<95	<0.20	<5
Fair	95 - 170	0.20 - 0.40	5 - 20
Poor	> 170	> 0.40	> 20

[1]IRI is a statistic used to estimate the amount of roughness in a measured longitudinal profile measured in inched per mile.
[2]Rutting is the average rut depth of both wheel paths.
[3]Cracking percent is the percent area with fatigue type cracking of all severity levels in the wheel paths within the total section area.

NMDOT BEST PRACTICES

Throughout the visit, several NMDOT best practices were identified. They included the following:

1. Recently developed or updated policy, specifications and design manual that specifically incorporate asphalt recycling techniques.

2. Having unique specifications (standard or special provisions) for each cold asphalt recycling and HIPR technique.
3. Having the equipment sections of specifications that clearly define control, metering, and calibration requirements.
4. Performing very thorough pavement investigations to better define variability of existing pavements and developing PCARs for making project/recycling technique decisions. This also minimizes the need for mix design changes during construction.
5. Specifying that the same cold milling equipment be used to obtain RAP samples for CIR mix design that will be used during construction and if a portion of the existing pavement surface is planned to be milled and removed during construction, the pavement has to be milled in a similar manner and removed prior to milling for sampling purposes.
6. Requiring eight hours of pre-construction training for contractor and DOT staff at least seven days prior to commencement of CIR construction.
7. Requiring contractor control plans on all projects.
8. Requiring the contractor to provide a CIR Emulsion supplier technician with at least five (5) years of experience in CIR operations that is approved by the State Asphalt Engineer through the Project Manager. The technician has to be at the project site at the start of the CIR operation to monitor the characteristics and performance of the CIR emulsion, as well as be available throughout the CIR operation to evaluate the CIR mix and make adjustments to the CIR emulsion formulation as required.
9. Allowing the use of engineered emulsions for CIR so that mechanical properties specified in the mix design can be obtained.
10. NMDOT requires that mix designs be performed in AASHTO Re:Source accredited laboratories.
11. The NMDOT Pavement Design Manual includes structural layer coefficients for each cold asphalt recycling and HIPR technique that were developed based on ITS and verified with FWD back calculation.
12. Construction of test strips prior to full production is required for all cold recycling and HIPR techniques require.
13. Having extensive quality control requirements used during construction, some with go/no go criteria performed daily during construction.
14. Each recycled material specification contains a single table detailing all material testing and inspection requirements, the parties responsible for performing them, and the frequency for materials selection/mix design, test strip, and production/construction.
15. NMDOT is collecting cost and performance data as a function of time that can be used to communicate the successful use of recycling, as well as the sustainable benefits (cost savings, reduced environmental impacts and positive societal aspects).
16. NMDOT has identified many alternative uses of RAP to maximize the recycling or reuse of it. A recent very successful example is using ½” minus RAP for chip seals.
17. Learning from past experiences and integrating changes into design procedures and specifications for continuous improvement. This includes post-project team meetings to discuss challenges and identify solutions, as well as annual statewide meetings as needed.

ALTERNATIVE USES OF RAP

The most common use of RAP by NMDOT is in hot mix or warm mix asphalt in which up to 30 percent RAP may be used. Other uses include process place and compact (unstabilized FDR); aggregate base course containing up to 50 percent RAP; crushed RAP for chip seal aggregates; RAP in fill material including subbase containing 40 to 60 percent RAP; and contaminated asphalt milling not meeting NMDOT specification requirements is used to surface unpaved roads, medians, rest areas, crossovers, and extending shoulders. When using more than 50 percent RAP in aggregate base course, challenges in meeting density requirements occurred, thus the current maximum of 50 percent. Use of crushed RAP millings (1/2" minus) have led to cost saving and good performance for chip seals. They meet the gradation requirements and are precoated with binder. The RAP millings were tried in micro-surfacing, but it was not successfully.

RESEARCH ACTIVITIES AND RESEARCH NEEDS

Currently on-going research supported by NMDOT includes work to determine how to characterize FDR and CCPR for inclusion in mechanistic empirical pavement design, as well as ITS and HWTT for advanced materials characterization of all cold recycled materials. This research is being conducted at the University of New Mexico. Previous NMDOT sponsored research included determining binder and mixture aging rates and the effect of them on mixture and pavement cracking. [(52)]

NMDOT identified three research needs. They are the need for:

1. The ability to determine the rate of RAP aging while in stockpiles.
2. The ability to measure oxidation in existing asphalt pavements at highway speeds while collecting pavement condition data so the suitability of it for different applications can be determined.
3. A guideline for recycling 100 percent of RAP for the best possible use.

CLOSING REMARKS

NMDOT is actively and successfully using multiple sustainable cold asphalt recycling and hot in-place recycling techniques. Specifically, NMDOT uses FDR, CCPR, HIPR, and some CIR. The support of NMDOT and NMDOT staff that participated in this effort is greatly appreciated. The input provided revealed several positive practices that will be of significant value to other agencies.

CHAPTER 5 VIRTUAL SITE VISIT: NYSDOT

INTRODUCTION

There are about 239,000 total lane miles of public roads in New York State. [53] NYSDOT maintains and operates about 38, 400 lanes miles of roadway system that includes Interstate, Primary (U.S.), and State routes and some other routes in 11 NYSDOT Regions. About 19 percent is Interstates, 36 is NHS non-Interstates and the remaining 45 percent is non-NHS. The primary pavement types are asphalt over PCC (61 percent), asphalt (34 percent) and PCC (5 percent). NYSDOT predominately uses CIR and HIPR Heater Scarifying (HS) recycling techniques. It has used CCPR in the past although it has not been used much recently. It has over 20 years of successful experience using CIR. Heater Scarification (HS) is the most common used HIPR technique that began to be used about 15 years ago. The depth of scarification is limited to a maximum two inches, and it must be surfaced with a HMA overlay. The CIR and HS recycling techniques are used fairly consistently across 9 of the 11 NYSDOT Regions with the exceptions being Region 10 (Long Island) and Region 11 (New York City).

CIR and CCPR may be made with emulsion, polymer modified emulsion or foamed asphalt. Emulsion and foamed asphalt are used for routes with low Equivalent Single Axle Loads (ESAL), while polymer modified emulsion or foamed asphalt are used for routes with high ESALs. Polymer modified emulsions were introduced to address some raveling concern and NYSDOT has recently been using emulsion with one percent Portland cement, while observing similar performance.

CIR it typically three to four inches thick and at least one inch below the milling depth of asphalt pavement is left remaining above the underlying subbase or PCC to maintain adequate structure to support the CIR equipment and prevent milling into the Portland cement base. About 2.1 million square yards of CIR was constructed by NYSDOT in 2020, while about 3.7 million square yards was constructed in 2021. CCPR has been successfully used on limited basis on very old PCC pavements. It is primarily used at the local level. About two million square yards of HS is performed annually. NYSDOT indicated that the use of these recycling techniques has been pretty consistent over the years, with a noticeable increase in the use of HS in the last three to four years. Table 21 presents as summary of asphalt recycling techniques use by NYSDOT.

NYSDOT was noted that RAP supply and demand in the state are fairly well balanced, as large stockpiles are not observed.

Table 21. Summary of Cold Asphalt and Hot In-place Recycling Techniques use by NYSDOT.

Recycling Technique	Cold			Hot	
	CIR	FDR	CCPR	HIPR Heater Scarifying	HIPR Repaving
Use (percent of total use)	50 to 65	N/A	Less than 1 projects per year	35 to 50	N/A
Square Yards (million)	2 to 4	N/A	N/A	1 to 2	N/A
Cost per Square Yard	$5.74	N/A	N/A	$5.78	N/A
Districts Using	All except in NYC/LI	N/A	N/A	All except in NYC/LI	N/A
Years of Experience	> 20	N/A	> 5	> 15	N/A

NYSDOT indicated that keys to its successful recycling program are the ease of contracting associated with it, combined with the department's commitment to consistently having a sizeable program. The majority of paving work is done under simplified contracts intended to be fast and result in competitive bids. The office of general services (OGS) purchases general goods for the state (i.e., milk and other goods) and allows for purchasing of vendor placed paving (VPP) and free on board (FOB) methods. FOB is a term in commercial law that normally specifies when respective obligations, costs, and risk involved in the delivery of goods shift from the seller to the buyer. [(54)] With FOB contracts are 100 percent state funded a contract item can be chosen ala carte. Bids are done in an "auction" format. A statewide contract is used for NYSDOT and municipalities throughout the state. Municipalities have many benefits from efficiency and a NYSDOT vetted specifications. With VPP contracts federal funds can be used. Sites are identified in advance and contractors bid on individual mini-construction projects.

PROJECT/RECYCLING TECHNOLOGY SELECTION CRITERIA

The NYSDOT Comprehensive Pavement Design Manual (CPDM) has a primary purpose to provide designers with a single-source compilation of current Department policy and guidance pertaining to pavement designs for projects falling under the jurisdiction of the NYSDOT. [(55)] The CPDM Chapter 3: Pavement Evaluation and Treatment Type Selection Process is focused on the process to be used. This chapter includes the project-level pavement evaluation and treatment type selection process, which describes specific procedures and identifies when further documentation is required (e.g., a Pavement Evaluation, a Treatment Selection Report, a Life Cycle Cost Analysis). Table 3-1 of CPDM Chapter 3 shows the relationships among pavement treatments, funding sources, work type (preservation, rehabilitation or new construction or reconstruction), processing, and implementation. It provides the requirements for the minimum service lives, pavement evaluation, treatment selection, and life cycle cost analysis for all projects on the State

System and all Federal Aid projects (regardless of jurisdiction). CIR and CCPR are considered preservation work along with inlay/overlays. Heater scarification is identified as a preservation treatment with no traffic restrictions on the use of it. NYSDOT indicated that NYSDOT and many other public agencies in the state specify it.

The CPDM Chapter 5: Appendix 5A, Pavement Rehabilitation Manual, Volume II: Treatment Selection includes Treatment Guidelines for each treatment NYSDOT uses with sections on:

- Conditions for Use
- Constructability
- Performance
- Expected Failure Modes
- Expected Service Life

Typical sections of pavement rehabilitation technique are also illustrated.

In summary, the procedure for treatment selection includes 10 steps that leads to selection of the best treatment strategy based existing pavement condition, consideration of treatment alternatives, treatment design life, and estimated cost. NSYDOT indicated that adequate contractor capacity to perform cold asphalt and heater scarifying recycling techniques was available in the state with many years of experience, so it is not a consideration when selecting recycling methods.

STRUCTURAL PAVEMENT DESIGN

The NYSDOT pavement design procedure is based on the AASHTO Guide for Design of Pavement Structures 1993. The DOT has tried using the AASHTOWare Pavement ME Design for major projects for the past three years, noting that researchers created a series of tables to simplify use of the software, but this limited the effectiveness of it. NYSDOT indicated that existing pavement structures are typically very thick, so normally a formal pavement design is not conducted. However, if the site investigation identifies localized structural issues, then it is addressed with a planned additional deep section repair.

MATERIALS

Table 22 is a high-level summary of materials used in each recycling technique. Details can be found in References 56 through Reference 58.

Binders

For cold recycled asphalt emulsion, polymer modified asphalt emulsion (PMHAE) or foamed PG64-22 are used. High float emulsion (HFMS-2) is most frequently used, and CSS-1h has been used. PMAEI HFMS-2 polymer modified emulsion has been used also. Polymer dose in polymer modified emulsions is typically about one percent. Excess polymer has led to workability issues. Cement may not be used with polymer modified emulsions as the combination can result in poor workability. In some cases, PG58-22 has been used deeper in a pavement structure. For heater scarifying recycling agent or emulsified recycling agent may be used.

Table 22. Summary of Materials Used in each Recycling Technique.

Material Parameters	Recycling Technique				
	Cold			Hot	
	CIR	FDR	CCPR	HIPR Heater Scarifying	HIPR Repaving
Binders	Emulsion, PM Emulsion, PG64S-22 (foamed)	N/A	Emulsion, PM Emulsion, PG64S-22 (foamed)	Recycling Agent	N/A
Virgin Aggregate	0, 10 or 20%	–	≥ 10% & ≤ 20%	–	N/A
Active Fillers	1% Portland Cement	N/A	1% Portland Cement	N/A	N/A
Processed Recycled Material Top Size	< 2.0”	N/A	< 2.0”	N/A	N/A
Other Gradation Requirements	For mix design only	N/A	For mix design only	N/A	N/A
Other Aggregate Requirements	N/A	N/A	N/A	N/A	N/A

Active Fillers

Portland cement is the only active filler used in cold recycled asphalt mixtures. The dose is one percent by weight of RAP. Cement may not be used in combination with polymer modified emulsion. Active filler is not used with the HS recycling technique.

Processed Material Gradations

For CCPR NYSDOT provides RAP stockpiles or the contractor may generate them. The only gradation requirement is that 100 percent pass the two-inch (2-in.) sieve. For HS recycling there are no gradation requirements.

MIXTURE DESIGN

NYSDOT requires that contractors have mix designs performed in AASHTO Re:Source accredited laboratories. NYSDOT staff indicated that thorough site investigation to understand site variability and engineering analysis is an important step in selecting projects that will include recycling techniques and for mix design purposes. Figure 11 is a flowchart illustrating the cold recycling sampling and mix design preparation process based on NYSDOT Materials Method 416. [(56)] Figure 12 is a flowchart illustrating how material and processes are selected for cold recycle mix designs among emulsion, polymer modified emulsion, emulsion with cement, if virgin aggregate is needed and whether or not foamed asphalt may be used. Traffic, rate of stabilization, and moisture conditions are factors used to guide materials selection. It was noted that there are adequate experienced contractors in the state to perform cold recycling and that some Regions may prefer foamed asphalt over emulsion.

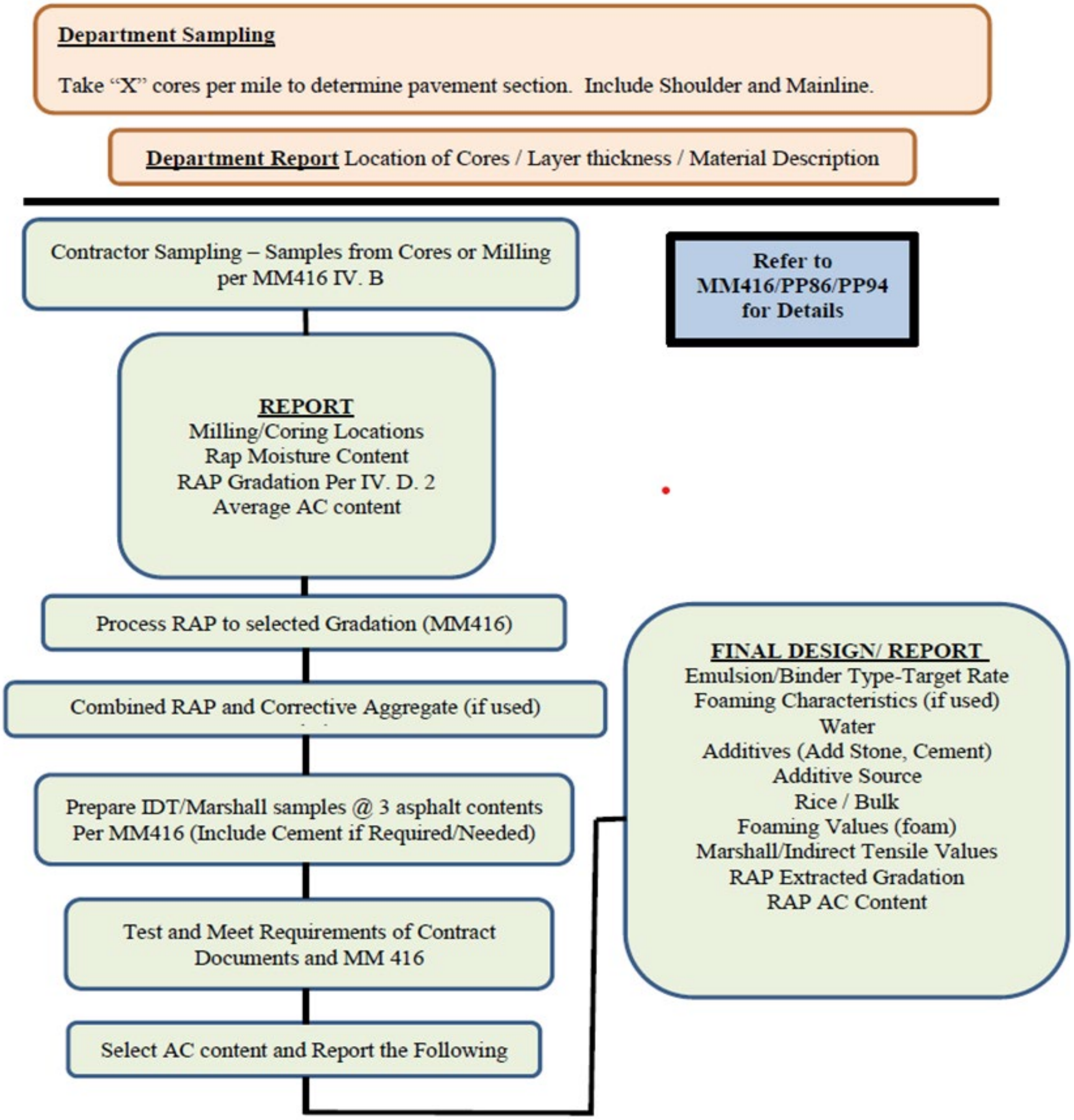

Figure 11. Chart. NYSDOT Cold Recycling Sampling and Mix Design Preparation Flowchart.

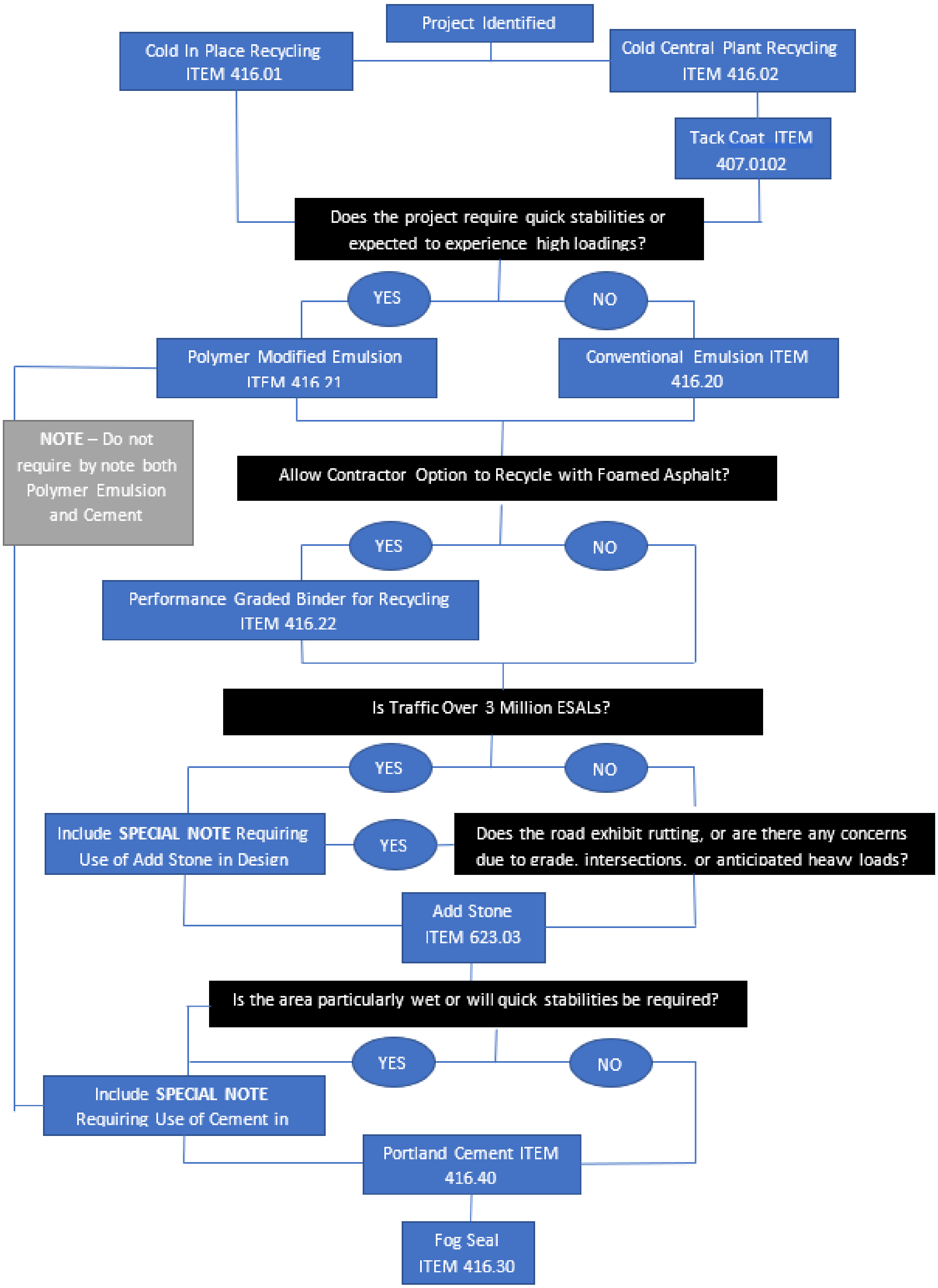

Figure 12. Chart. NYSDOT Flow Chart for Cold Recycling Item Selection.

Sampling for cold recycled asphalt mix design is performed by the contractor and can be conducted by obtaining 6-inch diameters cores or millings. [56] Table 23 shows the number of cores per project as a function of recycling depth and shoulder conditions. The depth of coring must be beyond the planned recycling depth. Cores are to be taken at equal distance apart along travel lanes and shoulder in both directions. For CCPR the method of sampling for CIR may be used or RAP stockpiles can be sampled per AASHTO PP 86, Section 5.2. [23] If millings are taken it is per AASHTO PP 86, Section 5.1.3. and Note 3.

Table 23. Total Number of Cores Per Cold Recycled Project. [56]

Depth of Recycling	Travel Lanes without Shoulders	Travel Lanes with Shoulder	
Travel Lanes		Shoulders	
3”	27	20	7
4”	20	15	5

For HS recycling three cores per lane mile or a maximum of 20 cores per project are sampled from the existing HMA pavement. These cores are to be from locations that represent the entire project condition. Representative RAP material samples for from either cores or milling are obtained by sieving RAP to AASHTO PP 86, Section 5.3., except processing RAP to model and meet gradation ranges in Table X (IV-3) are revised to those in Table 24 below.

Table 24. CIR/CCPR Process RAP Mix Design Gradation Controls.

Sieve Size	Percent Passing
¾”	75 - 100
#4	50 - 65
#30	10 - 30

Cold asphalt mix designs are specified in NYSDOT Material Method 416-1, and they rely heavily on AASHTO provisional practices and provisional specifications with some changes. [21, 22, 23, 24, 56] Cold recycled asphalt mix designs with emulsion are developed per AASHTO PP 86 and have to meet the requirements of AASHTO MP 31, with the exception of the raveling and ratio of residual asphalt to cement ratio requirements. Cold recycled asphalt mix designs with foamed asphalt are developed per AASHTO PP 94 and have to meet the requirements of AASHTO MP 38 with the exception of the raveling and ratio of residual asphalt to cement ratio requirements.

Table 25 is a high-level summary of mix design requirements for each recycling technique. Details can be found in References 21 through 24, 56 and 57. Marshall compaction is used for CIR/CCPR with 75 blows per face.

Table 25. Mix Design Summary Information.

Mixture Design Parameters	**Recycling Technique**				
	Cold			**Hot**	
	CIR	**FDR**	**CCPR**	**Heater Scarifying**	**HIPR Repaving**
Compaction method	Gyratory (6”)	N/A	Gyratory (6”)	N/A	N/A
Gyrations / Blows	30	N/A	30	N/A	N/A
Curing	PP 86 or PP 94	N/A	PP 86 or PP 94	N/A	N/A
Compaction Temperature (°F)		N/A		N/A	N/A
Binder dose selection	ITS_{dry} or RMS	N/A	ITS_{dry} or RMS	≥30% more than existing HMA Penetration (T 59) up to ≤90%	N/A
Coating	N/A	N/A	N/A	N/A	N/A
Raveling Test	N/A	N/A	N/A	N/A	N/A
Moisture Density Relationship	N/A	N/A	N/A	N/A	N/A
Moisture Sensitivity Test	CIR Emulsion TSR or RMS ≥70% Foamed CIR TSR or RMS ≥60% TSR or RMS ≥70% ≥60% or ≥70%	N/A	CCPR Emulsion TSR or RMS ≥70% Foamed CCPR TSR or RMS ≥60%	N/A	N/A
Rutting Test	Marshall Stability (dry) ≥ 1250 lbs	N/A	Marshall Stability (dry) ≥ 1250 lbs.	N/A	N/A
Cracking Test	ITS_{dry} ≥ 45 psi	N/A	ITS_{dry} ≥ 45 psi	N/A	N/A

Test specimens are prepared at three binder contents. The basis for optimum binder content is up to the contractor and is selected either based minimum dry indirect tensile strength (ITS_{Dry}) or tensile strength ratio (TSR) (AASHTO T283) or Retained Marshall Stability (RMS). If selected by NYSDOT minimum dry tensile strength is used. For CIR/CCPR NYSDOT uses a multiple index-based performance tests for cracking, rutting and moisture sensitivity. The Hamburg Wheel Track Test (HWTT) has been performed by NYSDOT for experimental and informational purposes. It was reported that in the dry condition good rutting performance has been observed with about 5000 wheel passed prior to 12.5 mm of rutting at 50°C. However, in the wet condition performance was not as positive at 50°C. Future testing is planned in the wet condition at room temperature.

For heater scarified recycling the only mix design requirement is that the selected recycling agent and dose result in a recycled mixture recovered binder penetration of greater than 30 of but less than 90 percent of the existing HMA prior to HS recycling.

FIELD CONSTRUCTION & ACCEPTANCE

Mix Design Changes During Construction

Some State DOTs and contractors have faced challenges with making mix design changes during construction. For cold recycled asphalt the NYSDOT specification allows for field changes in 0.05 to 2.0 percent increments and if changes exceed 10 percent of a design rate it must be approved by a Regional Materials Engineer. The allowable changes are summarized in Table 26. NYSDOT indicated that the biggest changes are normally need due to ambient temperature changes. Recycler or paver speed is controlled at 30 feet per minute to keep gradation consistent and keep the working zone compact. For HS recycling NYSDOT indicated less changes are common, though slight increases in RA dose are needed at times.

Table 26. Maximum Binder and Minimum Water Tolerances.

Depth of Cold Recycle	Emulsion		PG Binder	
	Maximum Emulsion (gsy)	Minimum Water (gsy)	Maximum PG Binder (gsy)	Minimum Water (gsy)
3-inch	≤ 1.45	≥ 0.36	≤ 1.09	≥ 0.72
4-inch	≤ 1.93	≥ 0.48	≤ 1.45	≥ 0.96

Note: gsy: gallons per square yard

Test Strips

Test Strips are required by NYSDOT for cold recycling to establish project target density.

Quality Control and Acceptance

Cold Recycled Asphalt

NYSDOT requires the following QC testing for CIR/CCPR. Corrective aggregate moisture content, gradation and rate validation (shovel and weight). Water, emulsion rate and temperature for emulsified asphalt. For foamed asphalt foam rate, water rate, PG binder temperature, expansion and half-life. For emulsified and foamed asphalt cement rate, milling depth, moisture content, asphalt content and gradation of recycled mixture, and paving tolerance are measured. On the first day of paving the frequency is increased for some measurements.

In addition to QC, at the beginning of a project the contract has to perform mix design verification testing. It includes theoretical maximum specific gravity, bulk specific gravity, air voids, IDT and TSR, as well as Marshall Stability and Retained Marshall Stability. The only difference in QC for CIR and CCPR is that CCPR requires stockpile gradations be performed.

For cold recycled asphalt one sample of emulsion or PG binder is sampled and tested per day for Acceptance. An expansion/half-life test is required once per day. Compaction of cold recycled asphalt is to be in accordance with section 402-3.07 C 70 Series Compaction Method and Table 416-2 of the Standard Specifications. [(56)] The peak density measured with a nuclear density gauge is the project target density (PTD). If two consecutive density readings are less than 96%, or greater than 110% of PTD, then a new PTD has to be established and approved by the Engineer. The minimum required passes with specific roller types are summarized in Table 27.

Table 27. Cold Recycled Asphalt Minimum Roller Pass Requirements.

Compaction Sequence	Roller Type	Compaction Type	Minimum Number of Passes
Initial	Steel or Pneumatic[1]	Vibratory or Static[2]	2
Intermediate	Steel or Pneumatic[1]	Vibratory or Static[2]	2
Finish	Steel	Static	2

[1] Either the initial or intermediate passes will use a pneumatic roller.

[2] Either the initial or intermediate passes will use a vibratory compaction.

The contractor is responsible for developing a Materials Management Plan (MMP) that explains and documents mix design and project specifics including planned quantities, equipment, and drawings. It also addresses corrective actions to be implemented for each item in the MMP.

The basis for payment for cold recycled asphalt is summarized in
Table 28.

Table 28. Cold Asphalt Recycling Techniques Payment Schedule.

Pay Item	Unit
Cold In-Place Recycling Asphalt Pavement	Square Yard
Cold Central Plant Recycling Asphalt Pavement	Square Yard
Asphalt Emulsion for Recycling	Gallon
Polymer Modified Asphalt Emulsion for Recycling	Gallon
Performance Graded Binder for Recycling	Gallon
Fog Seal	Gallon
Corrective (virgin) Aggregate	Ton
Portland Cement	Ton

Heater Scarifying

For heater scarify recycling acceptance is based on the recovered recycled asphalt penetration being greater than or equal to 30% more than existing pavement recovered Penetration (AASHTO T 59) and less than or equal to 90% of the existing pavement recovered Penetration. On the first day of production two cores are taken at two locations prior to scarification and four loose mix samples are taken at each core location. Recovered penetrations are measured on all of them. In subsequent production one in three days the same sampling and testing performed the first day is performed.

In-place density is specified in Section 402-3.07 80 Series Compaction and is the number of passes in shown in Table 29. A vibratory pass is defined as one movement of a roller over the pavement with both drums vibrating. In vibratory mode steel wheel roller must impart a minimum of 12 impacts per foot. A static pass is defined as one movement of a roller over the pavement. Where static compaction is required, an oscillatory Roller used in oscillation mode may be used in lieu of a pneumatic roller.

Table 29. Heater Scarification Compaction Requirements.

Pavement Courses	Static Compaction		Vibratory Compaction	
	Steel Wheel Rollers	Pneumatic Rollers	Vibratory Passes	Static Passes
≥3”	8	4	4	4
>1” to < 3”	6	3	3	3
≤ 1”	4	2	2	2
Type 5 Shim	2	-	-	-
Permeable Base	2	-	-	-

The basis for payment of HS recycled pavement is per square yard.

Curing and Opening to Traffic

NYSDOT specifications have minimum cure times for cold recycled asphalt. If asphalt emulsion is used the minimum cure time prior to being overlaid is 10 days, while is foamed asphalt is used the time is reduced to a minimum of 3 days. Cold recycled asphalt must be overlaid with 30 days of placement. The contractor is responsible for maintaining it until the overlay is placed. A fog seal at a maximum application rate of 0.1 gallons per square yard may be applied. The fog seal is recommended when rain it anticipated or if raveling is observed.

Lessons Learned

The extensive NYSDOT experience with cold recycled asphalt and heater scarifying techniques has revealed several important lessons learned. They include the following:

- NYSDOT indicated that keys to its successful recycling program are the ease of contracting associated with it, combined with the Department’s commitment to consistently having a sizeable program. The majority of paving work is done under simplified contracts intended to be fast and result in competitive bids. The OGS purchases general goods for the state (i.e., milk and other goods) and allows for purchasing of VPP and free on board FOB methods for 1R projects.

- NYSDOT indicated that VPP and FOB contracting mechanism does not work for 2R or 3R projects and as such limits the use of the cold recycled asphalt technologies that would work well on projects with federal funding including Interstates.
- NYSDOT is successfully re-recycling cold recycled asphalt and the time between re-recycling is about 15 years.
- Emulsion with one percent Portland cement active filler provides similar performance to polymer modified emulsion without active filler. Contractors noted a preference for use of polymer modified emulsion to eliminate an additional supply chain item. Different contractors have different equipment and preferences; thus, the contractor is allowed to decide if emulsion or foamed asphalt will be used.
- Index-based performance tests like the HWTT may be useful tools for designing cold recycled asphalt, but appropriate test conditions (conditioning and temperature) need to be determined specifically for these materials and sensitivity of the tests to anticipated field variability needs to be better understood before they could be included in specifications.
- MMP requirement for CIR to communicate quantities planned on being used to document planned grade control, cross section issues, etc. is very effective at clarifying issues prior to going to construction.
- Documented Pre-Recycling Meetings have been successful in identifying potential project challenges and addressing them, so the projects proceed more smoothly
- An annual stakeholder meeting takes place at the end of each season where NYSDOT and contractor personnel meet openly to discuss challenges and opportunities has led to improvements in materials, test methods, specifications, and constructability.

PAVEMENT PERFORMANCE AND COST

There are many options available for rehabilitating a pavement in need. Selection of the most appropriate and cost-effective alternative is an important engineering decision. NYSDOT does a preliminary life-cycle cost analysis to compare the cost of in-place recycling versus the pavement life. In-place recycling is commonly justified and often selected as the preferred treatment.

NYSDOT reported overall good performance with the cold asphalt recycling techniques. No information was provided on the heater scarifying technique. For CIR it was that suggested that prior to overlay some raveling may occur but rutting or shoving were rare. Over time eventually distresses in the pavement below the CIR at the time of construction would come back (i.e., soft subgrade) or cracking. However, the time for the distresses to appear was reported as longer than in the pavement rehabilitation had been straight overlay instead of CIR with overlay. The NYSDOT PMS includes a code to identify pavements with recycled layers. However, it was reported that the PMS is not always accurate and cracking in the PMS is subjective because the initial condition (prior to CIR) is not always captured. However, rutting can be captured accurately, but it is not an issue with NYSDOT pavements.

Furthermore, when comparing performance with and without CIR it was reported that the CIR retards crack propagation. An example of four roads near one of the NYSDOT interviewees home was shared with indication that local, side-by-side comparisons, show really good results for the

CIR. However, they indicated that multiple factors need to be considered to explain each unique pavement situation which requires looking at a lot of details that do not exist in a PMS. Another positive report was that NYSDOT is observing good performance of re-recycled CIR with the time between recycling being about 15 years on average.

It was indicated that there are several benefits with CIR including:

- Not generating a RAP surplus in the state.
- Structures with CIR are more robust than 1.5 or 2-inch mill and fills.
- Thirty to 40 percent initial cost savings over the conventional alternatives (overlay or mill and overlay).
- Opportunity to make deeper repairs in the pavement structure than with conventional alternatives.
- Many of the roads are lower volume, less than six million ESAL or less than three million ESALs, and use of CIR allows for a pavement that lasts longer and the time in years between construction cycles extended.
- The construction time for CIR is slightly slower or the same as conventional mill and fill.
- CIR offer sustainable benefits that are not always recognized that include conservation of natural resources (asphalt binder, aggregates) and a significantly reduced carbon footprint because the materials are recycled in-place.

CONTRACTOR PERSPECTIVES

With the COVID-19 Pandemic leading to virtual site visits, it was not possible to visit construction projects in New York. NYSDOT arranged for virtual interviews with a limited number of contractors to obtain their perspective on cold recycled asphalt and heater scarifying. Three contractor representatives participated in the cold recycled asphalt discussion, and one participated in the heater scarifying discussion. Multiple NYSDOT representatives participated in both interviews. A set of seven open end questions were asked and each contractor had the opportunity to respond to each question.

The questions and summary of response follow associate with ***cold asphalt recycling*** follow:

1. **Is the number of recycling projects let in the State each year well balanced with number of recycling contractors operating in the State?**
   The same contractors perform work for NYSDOT and municipalities. There is capacity for more NYSDOT work. The breakdown of NYSDOT and municipalities is typically about 50:50. NYSDOT lets fewer projects, but larger projects. When NYSDOT has additional funds, CIR is a fast way to get projects out and thus more NYSDOT projects are available to purse. It is important to be cautious about seasonal start dates in such years.

2. **Is there less bidding competition on DOT projects with recycling techniques than on other conventional paving projects?**
   There are fewer recycling contractors, only three, than those that do conventional paving. All three recycling contractors are vertically integrated with their own emulsion supply. If a project is CIR with an overlay, paving contractors use CIR subcontractors.

NYSDOT gets a competitive bid. The recycling contractors also work in neighboring states which helps build the market. In the 1980's a New York contractor visited New Mexico to learn more about the success there and brought back what they learned and shared it with NYSDOT and promoted it in much of the northeast as well.

3. **Do challenges or risks exist when transitioning from lab mix design to production start-up in the field or during production?**
   Specifications are still evolving and NYSDOT allows for changes in the field. Contractors have materials on the road and must make them work even though the materials on road are variable. The current NYSDOT process works well. The mix design is a starting point and field experience to understand what is happening is critical to success. The DOT has to be flexible within reason because of the material is variable, and that can be challenging for an agency initially.
   The mix design is a "warm fuzzy" check. Stability and TSR and very important. Early stability and cure are extremely important to prevent performance issues. Mix designs are helpful for getting unexperienced people more comfortable with CIR. Judgement and experience can't be forgotten in the process. Drainage issues are the biggest failure mechanism at the present time, which may warrant more attention in the future.

4. **Are there examples of techniques or production best practices used by contractors or DOT staff to make mixture adjustments during production that are not in DOT specifications, but could be to allow for rapidly acceptable changes to improve mixture quality?**

   Having flexibility to make adjustments during production is very important to success. With relatively small projects, it can be a challenge to get verification results prior to project completion for certain tests like TSR. Contractors have labs to do design and verification. Verification (including TSR) is done at start up and then monitored regularly throughout a project by contractor performed QC. Time window for receiving verification test results is an item for further discussion. This is a complicated discussion. Better field QC and acceptance is an area for ongoing and future research.

5. **Are there recommended best practices for answering the question, "How does an agency know it is getting the proper proportions of mixture components in recycled mixture?"**
   Using large enough quantities of supplemental virgin aggregate so it is possible to accurately track the square yardage being placed. Spread rates are calculated, depth of milling is known, and density is known.
   Mass flow meters are used and are very consistent. They can be sensitive to densities. When changing emulsion supplier, the specific gravity changes. It is also important to know the pavement density.
   NYSDOT requires that water is metered when emulsion and foamed asphalt are used. This is particularly important with foamed asphalt. Mass flow meter are required and helpful. It is also important to know the RAP moisture content.

6. **<u>Is there a mechanism(s) in place that allow for training/knowledge transfer, review of lessons learned, and partnering on improvements with DOT and contractor stakeholders participating?</u>**
   Liquid Asphalt Distributor Association (LADA) is a good entity for coordinating sharing of lessons learned and review of specification changes. This includes agency, contractors, and suppliers. There is a recycle committee that focuses on CIR. There may be a sense of competition between LADA and Associated General Contractors (AGC) member companies. A paving conventional contractor may prefer see reconstruction projects or add multiple overlays than in-place recycle with a thin overlay. Recycling contractors are subcontractors to paving contractors and may be viewed as additional work to a paving contractor.
   Training is done individually within each company.

7. **<u>What are some of future activities that could help support successful use of recycling technologies?</u>**
   Getting answers to the following questions would be helpful:
   - How much traffic can CIR really handle?
   - How can field QC be improved?
   - What new techniques and emulsions could/should be implemented

   Educating prime contractors about the benefits of using recycling technologies with a focus on the sustainability benefits of CIR, especially related to carbon footprint goals. Implementing use of environmental production declarations (EPDs) to illustrate the sustainable benefits of CIR. A key is to making CIR projects last even longer, like 3 to 4 more longer. NYSDOT has taken a step in this direction with the use of polymer modified emulsions. Use of Portland cement works well in areas with water (drainage) issues compared to polymer. It would be helpful if FHWA could put together a pool of industry experts (nationally or locally) to provide assistance (pre-planning to acceptance) for those with needs. This would keep the recycling process healthy and provide knowledge transfer.

The questions and summary of response follow associate with ***<u>heater scarification recycling</u>*** follow:

1. **<u>Is the number of recycling projects let in the State each year well balanced with number of recycling contractors operating in the State?</u>**
   There is only one HS contractor that performs work for NYSDOT and municipalities. There is capacity for more NYSDOT work, as the contractor does some work (about 10 percent of total) in neighboring states. The company has four trains and will be adding another. The breakdown of NYSDOT and municipalities is typically about 60:40.

2. **<u>Is there less bidding competition on DOT projects with recycling techniques than on other conventional paving projects?</u>**
   Other out of state recycling contractors have come into the market that helps with competition. However, heater scarification essentially bids against itself. If the bid price is too high, NYSDOT Regions will choose other options with the unique contracting methods available for Preservation work. So, there is not direct recycling contractor

versus recycling contractor bidding competition, but other preservation options the keep price in check. The industry has capacity to get work done that is advertised.

3. **Do challenges or risks exist when transitioning from lab mix design to production start-up in the field or during production?**
The key to preventing challenges is to identify the correct recycling agent dose in mix design and on start up to add slightly more than identified in the mix design. If correct, at start up minor tweaking may be necessary, but in general it has been a smooth transition. The turn around time on recovered penetration is within 24 hours and the recycling agent suppliers do the testing in the same labs the mix designs are performed in.

4. **Are there examples of techniques or production best practices used by contractors or DOT staff to make mixture adjustments during production that are not in DOT specifications, but could be to allow for rapidly acceptable changes to improve mixture quality?**
A lot of visual monitoring is important look for dryness or flushing. Using test results to know where production is.

5. **Are there recommended best practices for answering the question, "How does an agency know it is getting the proper proportions of mixture components in recycled mixture?"**
Calibrated meters are critical, along with verification of their performance every 90 days. At end of each day, yield is calculated and provided to the inspector. Inspector can verify this based on quantities. Recycling agent certifications are provided to NYSDOT and updated as appropriate. These work well.

6. **Is there a mechanism(s) in place that allow for training/knowledge transfer, review of lessons learned, and partnering on improvements with DOT and contractor stakeholders participating?**
Communication between NYSDOT and industry is excellent and important. Industry is always willing to provide presentations and information to those wanting more background (e.g., new State staff or industry people). The New York Construction Materials Association represents all industries (asphalt plants, quarries, etc.). Paving contractors are AGC member and CIR contractors are LADA members.

7. **What are some of future activities that could help support successful use of recycling technologies?**
Growing the market with education and exposure to the HS process. Sharing pavement performance successes. Actively reaching out to newer engineers and asking them to make field trips to demonstration projects so they see technologies that are options. Agencies have lost a lot of people and experience through retirements. New staff are not as familiar with newer processes, so they need to be shared with them. With NYSDOT a lot of communication is informal. Formal training is available upon request or when a need is identified. It is important not to over-promote products and it is important to encourage making the appropriate treatment selection for each project. Consulting engineers puts a lot of municipality projects together and have a lot of

influence on treatment selection. Because consultants are heavily used it is a challenge to keep agency staff knowledgeable.

Treatment selection is important, and the ideal candidate is a structurally sound pavement that is in between a mill and fill and not quite to the point of a CIR candidate. HS surfaced with hot mix is a very good treatment. HS with a chip seal can be done successfully but has had mixed performance.

Appropriate HS equipment with automated grade controls is important to success. Smoothness requirements on final riding surface depend on project as there is only so much grade correction that can be done with HS and a thin overlay, so ride quality is really project dependent. Interlocked speed and metered recycling agent are important. Depth can be controlled with 1.25 to 1.5 inches typical, though 2 inches can bd achieved. Finally, safety controls for propone cut-offs are important.

NYSDOT BEST PRACTICES

Throughout the visit, several NYSDOT best practices were identified that included the following:

1. Having very recently updated recycling technology specifications that are very clear and concise that have been modified based on DOT and industry experience and input.
2. Referencing NYSDOT standards, as well as relying on AASHTO provisional standards, when possible, makes is easier to obtain consistency across geographic regions.
3. Keys to NYSDOTs successful recycling program are the ease of contracting associated with it, combined with the department's commitment to consistently having a sizeable program. The majority of paving work is done under simplified contracts intended to be fast and result in competitive bids. Several million square yards are constructed annually.
4. A statewide contract is used for NYSDOT and municipalities throughout the state. Municipalities have many benefits from efficiency and a NYSDOT vetted specifications while both the entities, and contractors, benefit from a sizable annual program.
5. Having a CPDM with the primary purpose to provide designers with a single-source compilation of current Department policy and guidance pertaining to pavement designs for projects falling under the jurisdiction of the NYSDOT. The guidance provided reflects the collective experience of the Department of Transportation, the American Association of State Highway and Transportation Officials, and the Federal Highway Administration. The CPDM Chapter 5: Appendix 5A, Pavement Rehabilitation Manual, Volume II: Treatment Selection includes Treatment Guidelines for treatments NYSDOT uses with sections on:
   a. Conditions for Use
   b. Constructability
   c. Performance
   d. Expected Failure Modes
   e. Expected Service Life
6. NYSDOT equipment specifications and calibration procedures with verification are very clear and rigorous.
7. NYSDOT requires that mix designs be performed in AASHTO Re:Source accredited laboratories.
8. Having rigorous mix design requirements that include completing mix designs 2 weeks in advance of construction.

9. Using a comprehensive CIR/CCPR mix design method that includes index-based performance tests.
10. For cold recycled asphalt a Materials Management Plan is required to communicate quantities planned on being used, to document planned grade control, cross section issues, QC and identify potential challenges and corrective actions that must be submitted prior to the project Pre-Recycling Meeting to clear up confusion.
11. For cold recycled asphalt a Pre-Recycling Meeting is required with the engineer, regional materials engineer and recycling contractor foreman present from which minutes are distributed to each party clarifying expectations.
12. NYSDOT cold recycled asphalt specifications include maximum binder and minimum water tolerances in production.
13. For raw materials supplied to projects the AECTA (binder emulsion certifications) and documented quantities are supplied to the RE for each shipment.
14. For HS recycling each load of recycling agent must be accompanied by certified test result and documented quantities provided to the Engineer.
15. For HS a mass flow meter and measuring system capable of maintaining the RA application rate with 5 percent is required. The measuring system has to continuously verify and display the RA application rate and cumulative total with respect to the volume of scarified material for the road surface and has led to reduce need for calibrations and temperature corrections.
16. NYSDOT has identified alternative uses of RAP to maximize the recycling or reuse of it. CIR, up to 30 percent RAP in HMA, some is used for shoulder backing and some municipalities use some for patching materials. The potentially for using RAP for chip seals is also being evaluated.
17. NYSDOT and municipalities needs combined provide a sustainable market for recycling contractors and a single specification used by NYSDOT and municipalities makes it easier for recycling contractors to do work in the state.
18. There is adequate recycling contractor capacity in the state for the work let annually and competition is healthy.
19. Learning from past experiences and integrating changes into design procedures and specifications for continuous improvement is a healthy process in New York. This includes annual DOT and contractor meetings facilitated via an industry supplier association with the goal of continuous improvement.

ALTERNATIVE USES OF RAP

Most HMA produced in the state includes RAP. Surface mixtures typically include 20 percent RAP and base mixtures typically include 30 percent RAP, which is considered conservative by some. The potential use of recycling agents to increase RAP in HMA has been recently discussed, but not used to date. Use of crushed RAP millings for chip seals is currently being examined, as other states are reporting good performance coupled with cost and virgin material saving. Additionally, some RAP from CIR is used for shoulder backing and some municipalities use some for patching materials.

RESEARCH ACTIVITIES AND RESEARCH NEEDS

NYSDOT has conducted a lot of in-house research related to cold asphalt recycling. Recent efforts have focused on comparing NYSDOT test results with contractor test results. The Hamburg Wheel Track Test (HWTT) has been performed by NYSDOT for experimental and informational purposes on CIR. It was reported that in the dry condition good rutting performance has been observed with about 5000 wheel passed prior to 12.5 mm of rutting at 50°C. However, in the wet condition performance was not as positive at 50°C. Future testing is planned in the wet condition at room temperature. NYSDOT has also been participating in NCHRP Project 09-62 research efforts with real time in-place shear and raveling tests performed along with moisture measurements to see if the tests could be used determining when a CIR could be opened to traffic and surfaced, rather than using time bound curing periods. NYSDOT is also a pooled fund member on a NCAT/MnROAD effort looking a method of obtaining more consistency of materials and testing as well as inspection activities.

NYSDOT identified the following research needs:

- The ability to better understand the sensitivity of performance tests (index-based and performance based) to inherent variability that will occur in production. Specifically, there is a current engineering focus on improving mixture performance by using performance tests for design and potentially construction. However, some items like the difference in lab mix design RAP gradations and field produced millings gradations for CIR can have a significant impact on CIR measured with lab performance tests, but this variation in gradation is anticipated. Thus, it is important to understand the sensitivity of performance tests to that variability in production so that rational design and acceptance criteria can be established for the performance tests.
- Contractors interviewed suggested that better field QC and acceptance is an area for ongoing and future research with a focus on more rapid test turnaround time (TSR was an example noted).
- A pooled fund project is need that would provide support for DOT participation and travel expense for ARRA meetings to share knowledge and learn from peers.

CLOSING REMARKS

NYSDOT is actively and successfully using sustainable cold asphalt recycling and hot in-place recycling techniques. Specifically, NYSDOT uses CIR, some CCPR, and Heater Scarifying. The support of NYSDOT and NYSDOT staff that participated in this effort is greatly appreciated. The input provided revealed several positive practices that will be of significant value to other agencies.

CHAPTER 6 VIRTUAL SITE VISIT: SCDOT

INTRODUCTION

The SCDOT roadway system includes Interstate, Primary (U.S.), and Secondary (lower volume) routes. It is comprised of about 90,700 lane miles (approximately 41,000 centerline miles), with about 70 percent of the traffic on Primary and Secondary routes. The approximate lane miles breakdown by pavement type is 73 percent flexible pavement, two percent rigid, 20 percent composite and 5 percent unsurfaced. SCDOT focuses on the use of Cement Modified Recycled Base (CMRB), what some other agencies refer to a FDR with cement. SCDOT is a leader in the use of this in-place recycling method with over 30 million square yards having been constructed since 2013 as shown in Table 30 and Figure 13. Table 30 shows the total square yards constructed each year and the square yards of different CMRB thicknesses constructed. Thicknesses of 8, 10, 12, and occasionally 14 inches are constructed today, although 12 inches is most common, and 6 inches is rarely used. When an overlay is planned on routes other than Interstates or thick high volume primary routes, and over 15 to 20 percent patching is required, CMRB is very commonly used.

CMRB was first used by SCDOT in 1995 in District 4. (59) Use spread across the state in the surrounding Districts and is now used in all Districts. However, it is most commonly used by Districts in the northern and western portions of the state, as shown in Figure 14, because these Districts have been willing to implement the technology more rapidly. CMRB is used on secondary routes to Interstates, with secondary and primary routes being the most common applications. It is not often used on Interstates but has been with a key to success being having the ability to stage the use of the recycling process on larger volume routes. CMRB was used for an Interstate project in 2020 that included a shoulder widening with some RAP milled off, and aggregate base added. SCDOT is currently considering the use of FDR foamed asphalt due to desired depth and cure time. SCDOT indicated that the balance between RAP supply for HMA and demand depends on location, noting that contractors in urban areas that perform a lot of Interstate work have sufficient RAP but there are indications from rural contractors that do not perform a lot of Interstate work that demand exceeds available supply. Over half of the paving contractors in the state also self-perform FDR, so it appears to be being embraced by paving contractors. Finally, pre-milling prior to FDR may be performed for constructability which does prove additions RAP supply.

Table 30. Awarded CMRB in Square Yards Annually by Thickness Since 2013.

Calendar Year	Awarded CMRB Amount (SY) by Thickness					
	6"	8"	10"	12"	14"	Total
2013	-	899,977	729,548	0	0	1,629,525
2014	29,093	1,691,480	1,901,918	71,050	0	3,693,541
2015	212,478	2,525,937	1,755,809	0	0	4,494,224
2016	16,380	2,426,815	1,208,235	1,515,790	0	5,167,220
2017	70,366	240,244	177,112	3,253,312	0	3,741,034
2018	0	358,074	631,579	2,861,533	49,938	3,901,124
2019	0	198,264	544,760	2,170,250	0	2,913,274
2020	0	981,061	1,659,985	3,675,126	15,840	6,332,012
Sum	***328,317***	***9,321,852***	***8,608,946***	***13,547,061***	***65,778***	***31,871,954***

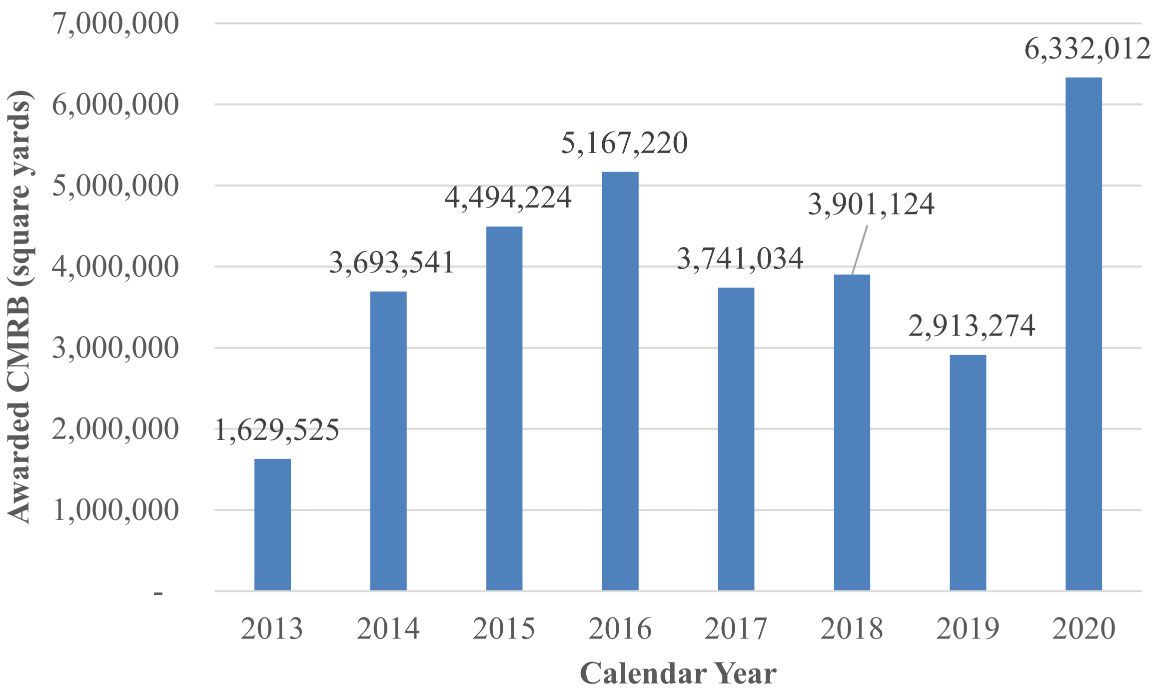

Figure 13. Chart. Awarded CMRB in Square Yards between 2013 and 2020.

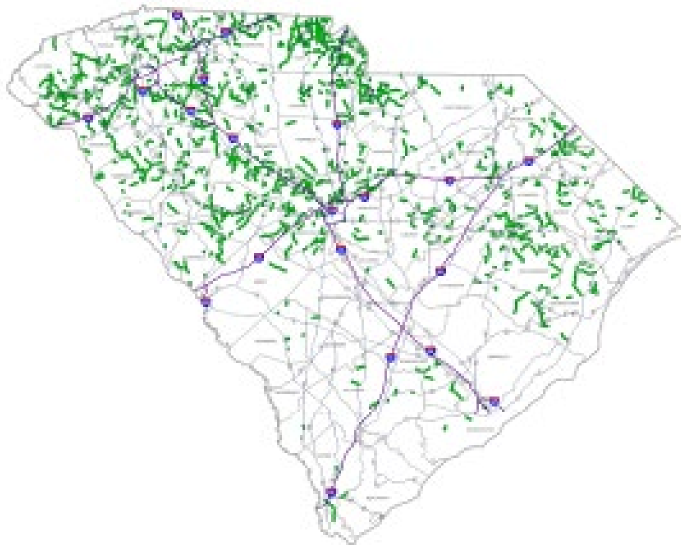

Figure 14. Map. Distribution of CMRB projects in South Carolina.

PROJECT/RECYCLING TECHNOLOGY SELECTION CRITERIA

SCDOT indicated that the driving factor on rehabilitation / reconstruction for the majority of routes that would use FDR with cement is based on lowest initial cost due to the existing condition or required structure of the road, and feasibility of using FDR in the construction process given existing pavement cross section and Management of Traffic (MOT) requirements.

Selection is primarily between CMRB versus traditional mill and fill at this time. Individual investigations for routes deemed to be potential candidates for other treatments would need to be performed. A decision to switch to from traditional mill and fill to FDR would be based on depth of distresses and existing versus required structural needs. As previously mentioned, when patching needs exceed 15 to 20 percent, then CMRB is very commonly used because it is more cost-effective, and it results in a uniform pavement structure. Traffic is indirectly considered since extended lane closures are only use for major projects. With CMRB only one lane is constructed at a time and opened at end of day. CMRB is not performed on concrete pavements. SCDOT indicated that there is adequate contractor availability in the state to construct CMRB across the state.

STRUCTURAL PAVEMENT DESIGN

The SCDOT pavement design procedure is based on the AASHTO Guide for Design of Pavement Structures 1972, and the layer coefficient (a_i) assigned to CMRB is 0.26. SCDOT indicated that the layer coefficient value was selected based on research associate with the first SCDOT CMRB project. [59] Research by the Texas Transportation Institute and the Portland Cement Association has permitted SCDOT to apply more mechanistic review that allows for less of an empirical process. It has allowed SCDOT to modify both depths and strengths. [60] The same resource led SCDOT to consider reducing the amount of cement in CMRB and using it in increased thicknesses. The structural design method is considered to be conservative and for project specific conditions, with high traffic, the required structural number may be adjusted based on mechanistic empirical analysis. The primary material properties used to assess CMRB are density and unconfined compressive strength as detailed in *Standard Method of Test for Sampling, Preparing and Testing of Cement Modified Recycled Base Compression Specimens in the Laboratory*, SCDOT Test Method 26 (SC-T-26). [(61)]

MATERIALS

Table 31 is a high-level summary of materials used in each recycling technique. Details can be found in References 61 through 63.

Binders

SCDOT uses Type 1 Portland cement for binder with CMRB. It has completed one FDR foamed asphalt project using a PG64-22 asphalt binder. Another FDR asphalt project is being considered that would use an engineered emulsion at the emulsion industry's request. SCDOT identified a project that may work with emulsion and is letting industry provide some potential solutions. This is new to SCDOT, and it would likely follow the general guidelines in the Basic Asphalt Recycling Manual. [(4)]

Table 31. Summary of Materials Used in each Recycling Technique.

Material Parameters	Recycling Technique				
	Cold			Hot	
	CIR	FDR Cement	CCPR	HIPR Remixing	HIPR Repaving
Binders	–	Portland cement	–	–	–
Active Fillers	–	Portland cement	–	–	–
Processed Recycled Material Top Size	–	100 % passing 3"	–	–	–
Other Gradation Requirements	–	95% passing 2"	–	–	–
Other Aggregate Requirements	–	N/A	–	–	–

Active Fillers

Type 1 Portland cement is the active filler typically used in CMRB. The dose is a function of unconfined compressive strength. Type 1L cement has been used but has led to long durations prior to opening to traffic.

Processed Material Gradations

The CMRB gradation requirements of the pulverized material are 100 percent (by weight) passing the three-inch (3-in.) sieve and 95 percent passing the two-inch (2-in.) sieve as shown in Table 32. Additionally, CMRB may be supplemented with virgin aggregates. (61)

Table 32. CMRB Gradation Requirements.

Sieve Size	Percent Passing
3.0 inch	100
2.0 inch	95

MIXTURE DESIGN

Table 33 is a high-level summary of mix design requirements for each recycling technique. Details can be found in References 61, 62 and 63. Portland cement doses of three, six, and nine percent are considered, and a moisture density relationship is established at the six percent cement dose. The "*Standard Method of Test for Moisture–Density Relations of Soils Using a 2.5-kg (5.5-lb) Hammer and 305-mm (12-in.) Drop*," AASHTO T 99-19 is followed with unconfined compressive strength test specimens compacted to 100 percent of the maximum dry density. (62) The recommended cement content is selected by the OMR from a plot compressive strength versus cement dose. SCDOT requires that contractors have mix designs performed in AASHTO Re:Source accredited laboratories and they have to be sealed by a registered professional engineer (PE) licensed in the state of South Carolina.

Table 33. Mix Design Summary Information.

Mixture Design Parameters	Recycling Technique				
	Cold			Hot	
	CIR	CMRB (FDR Cement)	CCPR	HIPR Remixing	HIPR Repaving
Compaction method	–	AASHTO T99 Method C	–	–	–
Gyrations / Blows	–	100% of T99 maximum dry density	–	–	–
Curing	–	Moist curing at 73±4°F and RH ≥ 95% for 7 days, then overnight in water	–	–	–
Compaction Temperature (°F)	–	Room temperature	–	–	–
Binder dose selection	–	% Cement at UCS ≈ 600psi	–	–	–
Coating	–	N/A	–	–	–
Raveling Test	–	N/A	–	–	–
Moisture Density Relationship	–	T99	–	–	–
Moisture Sensitivity Test	–	UCS	–	–	–
Rutting Test	–	UCS	–	–	–
Cracking Test	–	N/A	–	–	–

[1]The curing, conditioning and criteria differ among these materials.

FIELD CONSTRUCTION & ACCEPTANCE

Mix Design Changes During Construction

Some State DOTs and contractors have faced challenges with making mix design changes during construction. The SCDOT CMRB specification is very clear on this. Each load of cement is considered a section. A test strip is constructed with the first load of cement and subsequent sections and defined by a load of cement also. If a section does not meet the acceptance requirements one additional load of cement may be placed and the material has to be in specification, or a new test strip is initiated with the contractor having to submit a corrective action plan. SCDOT indicated that with CMRB sometimes changes need to be made during production and though not often, the primary reason is a change in the condition of the in-place pavement being recycled. Cement spread rate is typically not adjusted unless a soft or wet spot is encountered. At that time, the resident engineer may direct changes in the cement content to improve or dry out these areas. Moisture and density targets are monitored during compaction acceptance testing with adjustments being made to these values based on field proctors to adjust target values as needed. This is part of a "quick fix" and regular construction trouble shooting. This is not a normal and regular occurring practice. There are several items SCDOT requires to minimize and address making changes, when necessary, that include:

- More thorough site investigations if variability is anticipated.
- Mix designs are sealed by a professional engineer.
- Laboratories performing mix designs is AASHTO ReSource Accredited.
- Just in time training (JTT) pre-construction for contractor and DOT prior to commencement of CMRB construction.
- QC plans with corrective action plans.
- Test strips.
- Having an OMR representative available to teach just in time and partner with the contractor to address issues as they arise during production.
- Having a positive partnering relationship and history between SCDOT and the construction industry.

Test Strips

A section is defined as a load of cement. SCDOT requires a test strip be constructed with the first load of cement and full production can begin the same day as long as the test strip materials and compaction meet specification requirements.

Quality Control and Acceptance

SCDOT requires a QC plan for all CMRB projects. The QC plan has to include contingency plans for pulverization, mixing and compaction if specifications criteria are not met. It also has to include provisions for identifying in-situ moisture conditions, adjusting the moisture content to meet specifications, and maintaining moisture content through the curing period that details a description of the methods and minimum contractor testing for moisture. Pulverization has to produce a field gradation with 100 percent passing the three-inch sieve and 95 percent passing the two-inch sieve. At the start of compaction, the moisture content of the CMRB must be between the specified optimum moisture content and two percent above it. It needs to remain with plus and minus two percent during production. All grading and compaction have to be completed within two hours of the initial pass of the reclaimer. The compaction requirement is not less than 95 percent of the maximum dry density. Moisture content and maximum dry density are determined per SCDOT SC-T-29, *Field Determination of Maximum Dry Density and Optimum Moisture Content of Soils by the One-Point Method.* [64] At the completion of the CMRB compaction, grading is required with thickness monitored having a tolerance of plus one inch and minus one-half inch. The wearing course placed on CMRB has to meet smoothness requirements.

The SCDOT Quality Acceptance Sampling and Testing Guide Amendment to Figure 106B and 106C of the SDCOT Construction Manual provides sampling and testing frequency and test method details. (65)

SCDOT specifications include three curing options, Methods A through C that are specified on project plans. Upon completion of the CMRB construction the surface has to be cured using the specified method in the plans or contract. The three curing options are:

1. Method A: Surface (Single) Treatment Curing Method
2. Method B: Surface (Single) Treatment with Milling Curing
3. Method C: Surface (Double) Treatment with Milling

SCDOT indicated that Method A is not normally used, and the Method B is primarily used. With Method B, a surface treatment (chip seal) is placed at the end of a day's CMRB production. The reasons for applying a surface treatment are to promote curing and because the surface is not durable, thus not good for trafficking especially if it rains. Method C is only used in District 4. With Method C a surface treatment (chip seal) is placed at the end of a day's CMRB production to promote curing, is milled off and minor slope and grade adjustments may be made. A surface treatment is then applied to the milled surface. CMRB has to cure a minimum of three days and surfacing of it has to take place within seven days of the completion of the CMRB and no more than four miles can have temporary surface treatment on it at any time. When using Curing Methods B or C, the milled surface is not left open to the public for more than 72 hours prior to placing the wearing surface.

Prior to placement of the wearing surface, when Methods B and C are used, the CMRB course surface is milled to obtain a true and level finish for the asphalt placement. Traffic can beat up the chip seal and grades can be inconsistent. So, a profile mill is used to remove the chip seal after curing and provide the best chance for overall smoothness. Some CMRB may be removed and eliminates the "fluff factor" such a constructing 12-inch CMRB thar results in a compacted thickness of 13 inches. Smoothness of the HMA placed on the CMRB has to meet requirements that are a function of route type and speed limit. Tack coats are not used, while the grooved pattern from milling is supposed improve bond and prevent slippage.

Payment for CMRB is based on the square yards of CMRB per the schedule based on thickness shown in Table 34 and the Portland cement used is paid for by the ton. There is a pay item adjustment on thickness because deficient thickness reduces pavement structure. Note that CMRB constructed outside the designated area and Portland cement incorporated in excess of 5 percent of the amount specified are not paid for.

Table 34. Cold Asphalt Recycling Techniques Payment Schedule for Lot Densities.

Pay Item	Unit
Cement Modified Recycled Base (6" Uniform)	Square Yard
Cement Modified Recycled Base (8" Uniform)	Square Yard
Cement Modified Recycled Base (10" Uniform)	Square Yard
Cement Modified Recycled Base (12" Uniform)	Square Yard
Portland Cement for Cement Modified Recycled Base	Ton

Curing and Opening to Traffic

SCDOT requires that the construction operations from starting pulverization to final compaction be completed within three hours of the cement being spread. Curing was discussed in the section titled Quality Control and Acceptance.

Lessons Learned

The extensive SCDOT experience with CMRB has revealed several important lessons learned. They include the following:

- Shrinkage cracking in CMRB, occurring transversely and at lane butt joints, can reflect through the asphalt mixture placed on the CMRB resulting stains on the pavement surface that need to be crack sealed. It is believed that they occur due to poor pulverization/mixing and potentially to more cement than needed.
- Adequate pre-construction sampling coupled with quality control during construction are important to prevent hydrophobic subgrade materials combined with poor workmanship leading to inadequate strength of CMRB upon completion of curing.
- Existing pavements with significantly variable base structure along a project are not necessarily good CMRB candidates. They would require more upfront investigation to understand the conditions more thoroughly and the need to make more adjustments in the field.
- Edge cracking can be observed if misalignment of CMRB and asphalt surface layers occurs. Keeping CMRB 6 inches wider than the asphalt pavement width provides a good platform for compaction equipment when placing the asphalt surface and could reduce optional for edge cracking due to differential shrinkage in widening areas
- When CMRB composition changes during construction it is important for the contractor and SCDOT staff to understand why and make timely adjustments to correct the construction.
- If construction best practices are not followed while constructing CMRB specification requirements may not be achieved leading to a failing CMRB that will require reconstruction.

- With higher volume roads it is critical that adequate density be achieved prior to opening to traffic and to reduce the potential for slippage failures. Surface scarify milling and application of chips seals after scarify milling have been used successfully.
- Type 1 cement is specified by SCDOT, but Type 1L cement has been used due to availability. The lime is inert and a filler which slows down the reaction process. This created surface issues when traffic was placed on the CMRB at the end of the day. This issue seems to occur in different parts of state, regardless of clay or sand soils.
- When CMRB is being constructed by a contractor for the first time and/or the first CMRB for the construction division in the district (inspector) it is important to have a technical expert on-site. This highlights the importance of experienced technicians and/ inspectors.

PAVEMENT PERFORMANCE AND COST

Overall SCDOT reported good performance with the CMRB cold in-place recycling technique. Shrinkage cracking in the CMRB leading to reflective cracking in the asphalt surface mixture is the most common form of observed distress. Slippage cracking has been reported when thin asphalt surface lifts are applied without a tack coat or when a thin sand mix leveling course has been used to correct grades. SCDOT has begun some studies to judge the performance of CMRB materials but have not compared them directly to traditional methods. This effort was done to determine if in-service CMRB fulfills the design assumptions in the specifications/standard. Observations have been that the design assumptions are fulfilled in service. SCDOT always wants to improve the CMRB process even though there is a very low ratio of issues. However, when issues exist SCDOT diligently works through them in partnership with the recycling contractor.

There are options available for rehabilitating a pavement in need. Selection of the most appropriate and cost-effective alternative is an important engineering decision. SCDOT indicates that CMRB pavements have performed well although they have not been directly compared to the performance of traditional asphalt pavements. However, it has found that CMRB can be more effectively used to rehabilitate existing primary and secondary routes. For SCDOT rehabilitation technique selection is primarily between CMRB versus traditional mill and fill. Equivalent structural designs are compared and thus should have the same maintenance requirements over the design life. A decision to switch to select CMRB over traditional mill would be based on depth of distresses and existing versus required structural needs. When patching needs exceed 15 to 20 percent, then CMRB is very commonly used because it is more cost-effective and it results in a uniform pavement structure with less potential performance risk. Because equivalent structural designs are considered, the cost comparison is analogous to a life cycle cost analysis and some CMRB candidates on lower volume roads also allow for construction of perpetual structures due to lower cost associated with deeper mixing designs when compared to traditional reconstruction. CMRB might require crack sealing if desired to seal shrinkage cracks in worst case scenarios, and some Districts crack seal more aggressively than others. CMRB is considered a perpetual base with just resurfacing required after the design life.

SCDOT indicates that there are initial cost benefits with CMRB for roads needing additional structure or greater amounts of patching. As previously noted, when more than 15 to 20 percent patching is needed CMRB becomes a more cost-effective alternate that provides for a more uniform pavement structure. Additional cost data could be compiled to compare CMRB and traditional pavement costs, though the data is not readily available. SCDOT suggested that CMRB costs about five to six dollars per square yard plus cement and the asphalt surfacing in the mature SCDOT market.

Other benefits to using CMRB reported by SCDOT were faster production rates. This can allow for more square yards in the same amount of time when compared to traditional methods of rehabilitation or to shorter lane closure durations. An example of CMRB reducing the construction of a pavement by several months when compared to traditional patching and paving was shared. Use of in-place recycling also allows more contractors to perform work, to some degree, without competitive advantage associated with plant haul distance/time limitations.

CONTRACTOR PERSPECTIVES

With the COVID-19 Pandemic leading to virtual site visits, it was not possible to visit CMRB construction project. SCDOT arranged for a virtual interview with a limited number of contractors to obtain their perspective on CMRB. A set of seven open end questions were asked and each contractor had the opportunity to respond to each question. The questions and summary of response follow:

1. **Is the number of recycling projects let in the State each year well balanced with number of recycling contractors operating in the State?**
   There are a lot of contractors in state leading to a competitive environment and it is difficult for out-of-state contractors to move in and compete. SCDOT has a lot of work and local contractors have stepped up to construct CMRB in a well-balanced environment (not excess capacity). There is enough work to keep it competitive but not enough to grow it. There is contractor interest in growing a CIR market in South Carolina, but CIR does not lend itself to correcting subgrade issues. In District 2 the stabilizer needs to match the soil conditions and value engineering has been used to accomplish this. A planned two-mile CIR project with staging and grade corrections due to undulating profile and traffic was constructed. The CIR was cost prohibitive, so CMRB with foamed asphalt was identified as a potential solution.

2. **Is there less bidding competition on DOT projects with recycling techniques than on other conventional paving projects?**
   Contractors indicated that there was not more competition on recycling than on HMA paving. There are fewer recycling contractors than paving contractors. Some paving contractors (about 50-85 percent) have their own reclaimers. Mobility is easy with recyclers, but harder for asphalt plants and paving contractors with plants. SCDOT stared a robust recycling program 15-20 years ago. Initially contractors were uncertain, but when it continued, the contractors invested in recycling equipment. The South Carolina market is mature and competitively bid. If states put projects out there, contractors will respond. This is what happened in South Carolina. It started with 300,000 square yards and grew to three to 5 million square yards per year. It was a struggle at first because asphalt producers and truckers would not sell to the recyclers. They thought it took away from their business. It can be a challenge to change the mentality that in-place recycling is good for the asphalt pavement industry. Things have changed in South Carolina. The reasons for change are to: 1) sell them on fixing base and there will be plenty of asphalt to place on top. 2) Eventually, contractors will follow

suit if the state keeps projects coming. CMRB is using a material that is already bought and paid for. CMRB fixed the base and older CMRB projects are now milling and filling the surface (perpetual pavement).

3. **<u>Do challenges or risks exist when transitioning from lab mix design to production start-up in the field or during production?</u>**

The risk is mitigated well with pre-investigation (very important) to identify materials and differences. If there are some unsuitable soils, it is usually a small area and a plan to correct it is in place. SCDOT involves contractors in the process. A team of SCDOT and contractors have created the viable processes. If there are issues, a phone call gets the answer and approval within minutes. Failures are a thing of the past unless there is something extremely obscure encountered. If an issue occurs, it often only takes a conversation to solve it. Issues are worked through together with a positive partnership. The partnership is a key to allow adaption instead of rigidly adhering to specifications. A focus on immediate fixes to allow the roadway to be opened at end of day is key. Mix design shortcuts can cause issues. Thorough material classification is needed.

The process is only as good as last project, so everyone has the "big picture" in mind. What happens in lab and field are two different things (so many different conditions). If SCDOT does not listen to the contractor, there will be failures. The road will fail and then they will pay contractors to fix it again. It is important to get with knowledgeable contractors and listen to their input. SCDOT listens and slight tweaks may only last for a few hundred yards, but they need to be made for a successful project. Perhaps there is a need for three mix designs instead of two on a project with variable in-situ soil conditions.

Quality improvement committees are in place, one each for asphalt, aggregates, concrete and recycling. They meet twice per year to identify key issues from the past to address for the next year. There are 15 members with FHWA representation and 50 percent SCDOT and 50% industry representation. ARRA guidelines and BARM have been a tremendous asset (e.g., mix design field troubleshooting). Information in these documents work.

Industry would like to see FDR with emulsion used. A previously planned project did not go well. Lime was added to address clay soils, and it worked. The SCDOT concluded emulsions may not work. Emulsion projects are not being let. When starting with a new technique for the first time it is important to have an experienced person available on-site. Detailed and longer specifications are not always the answer. Experience is vital to success. The learning curve can be long and expensive. Knowledge to answer questions like: How much water? Time of day impact? Cloud cover impact? Preparation prior to opening to traffic?... Laura (SCDOT) has spent a lot of time in the field to provide experienced on-site assistance.

Relationships between the DOT and contractors are important, as well various contractors. All need to work together for the good of the recycling processes. All want the process to succeed so all need to be willing to learn and embrace new things every day, even after a lot of years of experience.

4. **<u>Are there examples of techniques or production best practices used by contractors or DOT staff to make mixture adjustments during production that are not in DOT</u>**

specifications, but could be to allow for rapidly acceptable changes to improve mixture quality?
See above.

5. **Are there recommended best practices for answering the question, "How does an agency know it is getting the proper proportions of mixture components in recycled mixture?"**
Measuring yield and monitoring it closely is very important. The load in each tanker is known and the roadway geometry is known, as well as the depth of recycling. Spread rate is easily calculated and can be verified with spot checks using the cloth method. Laying out each load is easy, and it is helpful to calculate the distance each load will cover, mark it on the roadway and have the contractor and inspector monitor to see that it is reached. If not, figure out why. At the end of the day a check of yield can be done with square yards and volume. It is helpful to summarize data by station. Suppliers provide tickets with each load that are provided to the DOT. The controls on the machine are also important to watch as a source of verification also. If a scale is not near the site, it may not be possible to get results until the next day, thus making it very important to be monitoring each load on the project. Rock Solid Stabilization and Reclamation has a free application for doing calculations. A second app includes moisture and truck management information.

6. **Is there a mechanism(s) in place that allow for training/knowledge transfer, review of lessons learned, and partnering on improvements with DOT and contractor stakeholders participating?**
Quality improvement committees are in place, one each for asphalt, aggregates, concrete, and recycling. They meet twice per year to identify key issues from the past to be address for the next year. There are 15 members with FHWA representation and 50 percent SCDOT and 50% industry representation. ARRA guidelines and BARM have been a tremendous asset (e.g., mix design field troubleshooting). Information in these documents work.

7. **What are some of future activities that could help support successful use of recycling technologies?**
FHWA should continue to support ARRA. It would be helpful to provide sponsorship for State DOT travel to attend ARRA meetings. Support for demonstration projects is important also. There is a need for technology transfer of success stories. There is a need sharing the benefits of recycling and a need for EPDs and LCA to show positive environmental impacts. It would be good to be able to show how much recycling technologies help the states and country. Standardization of these tools is important and the FHWA Sustainability Technical Feedback Group is developing tools.
It would be helpful if FHWA put funding guidelines out and assisted with getting pilot projects going. Getting focused on in-place recycling to get states started. There needs to be a sustainable market to support equipment investments and support for recycling programs will encourage investment (some equipment is $2M). Only one project per year or sporadic, makes it challenging for a contractor to get started.

> It would be helpful if FHWA could put together a pool of industry experts (nationally or locally) to provide assistance (pre-planning to acceptance) for those with needs. This would keep process healthy and provide knowledge transfer.

SCDOT BEST PRACTICES

Throughout the visit, several SCDOT best practices were identified that included the following:

1. Having identified a patching level at which CMRB is more cost-effective than patching prior to rehabilitation.
2. A recently developed or updated CMRB specification and design manual that specifically incorporate asphalt recycling techniques.
3. Requiring contractor control plans on all projects.
4. Requiring that CMRB mix designs be performed in AASHTO Re:Source accredited laboratories, but SCDOT selects the cement dosage.
5. Requiring construction of a test strips, though full production can begin the same day as long as the test strips meets specification requirements.
6. Having quality control requirements used during construction, some with go/no go criteria performed daily during construction.
7. Agency and contractor just-in-time training on CMRB construction.
8. Recognition that using supplemental virgin aggregate can improve CMRB quality.
9. There is a continuous need for just in time training of SCDOT and contractor staff on CMRB specifications, materials and construction practices with workforce turnover.
10. Having a standing quality improvement committee for recycling with SCDOT, Contractor and FHWA representatives.
11. Learning from past experiences and integrating changes into design procedures and specifications for continuous improvement as well as sharing them while SCDOT conducts just in time training.

ALTERNATIVE USES OF RAP

The most common use of RAP by SCDOT is in hot mix or warm mix asphalt. In 2019 SCDOT used approximately 2.9 million tons of asphalt mixture, integrating about 600 thousand tons of RAP. It is forecasting that the budget will increase from $450 million to 600 million by 2024. Nearly all mix produced in the state includes RAP. SCDOT has been using RAP since 1997, and 20 to 22 percent is typically used in asphalt mixes. RAP use has been consistently in this range for the past several years. The most common alternative use of RAP in South Carolina is in CMRB (a.k.a., FDR), which is logical since SCDOT is a leader in the use of this in-place recycling technique in the U.S. Recently, some design build teams have started using RAP and aggregate base blended (60/40) to serve as aggregate base option on lower volume road and shoulder alternatives. Milling on Interstate design build projects can create a significant amount lot of RAP.

RESEARCH ACTIVITIES AND RESEARCH NEEDS

Two SCDOT reports document CMRB research completed to date. One is on the first CMRB project constructed by SCDOT written in 1995 and the other is on the long-term evaluation of the same project published in 2013. [59,66] The 1995 report stated, "*In summarizing, we in District 4* *have been very pleased with the results of the process of pavement reclamation. It has enabled us to reconstruct roadways in place for a fraction of the cost of complete reconstruction. Maintenance costs have been minimized on all of these roads since their completion.*" The 2013 report indicated, "*In conclusion, the process of reclaiming an existing pavement with the process of full depth reclamation with Portland cement has proven to be an economical and long-lasting solution for SCDOT. It will continue to be used as a repair strategy for our failing roadways.*"

Additionally, SCDOT has completed cement treated base studies in an effort to finding a way to design CMRB materials mechanistically due to some failures observed with other applications. There are two on-going research activities. One is an extensive field evaluation which includes FWD testing and cores from various geographical and route types utilizing CMBR across the state. The other project is on LTE which may be completed by December 2021. The National Center for Asphalt Technology (NCAT) is currently reviewing CIR and CCPR specifications and lessons learned (acceptance/inspection/quality control) by the Virginia DOT and other agencies to develop best practice guidelines and specifications for SCDOT consideration.

SCDOT identified the following research needs:

- Evaluation of the CMRB mix design process with focus on optimization of unconfined compressive strength mix design criteria to provide adequate structural capacity without excess shrinkage cracking in CMRB.
- Evaluation of the CMRB modulus and layer coefficients used for structural pavement design.

CLOSING REMARKS

SCDOT is actively and successfully using the CMRB sustainable cold asphalt recycling technique. The technology is well integrated in the DOT and applied across with the recycling program being significant enough that in-state contractors are performing the work. The support of SCDOT and SCDOT staff and contractor personnel that participated in this effort is greatly appreciated. The input provided revealed several positive practices that will be of significant value to other DOTs.

CHAPTER 7 VIRTUAL SITE VISIT: VDOT

INTRODUCTION

The VDOT has responsibility for about 128,000 total lane miles in the state. They include about 27,000 lane miles of Interstate and Primary routes and about 100,500 lane miles of Secondary routes (some of which are gravel, not hard surfaced). The Interstate and Primary routes are about 86 percent flexible, 2 percent rigid, and 12 percent composite structures. With a few jurisdictional exceptions, VDOT owns all roads in the state. Secondary routes vary widely with some being typical 2-lane farm to market roads, some could be residential roads, and in the northern Virginia region, some secondary routes carry Interstate level traffic. VDOT uses CIR, CCPR, and FDR cold recycling techniques and has over 10 years of successful experience with them. Unlike some other DOTs, VDOT has a successful track record of using cold recycled asphalt technologies on high volume roads including Interstate routes. VDOT policy states that for all Interstates and for any routes with a two-way Average Daily Truck Traffic (ADTT) of 200 or more, when cold recycling materials are used, there must be a minimum of four inches combined thickness of asphalt concrete. VDOT has also used multiple recycling techniques on the same project, especially for high volume roads. For example, FDR and CCPR have been used on the same projects.

Use of recycling techniques can be considered for all projects across the state, but some Districts have utilized them more than others. It was noted that stockpiled RAP supply is more prevalent in the eastern and northern portions of Virginia, where a larger percentage of recycling work has been performed due to a larger amount of cold milling, leading to an overabundance of stockpiled RAP. Although it is not as abundant, some stockpiled RAP is available in central and western Virginia. VDOT has the option to advertise with two alternate pavement structures (e.g., conventional and CCPR) with separate pay items/prices; however, this has not often been utilized.

For CIR, both engineered emulsions and foamed asphalts are allowed; early applications tended to use the engineered emulsion, while the majority [but not all of the] more recent projects have used the foamed asphalt. CIR is typically placed in a structural layer with a thickness of 3 to 6 inches and is typically surfaced with HMA. CCPR is normally produced with foamed asphalt, although emulsion and foamed asphalt are both options. It is also typically placed in thicknesses of 3 to 6 inches; however, multiple CCPR structural layers may be used, and regardless of thickness, it is normally surfaced with HMA (a seal coat surface is allowed on low volume roads but has not yet been done). FDR is primarily produced with Portland cement, though emulsion and foamed asphalt are options, as well as lime kiln dust. FDR thickness can range from 6 to 12 inches (10 to 12 most common) and typically will include a portion of the subgrade along with existing HMA and aggregate base (if present). Advanced milling, also referred to as pre-milling (milling performed prior to the recycling operations), may be performed prior to FDR or CIR to account for vertical geometric constraints that would be impacted by the fluff factor that occurs with this operation. It is estimated that both FDR and CIR can increase in volume by 10 to 15% compared to the in-place material after recycling. Pre-milling has been used in various projects-to address this concern. In Northern Virginia pre-milling 4 inches is common (the Contractor can pre-mill or can manipulate FDR materials by removing excess FDR material to maintain grade, but they typically choose to pre-mill). Another technique VDOT is using with FDR is to widen existing lanes by use of shoulder trenching prior to FDR operations: material on the outside of the

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lane is removed, then the fluff material generated by the FDR operation is used to backfill the trench. This technique has been used on lower volume roads to widen the existing lanes.

Although VDOT's initial usage of recycling technologies began earlier, the Department's first use of FDR in earnest was in 2008**;** CIR and CCPR usage started in 2011. FDR and CIR have been used on more projects than CCPR, but the volume of CCPR used is larger than the other methods. Although VDOT's well-deserved national reputation as a leader in the use of cold recycling technologies stems largely from experience on high volume routes, in Virginia these technologies can be considered for any project. Use of the three recycling processes (CIR, CCPR, and FDR) is similar from year to year, when one excludes two large recycling projects on I-64 completed in 2017 and 2019. Two potential drivers of this negligible annual increase in projects were noted: (1) there are no funds dedicated to recycling, and (2) and management performance indicators currently in use may incentivize the selection of techniques with short-term value. Additionally, in Virginia, projects are developed [and funded] as either Maintenance projects or Construction projects; since these functions are separate, and since the recycling techniques are not specifically maintenance or construction, no one entity "owns" the recycling initiative. Furthermore, recycling techniques are not considered standard practice by some staff and thus are not embraced by everyone. Significant research and marketing efforts have taken place, but it has been a challenge to move it into a routine practice like mill and fill or surface treatment applications. Table 35 presents as summary of statistics on cold recycled techniques use by VDOT.

Table 35. Summary of Cold Asphalt and Hot In-place Recycling Techniques use by VDOT.

Recycling Technique	**Cold**		
	CIR	**FDR**	**CCPR**
Projects[1], 2008 to 2021	8	25	7
Use (percent of total use)	Information	not	available
Quantity (Square Yards (SY) or tons)[2]	377,979 SY	1,036,755 SY	206,942 SY + 363,670 tons
Cost per Square Yard (SY) or tons[3]	$13.00 to 17.65 per SY	$7.00 to 12.00 per SY	$11.50 to 49.00 per SY; $48 to 65.00 / ton
Districts Using	Some more than others, eastern focused.		
Years of Experience	>10	>13	>10

[1] Total projects may be more than reported here.
[2] Square Yardage & Tonnage may not represent total usage to date (actual may be higher).
[3] Early CCPR projects were SY and the most recent are tonnage based.

PROJECT/RECYCLING TECHNOLOGY SELECTION CRITERIA

The VDOT has a Materials Manual of Instructions (MOI) that provides detailed guidance on selection of projects for using recycling technologies. [(67)] Section 608, Chapter VI of the MOI includes multiple criteria.

There six items to consider that include:

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1. Initial Project Selection Criteria:
   - Distress rating data: "Restorative Maintenance" or "Reconstruction" are good candidates, but projects identified for "Corrective Maintenance" may be suitable also.
   - Project length: FDR greater than 3 miles; CIR greater than 5 miles and CCPR of any length.
   - VDOT has published guidance which states that, if patching exceeds 15 percent or if based on the maintenance history, a prior overlay did not fulfill the design life, then substantial rehabilitation is triggered; however, this is not followed in practice.
   - Pavement Management System (PMS) history: total thickness, layer composition, and Critical Condition Index (CCI).
2. Project Level Pavement Forensic Investigation:
   - Ground Penetrating Radar (GPR) is encouraged, and soil boring is required for FDR.
   - Unified Soil Classification System (USCS) is used to select stabilizing agent; if the soil is cohesive, lime is selected and if the soil non-cohesive, Portland cement or bituminous with cement is selected for silty material.
3. Project Level Recycling Conditions:
   - Correct failed subgrade, unbound subbase/base using FDR.
   - Correct deterioration in bound flexible layers using CIR.
4. Consider using CCPR for new pavements and rehabilitation projects
5. Surface Layer Type:
   - CIR, CCPR, and FDR are usually surfaced with asphalt concrete; a surface treatment may be used on low volume roads.
6. Final Project Selection:
   - Competing options final selection is based on cost, time, any project specific constraints, and it is noted that 10-15 percent "fluff" (volumetric expansion, not necessarily related to water content) with CIR and FDR needs to be considered.

Section 608 of the VDOT MOI also directs the pavement engineer to consider recycling as a solution when more than four inches of milling would be needed to remove deteriorated pavement. Should recycling not be chosen, justification as to why it was not selected is to be included in the project pavement design report. As mentioned earlier, recycling may also be used for existing lane widening by utilization of shoulder trench widening with FDR and CCPR backfill. Shown below in Figure 15 is an excerpt from Section 600 of the VDOT MOI; this illustrates the detailed pavement evaluation process flow used. It is worth noting that VDOT performs structural designs, while contractors are responsible for performing mix designs.

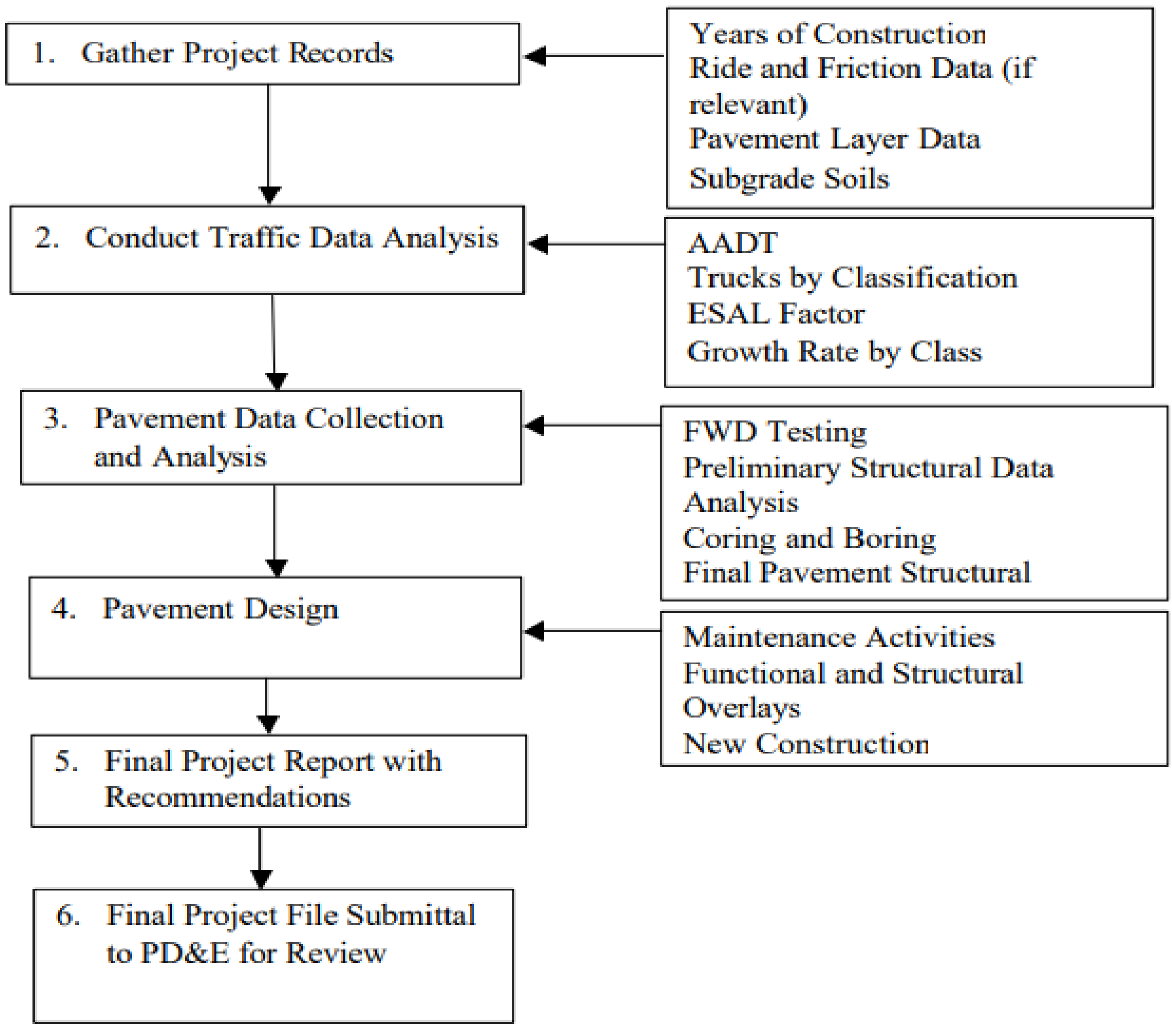

Figure 15. Chart. Detailed Pavement Evaluation Process Flow.

STRUCTURAL PAVEMENT DESIGN

VDOT has final approval on all pavement designs. Typically, development of pavement designs is performed by the Department or the Department's designee. VDOT uses ~~both~~ the AASHTOWare Pavement ME design procedure for new construction (new lane-miles or new alignment, new or existing routes) and for reconstruction on Interstates and Primaries. ME Software version 2.2.6 is utilized for design purposes. Due to limitations within this software version, chemically stabilized materials such as FDR are modeled as a high-quality aggregate base in the flexible system. Furthermore, CCPR is not modeled in the AASHTOWare Pavement ME software at this time; instead, a HMA base mix is used and the thickness of CCPR used to replace the HMA base mix is 1.26 times the base mix thickness required. For rehabilitation projects such as mill-and-fill or straight overlays, the AASHTO Guide for Design of Pavement Structures 1993 is used. When cold recycled asphalt is to be used, the following layer coefficients (a_i) are assigned: FDR = 0.25; CIR and CCPR = 0.35. Other inputs (e.g., terminal serviceability, reliability, etc.) are provided in section 604 of the VDOT MOI.

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MATERIALS

Binders

VDOT typically uses the term "Stabilizing Agent" rather than binder. The contractor selects the binders required to meet the mix design engineering property requirements. If during production there are changed conditions such as product availability constraints, Contractors would have the option to change binders provided that a new mix design with the new stabilizing agent was submitted and approved.

CIR may be produced with emulsion or foamed asphalt; emulsion has been used more commonly, and when it is used, it is an engineered emulsion. CCPR is typically produced with foamed asphalt, although emulsion and foamed asphalt are both options as long as the mix design engineering requirements are met. FDR may be produced using Portland cement, lime, foamed asphalt, or asphalt emulsion. Type 1 Portland cement has most commonly been used for FDR.

Active Fillers ("Stabilizing Agents" in Virginia)

Portland cement, at a dose of one percent by weight of RAP, is used as an active filler in CIR and CCPR. The cement is used to assist with obtaining high early strength. When emulsion is used for FDR, hydrated lime has to be used.

Processed Material Gradations

The contractor provides the RAP used for CCPR and it may be either existing stockpiled RAP, RAP from the current project, or a combination of both. For lane widening projects, the RAP from existing stockpiles may be used if no RAP from the project is available. As shown in Table 36 VDOT requires CCPR RAP stockpiles used for CCPR to have 100 percent passing the 1.5-inch sieve and limited deleterious materials. An individual RAP QC plan is not required as RAP QC is considered to be part of the CCPR QC plan requirements. An example field experience was a contractor on one of the large VDOT CCPR recycling projects having an existing RAP stockpile from other projects which was found to be good quality, consistent material. The contractor proceeded to process this RAP material into "dedicated" RAP stockpiles for CCPR with it processed to pass the ½ inch sieve.

Table 36. Summary of Materials Allowed Used in Recycling Technique.

Material Parameters	Recycling Technique		
	Cold		
	CIR	FDR	CCPR
Binders	Emulsion or Foamed	Portland cement, lime, other cementitious materials	Emulsion or Foamed
Virgin Aggregate	Allowed; Crushed RAP also allowed	Allowed; Crushed RAP also allowed	Allowed; Crushed RAP also allowed
Active Fillers ("Stabilizing Agent" in Virginia)	Portland cement	Hydrated Lime when emulsion is used	Portland cement
Processed Recycled Material Top Size	< 1.5"	< 2.0"	< 1.5
Other Gradation Requirements	> 55% p3/8"	> 55% p3/8"	JMF tolerances on 1.5", ¾", 3/8", #4 and #200
Other Aggregate Requirements (incl. Virgin Agg. Requirements)	LA Abrasion, Sand Equivalent, Max Size, Water Absorption, Crushed RAP-Deleterious materials, and max size	LA Abrasion, Sand Equivalent, Max Size, Water Absorption, Crushed RAP-Deleterious materials, and max size	LA Abrasion, Sand Equivalent, Max Size, Water Absorption, Crushed RAP-Deleterious materials, and max size

MIXTURE DESIGN

VDOT requires, via individual project special provisions, that contractors perform the mix designs, which includes sampling the materials from the roadway (typically by spot-milling or by coring, approximately every 2500 feet to obtain materials for mix designs) or sampling the materials from a stockpile when CCPR is used. CIR mix design requirements are per VDOT SP315-000410-01 and the mix design properties considered, test methods used and mix design property criteria are summarized in Table 37 and Table 38; note the differences in the requirements for emulsified vs. foamed asphalt. As with CIR, CCPR may also use either emulsion or foamed asphalt; the mix design properties considered, test methods used and mix design property criteria are per VDOT SP211-000400-01. The criteria for CCPR, both for emulsified and for foamed, is identical to that for CIR. For cold recycled asphalt technologies VDOT uses several index-based performance tests for cracking, rutting, raveling and moisture sensitivity. Depending on the type of material, (CIR, CCPR, or FDR. the tests include Marshall stability, retained Marshall stability, ITS and retained ITS, and raveling.

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Table 37. CIR and CCPR Emulsified Mix Design Criteria.

Item	Property	Test Method	Criteria
1	Moisture Density Relations	AASHTO T 180, Method D	Determined by Design
2	Marshall Stability Test (min)[1, 2]	ASTM D5581 or AASHTO T 245	2945 lbs (ASTM) 1475 lbs (AASHTO)
3	Retained Stability[1, 3]	ASTM D5581 or AASHTO T 245	70% of results from Item 2
4	Raveling [4]	ASTM D7196	Maximum 6%
5	Materials Gradation Test prior to Stabilization	AASHTO T 27, washed	Gradation to control field production.

[1]The Contractor may test this property using either ASTM D5581 or AASHTO T 245 and compare to the criteria corresponding to that test.

[2]Three specimens produced at 75 blows per side (or 30 gyrations per AASHTO T 312), cured at 140ºF to constant mass, and held at 104ºF for 2 hours in oven immediately before testing.

[3]An additional 3specimens shall be produced at cured at 140ºF to constant mass. Specimens shall then be vacuum saturated to 55-65%, in a 77ºF water bath for 23 hours and 104ºF water bath for an additional hour immediately before testing

[4]Specimens shall be produced using a gyratory at 20 gyrations and cured at 50ºF for 4 hours at 50% humidity.

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Table 38. CIR and CCPR Foamed Asphalt Mix Design Criteria.

Item	Properties	Test Method	Criteria
1	Moisture Density Relations	AASHTO T 180, Method D	Determined by Design
2	Dry Indirect Tensile Strength (ITS)[1]	AASHTO T 283 Section 11	53 psi minimum
3	Retained Indirect Tensile Strength[2]	AASHTO T 283 Section 11	Min 70% of the Dry ITS
4a	Expansion Ratio (Aggregate temperature 50ºF to 77ºF)	Wirtgen 2012 Cold Recycling Manual	10 times
4b	Expansion Ratio (Aggregate temperature greater than 77°F)	Wirtgen 2012 Cold Recycling Manual	8 times
5	Half-Life	Wirtgen 2012 Cold Recycling Manual	6 second minimum
6	Materials Gradation Test, prior to stabilization	AASHTO T 27, washed	Gradation to control field production.

[1]Three (3) specimens shall be produced using 75 blows per side (or 30 gyrations per AASHTO T 312) compacted at or below Optimum Moisture Content and oven dried at 104ºF (40°C) for 72 hrs. and cool to ambient temperature for 24 hrs.

[2]Three (3) specimens produced and cured according to Item 2 Dry Indirect Tensile Strength. Specimens shall be oven dried at 104ºF (40ºC) for 72 hours, and then submerged in 77ºF (25ºC) bath for 24 hours prior to testing.

FDR mix design properties considered, test methods used, and mix design property criteria are per VDOT SP315-0004200-01 and are summarized in Table 39.

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Table 39. FDR Mix Design Criteria.

Test	Test Method	Criteria
Liquid Limit, Plastic Limit, and Plasticity Index of Soil	VTM-7	Report
Dry Preparation and Mechanical Analysis of Soils, Select Material, Subbase and Aggregate Bases	VTM-25	Report
Classification of Soils	AASHTO M 145	Report
Moisture-Density Relations of Soil-Cement Mixtures	AASHTO T 134	Report
Moisture Density Relations for Bituminous Stabilizing Agents	AASHTO T 180	Report
Compressive Strength of Soil-Cement Cylinders	ASTM D 1633	250 - 450 psi at 7 days
Determining the Strength of Soil-Lime Mixtures (Minimum)	VTM-11	150 psi
Dry Indirect Tensile Strength (ITS) for Foamed Asphalt Stabilizing Agent (Minimum)	AASHTO T 283, Section 11	45 psi
Marshall Stability Test for Asphalt Emulsion Stabilizing Agent (Minimum)	ASTM D5581 AASHTO T 245	2500 lbs 1250 lbs

FIELD CONSTRUCTION & ACCEPTANCE

Mix Design Changes During Construction

Some State DOTs and contractors have found the need to make changes to the mix design based on what occurred while placing the construction control strips. This has typically not been an issue in Virginia; consequently, the specifications do not directly address how to handle potential field changes.

Quality Control and Acceptance

CCPR & CIR

CCPR & CIR, general

The VDOT specifications include rigorous equipment requirements that help assure planned quantities of materials are provided during construction. Some examples from the CIR specification follow:

- The machine shall have the ability to meter dosage rates for stabilizing agents and water relative to the machine's ground speed.
- Any additives such as water, lime slurry, etc. added by the equipment at the milling head or mixing unit shall be controlled through liquid metering devices capable of automatically adjusting for the variation in bituminous material going into the mixing unit, by means of weighing device or proportional control systems.

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- The metering devices shall be capable of delivering the amount of additive to within +/- 0.2% of the required amount, except that a capability of adding up to 5% water by weight of the pulverized bituminous material is mandatory.

For CIR and CCPR the acceptance requirements are similar, with the exception that CCPR gradation requirements are more rigorous. For example, for CIR they include:

- 2 gradations per day conforming to the JMF. If the gradation does not conform, the contractor needs to make corrective actions. Note, this is a process control (e.g., slow down process, etc.). No price adjustment is made.
- Stabilizing agent dosage rate by reading a calibrated meter 10 times per lot. The dose rate has to be within 0.20 percentage points of the approved JMF. The lot size for CIR is each day's production unless the paving length is less than 3,000 feet or greater than 7,500 feet. A standard lot is 5000 feet with 1000-foot sublots.

CIR & CCPR, field compaction

The Contractor is responsible for establishing, verifying, and monitoring the compaction of the recycled layer. This is accomplished through the use of compaction control strip (i.e., a roller pattern and control strip) at the beginning of production, and test sections (lots) throughout production.

CIR & CCPR Roller Pattern & Control Strip

Compaction control strips are required by VDOT for CIR and CCPR and used to determine the maximum practicable compaction achievable as well as to establish the initial rolling patterns; these represent good opportunities for transitioning from the lab to the field. These compaction control strips also function as trial sections and the Contractor is required to place them at least one week before the start of production.

In general, VDOT did not report significant issues with this transition unless there were significant in situ condition changes, such as localized moisture conditions.

These compaction control strips are constructed at the beginning of the project, in accordance with Virginia Test Method (VTM) 10. The Contractor will use the same equipment to construct this strip as is intended to be used on the remainder of the project. After establishing the roller pattern and constructing the control strip, the control strip will be deemed acceptable if both the field Proctor and the control strip nuclear density average is at least 98% of the maximum dry density from the approved Job-Mix-Formula (JMF) (mix design).

In addition, a single moisture content sample is taken from the uncompacted layer.

CIR & CCPR, Compaction Equipment

At least one pneumatic tire roller shall have a minimum gross operating weight of at least 50,000 pounds. At least one double steel-wheeled vibratory roller shall have a gross operating weight of at least 24,000 pounds and a width of 78 inches. The vibratory setting on rollers shall be at the highest frequency and lowest amplitude setting.

CIR & CCPR, Density testing during production

Density testing for both CIR and CCPR is conducted using a nuclear gauge, in backscatter mode for a layer depth of 3.0 inches or less, and in direct transmission mode for a layer depth greater than 3.0 inches. Rolling shall start no more than 30 minutes after initiation of paving. Finish rolling shall be completed no more than one hour after paving is completed. Testing frequencies are as follows:

- The Contractor tests each lot for density acceptance with nuclear density readings from two random test sites selected by the Engineer per sublot.
- Each day's production is considered a lot: a standard lot is 5000 feet with 1000-foot sublots. The Contractor verifies the results of every lot by performing a field proctor (AASHTO T180, Method D). The field proctor shall be at least 98 percent of the JMF proctor's MDD. The payment schedule is based on Table 40Table 40.

Table 40. Payment Schedule for CIR and CCPR Density.

Percent of Target Control Strip Density	Percent of Payment
98.0 or greater	100
97.0 to less than 98.0	95
96.0 to less than 97.0	90
Less than 96.0	75

CIR & CCPR, Thickness

Depth for CIR and CCPR is checked by the Contractor two times per 5000 feet, by trenching or coring. A lot is considered acceptable if the mean result of the tests is within the tolerance of the plan depth for the number of tests taken as shown in Table 41 for CIR and Table 42 for CCPR.

Table 41. Process Tolerance for CIR Thickness.

Plan Depth (in)	Tolerance (in, ±)		
	2 tests	3 tests	4 tests
≤ 4	0.45	0.35	0.30
>4 ≤ 6	0.65	0.50	0.40

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Table 42. Process Tolerance for CCPR Thickness.

Plan Depth, inches	Tolerance, inches (Plus or Minus)		
	2 tests	3 tests	4 tests
≤ 4	0.45	0.35	0.30
>4 ≤ 8	0.65	0.50	0.40
>8 ≤ 12	0.90	0.70	0.50
>12	1.00	0.80	0.60

Note that for both CIR and CCPR, excess thickness is not eligible for payment.

CIR & CCPR, Gradation

For CIR, the Contractor verifies the unstabilized gradation twice per production day. One test is conducted at the beginning of each production day. Should there be a change in the pavement structure being recycled, the contractor shall verify the unstabilized gradation. Any gradation not meeting the approved job-mix-formula (mix design) will require immediate corrective action from the Contractor.

For CCPR a lot is 4000 tons, and 8 tests are performed per lot for gradation, and tolerances are shown in Table 43. For stability or strength one test is performed per day or 1000 tons. The lot size for CCPR is each day's production unless the paving length is less than 3,000 feet or greater than 7,500 feet. A standard lot is 5000 feet with 1000-foot sublots.

Table 43. CCPR Gradation Process Tolerances.

Tolerance on Each Laboratory Sieve and Asphalt Content: Percent Plus and Minus					
No. Tests	1 ½"	3/4"	3/8"	No. 4	No. 200
1	0.0	8.0	8.0	8.0	2.0
2	0.0	5.7	5.7	5.7	1.4
3	0.0	4.4	4.4	4.4	1.1
4	0.0	4.0	4.0	4.0	1.0
5	0.0	3.6	3.6	3.6	0.9
6	0.0	3.3	3.3	3.3	0.8
7	0.0	3.0	3.0	3.0	0.8
8	0.0	2.8	2.8	2.8	0.7
12	0.0	2.3	2.3	2.3	0.6

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CCPR other Measures - Strength

Table 44 and Table 45 are Marshall Stability and Indirect Tensile Strength acceptance criteria for CCPR emulsion and CCPR foamed asphalt respectively. The frequency of testing for each is one per 1000 tons or one per day.

Table 44. CCPR Emulsion Marshall Stability Payment Adjustments.

Marshall Stability (6" specimen)	Marshall Stability (4" specimen)	Percent of Payment
2945 lbs or greater	1475 lbs or greater	100
2500 to 2944 lbs	1250 to 1474 lbs	95
Less than 2500 lbs1	Less than 1250 lbs1	Remove and Replace

[1]The Contractor shall immediately cease production and notify the Department when results fall below 2500 lbs (6 inch) or 1250 lbs (4 inch). The Contractor shall make any necessary corrective actions to the mix and provide verification to the Engineer that it conforms to the approved job-mix formula before resuming production.

Table 45. CCPR Foamed Asphalt Marshall Stability Payment Adjustments.

Dry Indirect Tensile Strength	Percent of Payment
53 psi or greater	100
45 psi to 52 psi	95
Less than 45 psi[1]	Remove and Replace

[1]The Contractor shall immediately cease production and notify the Department when results fall below 45 psi. The Contractor shall make any necessary corrective actions to the mix and provide verification to the Engineer that it conforms to the approved job-mix formula.

Full Depth Recycling

FDR, general

For FDR the application rate has to be within 0.20 percentage points of the optimal stabilizing agents content provided in the approved JMF, checked at start of each day's production and twice for every 1000 linear feet. Water content is monitored to ensure approved JMF ± 2% of optimum. Weather limitations: at least 40°F when cement stabilizing agent is used or 50°F when foamed asphalt or emulsion is used. Recycling operations shall not begin if the weather forecast is for a freezing temperature within 48 hours after placement.

FDR, field compaction

<u>Trial Section</u>

At the beginning of a project, the Contractor constructs a 2500' long trial section, using the same equipment that he intends to use on the remainder of the project. Part of the trial section activity is to perform a roller pattern and control strip in accordance with Virginia Test Method (VTM) 10; however, the density acceptance during production is still based on the maximum theoretical density from the JMF, as discussed below.

FDR Compaction Equipment

Compaction equipment must be capable of working within the constraints of the excavation and compacting the stabilized material in conformance with the density requirements provided in the approved JMF.

FDR, Density during production

For FDR acceptance a lot is defined as 1 day's production or 5000 linear feet with 5 sublots (each 1000 feet) per lot.

In-place density is monitored with a nuclear gauge operated in direct transmission mode with a target of greater than 97 percent of the maximum density from the approved job-mix formula (mix design). Density is measured from two stratified random locations within each sublot. The average of these sublot density measurements is compared to the maximum density from the approved job-mix formula and a pay determination is made. Table 46 shows the payment schedule for density:

Table 46. Payment Schedule for FDR Lot Densities.

Percent of Density from Approved JMF	Percent of Payment
97.0 or greater	100
96.0 to less than 97.0	95
95.0 to less than 96.0	90
Less than 95.0	75

FDR, Thickness

Depth checks are performed twice per lot by the Contractor in accordance with VTM-38, Method B. Acceptance for depth is based on the mean result of measurements taken from that lot, as shown in Table 47 below.

Table 47. Process Tolerance for FDR Depth Checks.

Plan Depth, inches	Tolerance, inches (Plus or Minus)			
	1 test	2 tests	3 tests	4 tests
>6 ≤ 8	0.9	0.65	0.5	0.4
>8 ≤ 12	1	0.9	0.7	0.5
>12	1.2	1.0	0.8	0.6

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Note that for FDR, excess thickness is not eligible for payment.

FDR, Gradation

Gradation is checked 2 times per day.

FDR, other measures --- Stabilizing Agent Dosage Rate

The dosage rate is verified at the start of a day's production and then twice per 1,000 linear feet. For dry stabilizing agents, VTM-141 is followed to determine the rate. The dosage rate is required to be within 0.2 percentage points of the approved job-mix formula (mix design); if it is not, paving is required to stop until correction action has been taken by the Contractor.

Curing and Opening to Traffic

CIR & CCPR

VDOT specifications require that cold recycled materials be cured until they have maximum moisture contents of 50 percent the optimum moisture content or until approval of the Engineer before the next layer is placed. For CIR and CCPR, after compaction a fog seal application rate of 0.06 gallons per square yard (gsy) (0.04 gsy residual) and grit application of 2 to 3 pounds per square yard (psy) is applied to reduce raveling. After this sealing, traffic is restricted as follows: for CCPR, no traffic is permitted for at least 2 hours; for CIR, as a rule, no traffic is permitted until the water content of the CIR material is a maximum of 50 percent of the optimum water content (however, in practice, traffic has sometimes been allowed at over 50% when approved by the Engineer). After these conditions are met, then rolling traffic may be permitted. A tack coat has to be applied prior to any additional surfacing.

FDR

If stabilizing with cement stabilized materials, the compacted material shall be kept moist until covered with an asphalt-based layer; if stabilizing with bituminous materials, the FDR shall be cured until the moisture is a maximum of 50 percent the optimum moisture content or until approval of the Engineer. Subsequent asphalt-based layers can be placed any time after finishing, as long as the FDR is sufficiently able to support the required construction equipment without marring or permanent distortion of the surface.

Lessons Learned

The extensive VDOT experience with cold recycled asphalt techniques has revealed several important lessons learned. They include the following:

- VDOT has demonstrated that multiple cold asphalt recycling techniques can be successfully used on low and high-volume roads.
- When performing night work early in the construction season when it is cool, CCPR with emulsion may not be successful due do slow breaking.
- It is worthwhile to have post-season meetings with all stakeholders to review the previous season, identify lessons learned and items that can be worked on to improve success with cold recycling technologies.

- Regarding mix designs: gradations tend to get finer from mix design to production, but in general, the finer gradation works well with the foamed asphalt emulsion. Finer gradation seemed to provide for better dispersion and coating.
- At least one company has a "mini cold mix plant" available for laboratory mix designs (cost order-of-magnitude, approximately. $65,000 in 2021).
- The temperature of RAP plays a role in production and workability of CIR and CCPR. That is, for CIR and CCPR, environmental temperature is critical, as emulsion dispersion is affected depending on aggregate temperature.
- Production and placement may not be pursued due to cool weather concerns.
- Loading CCPR directly into trucks and placing it does not pose problems, as long as "best practices" are used when loading (to minimize segregation and deformation).
- For CCPR, the testing lab's coordination of material sampling to minimize moisture loss is vital, and "storing" the sample for transportation was key.
- Samples are best "preserved" by wrapping in a plastic bag or plastic wrap, then placing in a sealed bucket.
- VDOT may need to consider revising the VTMs to cover proper sampling, transport, gradation testing, conditioning, curing, and how to conduct and use the proctor density.
- Yield should be calculated and monitored during production.
- Compaction control strips are required by VDOT and used to determine the maximum compaction achievable as well as to identify starting rolling patterns.
- On-site technical representatives through steady-state production is helpful, though less important as the industry matures.
- High moisture due to rain and high humidity slows curing but overall does not usually create a major issue; however, at least one of VDOT's projects did have an issue with this.
- Current specifications could be revised to clarify what the target density should be (for all three types of recycling methods under discussion).
- Need to determine whether thin lift nuclear gauges in backscatter is an appropriate method, or whether direct transmission should be performed.
- Depth can be checked by the "digging" method when moisture samples are taken.
- On sunny/ warmer days, materials cure quickly and need to be monitored frequently.
- It is not clear where within the layer the moisture sample should be measured (this is an issue since moisture cure takes longer at the bottom of a layer, when the depth is thick). The location for taking the moisture sample should be clarified.
- If surface layer is "crusting" and "raveling", then there is a mix issue (either placement or production).
- One can see color change as material cures (turns to a grayish tint) and if the material has a dark appearance after curing, then it could be low in or have a lack of cement. (Most projects with CIR and CCPR have 1% cement and don't have a problem, but in some cases, the day after placement with inadequate ~~no~~ cement, the material had a dark appearance instead of a grayish tint.)
- As a rule, VDOT has not experienced issues with hauling CCPR to projects. In production of CCPR, the producer can ship around optimum moisture content, and contractor receives the mix at slightly lower moisture content, though still in specification, and this can aide with faster curing while not compromising material properties (strength, compaction, etc.).

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- Just in time training – get basic background to VDOT staff and contractor. This is a typical practice at the beginning of the project.
- With CCPR there is a lab at the plant for more frequent testing. Time from sampling to testing is very important in the results. At the project level, contractors compact immediately, and agency would often do it later. This has led to differences and thus both labs should have the same "wait time" and this should be discussed at pre-paving meetings.
- An asphalt MTV should not be used to transfer CCPR from a truck to a paver; material can get "gummed up" in an MTV with remixing. Instead, a pickup conveyor (without remixing) may be successfully used.
- Be open to change, especially if a specification has a lot of method requirements as changing conditions require changes, especially around density.

PAVEMENT PERFORMANCE AND COST

VDOT reported overall good performance with the cold asphalt recycling techniques. Techniques used to assess performance include visual observations, FWD, and instrumentation in pavements.

VDOT is unique in that it has supported the use of cold asphalt recycled test sections on the NCAT test track. These pavements have also been instrumented and so pavement responses to loading data are collected. VDOT is pleased with the performance of the recycling projects and the NCAT test sections have not shown any performance issues.

Some reflective cracking has been observed when recycling composite pavements due to joints in the concrete pavements. Although similar observations have been made for CCPR, no distress has been observed in VDOT's CCPR projects to date.

For FDR there is an on-going performance assessment, and performance appears positive. However, the following have been reported:

- Some block cracking in a pavement that received additional cement to address a soft area, which may have received too much cement.
- A section of thick FDR with a thin HMA overlay exhibited a significantly high amount of transverse cracking within 12 to 18 months after construction.
- In some parts of Virginia, transverse cracking is more of an issue; most of these cases appear to result from too much cement.

Direct comparisons of conventional rehabilitation and recycling rehabilitation are difficult to find. A reasonable sample size for comparison simply is not available. Generally, recycled sections are performing well. The NCAT test track sections show the recycled sections are a perpetual pavement. At this point it is a challenge to compare to equivalent alternatives (in terms of structural value), but VDOT has seen no evidence to suggest that recycling projects will have a shorter service life than structurally similar hot-mix-asphalt pavements. In terms of maintenance, no unscheduled maintenance activities have had to occur for any recycled pavements to date.

It was indicated that there are several benefits with cold asphalt recycling including:

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- Use of CCPR has reduced the large quantities of RAP previously stockpiled in some parts of Virginia.
- Use of CIR could reduce the development of excess RAP stockpiles.
- Increased speed of construction is believed intuitively, but not quantified to date.
- Innovative management of traffic (MOT) techniques have been developed to support rapid cold asphalt recycling.
- LCCA may be improved with the use of recycled materials, but additional supporting data (such as actual service life) is needed for confirmation. Currently, there is limited data available on the service life of recycled sections to fully analyze.
- LCA benefits have been documented and additional data is currently being collected to report LCA benefits.

CONTRACTOR PERSPECTIVES

With the COVID-19 Pandemic leading to virtual site visits, it was not possible to visit construction projects in Virginia. VDOT arranged for a virtual interview with a limited number of contractors to obtain the industry perspective on cold recycled asphalt. One contractor representative participated in the cold recycled asphalt discussion. Multiple VDOT representatives participated in the interview. A set of seven open end questions were asked and the contractor had the opportunity to respond to each question.

The questions and summary of response follow associate with ***cold asphalt recycling*** follow:

1. **Is the number of recycling projects let in the State each year well balanced with number of recycling contractors operating in the State?**
   VDOT could use more projects. It has a lot of high-profile projects but could benefit from doing more low-volume projects. There are two FDR contractors in the state and a third that does work in North Carolina. There is only one known CIR contractors in the state. High-profile projects may have an option for in-place recycling, and it has been chosen. Recycling options have not yet become routine. Large sustainability conscious private companies like Microsoft, Google and Amazon that have massive parking lots have embraced use of cold recycled asphalt. These companies may be motived to reduce their carbon footprint. There have not been city or county projects in recent years. Industry has done marketing but has struggled getting into the design phase early enough when project scoping is occurring. Part of the reason could be if significant grade changes are needed, recycling may not be a good candidate. Municipalities are covered by VDOT except for a couple of counties and major cities.

2. **Is there less bidding competition on DOT projects with recycling techniques than on other conventional paving projects?**
   There are few recycling contractors, and likely only one that would take the recycling option if available. There are not enough projects let annually to get contractors to invest in the equipment and this will continue until VDOT develops a more robust program. One Virginia contractor was really motivated to use CCPR to use RAP stockpile inventory. The company did a lot of preliminary experimentation and saw future

benefits in investing in recycling equipment. Can see the same with CIR if projects exist.

The VDOT MOI has three miles as the minimum project length for CIR, which could be limiting its use. However, if there were large spot repairs on a six lane-mile project it may still be cost effective as more work closer together makes it more attractive for a contractor. There are often extraneous factors (e.g., personal opinion, etc.) that continue to pose challenges.

3. **Do challenges or risks exist when transitioning from lab mix design to production start-up in the field or during production?**

   Some challenges existed initially and consultants with experience were engaged to assist industry. It can be a challenge to keep the product consistent throughout a project. One contractor purchased a screen deck system to ensure consistency which helped minimize challenges. This adds cost but pays off in consistency and quality. The same equipment has been used screening for RAP in asphalt mixtures to improve consistency. It was suggested that density is the main criteria measured in the field and using mix design lab density as a basis has posed challenges. VDOT suggested that that in the future production density should be based on control strip density. Another potential challenge identified was getting representative samples for mix design. It was suggested that use of a drill rig with an auger may be better than crushing cores for mix design.

4. **Are there examples of techniques or production best practices used by contractors or DOT staff to make mixture adjustments during production that are not in DOT specifications, but could be to allow for rapidly acceptable changes to improve mixture quality?**

   One contractor indicated that additional screening for consistency is the most important thing it has done that is not required by specifications. The contractor indicated that some gradation ranges may be too tight on control sieves for a recycled material and may need to be adjusted, especially if contractors do not do the additional screening. VDOT indicated that research on the impacts of gradation has been funded and will begin in 2022, with the purpose of evaluating the influence of gradation on performance and determining what, if any, specification tolerance revisions are needed.

5. **Are there recommended best practices for answering the question, "How does an agency know it is getting the proper proportions of mixture components in recycled mixture?"**

   Wirtgen KMA plants for CCPR have been used by Virginia contractors have computerized printouts based on a calibrated weigh belt. Reports are submitted with dose rate and calculated asphalt content. These seemed to match appropriately. Checking gradation results was identified as a good check also and the current specifications are appropriate and adequate.

6. **Is there a mechanism(s) in place that allow for training/knowledge transfer, review of lessons learned, and partnering on improvements with DOT and contractor stakeholders participating?**

In the past holding project close-out meetings for lessons learned exchange has been helpful and hopefully, this will continue in the future. The Virginia Education Center for Asphalt Technology (VECAT) has training for field and plant recycling for testers and inspectors. It was noted that training needs also relate to the number of projects. If there are a limited number of projects annually, there may be a need for re-training.

7. **What are some of future activities that could help support successful use of recycling technologies?**

In 2011, the I-81 project was successful, but use of recycling technologies has not taken off which has surprised some. A reason could be risk aversion to new processes and willingness to try something new. There are still only one or two projects per year compared to NYSDOT that does over 20 projects per year.

A contractor that operates in four states indicated that it has promoted recycling with presentations up and down the coast, submit for awards, and put articles in magazine articles but it does not seem to help grow the market in Virginia.

During the interview process, the following points were borne out of the discussion which took place:

- There is a need to identify methods to increase the number of recycling projects and techniques that could be used to support increased use of cold recycled materials.
- Value engineering (VE) proposals by Contractors (to split cost savings with the agency) could increase the market. It may be helpful for VDOT to encourage contractors to take the initiative to submit VE proposals.
- There is a lack of dedicated funding for recycling.
- Resistance to performing deep fixes, even though they may be a better option for pavement life.
- The relatively low initial cost of thin overlays can be a driving factor as opposed to overall pavement life.
- A limited budget being spread over many roads leads to thin overlays on many projects.
- One large recycling project eliminates the need to do many thin overlays over the life cycle.
- In general, recycling techniques have been recognized to provide shorter overall project durations. However, in areas where there is a need to return the road to service quickly, such as urban areas, the daily construction shifts might be longer due to material curing, so during project development, evaluation of the recycling process, construction shift allowance time, and maintenance of traffic operations should be evaluated.
- There is a public dashboard process (Good/ Fair/ Poor) to report performance relative to targets. This target system tends to promote the use of surface repairs on structurally deficient pavements, which leads to the use of thin overlays in order to return more quickly to "Good" ratings, but the pavements may not stay in the "Good" category for very long.
- Typically, an organization faces challenges when implementing a new technology such as recycling, based on experience of Agency and local Industry

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personnel, particularly when it is proposed to be used in lieu of a "tried & true" method (e.g., mill and fill as a means of maintaining pavement).
- VDOT does limited forensic investigations when developing pavement rehabilitation projects. This limitation my lead to over-use of thinner treatments which thicker treatments may be needed.

VDOT BEST PRACTICES

Throughout the visit, several VDOT best practices were identified that included the following:

1. Application of multiple cold asphalt recycling techniques on low and high-volume roads.
2. Materials Division Manual of Instructions: section 600 and 608 selection guidelines for cold recycled asphalt project is very clear and comprehensive.
3. Having minimum project length requirements for different cold recycling technologies (although it should be noted that this approach is not universally acknowledged within VDOT as a best practice, as the minimum lengths are somewhat arbitrary)
4. Allowing CCPR for any construction (new or rehabilitation).
5. Requiring mix designs developed in qualified labs 30 days prior to construction
6. Mix designs are performed by the contractor and requirements are rigorous.
7. VCAT has certification courses for technicians on recycled projects and recertification is required every 5 years.
8. Sampling requirements are included in project special provisions because recycling projects can be unique.
9. Comprehensive mix design method that includes index-based performance tests.
10. Mix design requirements for CCPR are more rigorous than for CIR. However, the degree of benefit to the more rigorous process has not been evaluated.
11. Requiring quality control plans 30 days prior to construction with rigorous requirements and contingency plans for materials, construction operations, weather, etc.
12. Holding preconstruction meetings (beyond just in time training) to work out details of trial section.
13. Holding just-in-time training events for cold recycled asphalt pavements.
14. VDOT equipment specifications and calibration procedures with verification are very clear and rigorous.
15. Requiring control strips be constructed at the beginning of construction with minimum density requirements that must be met in order to proceed.
16. Requiring a qualified technical expert be on site with early recycling project for some trial sections to start and/or if first trial section failed for others.
17. Having a high frequency of stabilizer dose monitoring.
18. Including construction records in the acceptance requirement of standard specifications.
19. Application rate of binder (foam or emulsion) or additives is checked with tanker loads versus work accomplished that day to assure proper dose rates are used.
20. Using of fixed stabilizer dose for bidding purposes
21. Conducting significant research related to cold recycled asphalt, publishing the research and openly communicating it in multiple public forums.

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22. Holding post season meetings with stakeholders (VDOT and industry) to review the previous season, identify lessons learned and items that can be worked on to improve success with cold recycling technologies.
23. Recognition that there is continued need for communicating the benefits of using cold recycling technologies such as:
    a. Open meetings, seminars, workshops, and back to basics training for all stakeholders.
    b. Community outreach programs.
    c. Just in time training on projects.
    d. Fact sheets to explain recycling benefits to VDOT staff.

ALTERNATIVE USES OF RAP

Like in most states, HMA produced in the state incorporates RAP and this has been common practice for many years. Recently completed research at Virginia Transportation Research Council (VTRC) on optimizing RAP content in unbound base aggregate has indicated the depending on the RAP binder content, 20 to 30 percent RAP is optimal in base aggregates. [68]

RESEARCH ACTIVITIES AND RESEARCH NEEDS

VDOT has conducted a significant amount of in-house research related to cold asphalt recycling. It has included laboratory testing and full-scale pavement testing including instrumentation of constructed pavements in Virginia, as well as at the NCAT Test Track. The topics have ranged from project specific reports, to stockpiling procedures, to use of cold recycled asphalt techniques for low and high-volume road, including structural capacity assessment, to life cycle assessment of pavement construction using cold recycled asphalt techniques. The research efforts have been documented in eight VDOT research reports, as well as published in technical journals. VDOT has also**:** led or had significant roles in cold recycled asphalt related national research, including NCHRP Project 09-51, Material Properties of Cold In-Place Recycled and Full-Depth Reclamation Asphalt Concrete for Pavement Design (NCHRP Research Report 846)**;** served as the Prime Contractor on NCHRP Project 09-62, Rapid Tests and Specifications for Construction of Asphalt-Treated Cold Recycled Pavements (NCHRP Research Report 960)**;** and is the Prime Contractor on NCHRP Project 14-43, Construction Guide Specifications for Cold Central Plant Recycling and Cold In-Place Recycling.

VDOT identified the following research needs:

1. How to define and communicate cold asphalt recycling benefits so that the technologies are broadly embraced in Virginia.
2. Project selection guidelines (refine traffic levels, thin overlays) for various applications.
3. Appropriate moisture levels at which cold recycled asphalt could be opened to traffic.

VDOT indicated that there were not any significant industry changes related to cold asphalt recycling at this time as this is done on a regular basis. Items under discussion included thin

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treatments over cold recycled asphalt and eliminating mix design requirements for FDR, other than cement dose, for low-risk situations.

CLOSING REMARKS

VDOT is actively and successfully using sustainable cold asphalt recycling and hot in-place recycling techniques, albeit on a limited basis. Specifically, VDOT uses CIR, FDR and some CCPR. The support of VDOT and VDOT staff that participated in this effort is greatly appreciated. The input provided revealed several positive practices that will be of significant value to other agencies.

REFERENCES

1. Muench, S.T., G. Migliaccio, J. Kaminsky, M.Z. Ashtiani, A. Mukherjee, C.G. Bhat, and J. Anderson. *Sustainable Highway Construction Guideline*. NCHRP Research Report 916, National Academy of Sciences, Washington, DC, 2019.
2. Williams, B.A., J. R. Willis, and J. Shacat. *Annual Asphalt Pavement Industry Survey on Recycled Materials and Warm-Mix Asphalt Usage: 2019, 10th Annual Survey*. Information Series (IS) 138, National Asphalt Pavement Association, Greenbelt, MA, September 2020.
3. Hand, A., and T. Aschenbrener. *Resource Responsible Use of Reclaimed Asphalt Pavement in Asphalt Mixtures*. FHWA-HIF-22-003, Federal Highway Administration, Washington, DC, 2021.
4. *Basic Asphalt Recycling Manual.* 2nd Edition, Asphalt Recycling & Reclaiming Association's (ARRA), Glen Ellyn, IL, 2015.
5. Apeagyei, A. and B.K. Diefenderfer. *Evaluation of Cold In-Place and Cold Central-Plant Recycling Methods Using Laboratory Testing of Field-Cored Specimens*. J. Mater. Civ. Eng., 25(11), 1712–1720, 2013.
6. Harvey, J., J. Meijer, and A. Kendall. *Life Cycle Assessment of Pavements*. Tech Brief, FHWA-HIF-15-001, Federal Highway Administration, Washington, DC, 2013.
7. Robinette, C. and J. Epps. *Energy, Emissions, Material Conservation, and Prices Associated with Construction, Rehabilitation, and Material Alternatives for Flexible Pavement*. Transportation Research Record, Transportation Research Board, Volume 2179, Issue 1, Washington, DC, 2010.
8. Wagner, C. *Overview of Project Selection Guidelines for Cold In-place and Cold Central Plant Pavement Recycling*. FHWA-HIF-17-042, Federal Highway Administration, Washington, DC, 2017.
9. *Recommended Construction Guidelines for Cold In-place Recycling (CIR) Using Bituminous Recycling Agents.* CR101, Asphalt Recycling and Reclaiming Association, Glen Ellyn, IL, 2017.
10. *Recommended Construction Guidelines for Cold Central Plant Recycling (CCPR) Using Bituminous Recycling Agents*. CR102, Asphalt Recycling and Reclaiming Association, Glen Ellyn, IL, 2017.
11. *Recommended Mix Design Guidelines for Cold Recycling Using Bituminous Recycling Agents*. CR201, Asphalt Recycling and Reclaiming Association, Glen Ellyn, IL, 2016.
12. *Recommended Mix Design Guidelines for Cold Recycling Using Foamed (Expanded) Asphalt Recycling Agent.* CR202, Asphalt Recycling and Reclaiming Association, Glen Ellyn, IL, 2017.
13. *Recommended Quality Control Sampling and Testing Guidelines for Cold Recycling Using Bituminous Recycling Agents.* CR301, Asphalt Recycling and Reclaiming Association, Glen Ellyn, IL, 2017.
14. *Recommended Construction Guidelines for Full Depth Reclamation (FDR) Using Bituminous Stabilization. FDR101*, Asphalt Recycling and Reclaiming Association, Glen Ellyn, IL, 2017.
15. *Recommended Construction Guidelines for Full Depth Reclamation (FDR) Using Cementitious Stabilization* FDR102, Asphalt Recycling and Reclaiming Association, Glen Ellyn, IL, 2017.

16. *Recommended Construction Guidelines for Full Depth Reclamation (FDR) Using Lime Stabilization.* FDR103, Asphalt Recycling and Reclaiming Association, Glen Ellyn, IL, 2017.
17. *Recommended Mix Design Guidelines for Full Depth Reclamation (FDR) Using Emulsified Asphalt Stabilizing Agent.* FDR201A, Asphalt Recycling and Reclaiming Association, Glen Ellyn, IL, 2018.
18. *Recommended Mix Design Guidelines for Full Depth Reclamation (FDR) Using Cement or Cement Kiln Dust (CKD) Stabilizing Agent.* FDR202, Asphalt Recycling and Reclaiming Association, Glen Ellyn, IL, 2016.
19. *Recommended Quality Control Sampling and Testing Guidelines for Full Depth Reclamation (FDR) Using Bituminous Stabilizing Agents.* FDR301, Asphalt Recycling and Reclaiming Association, Glen Ellyn, IL, 2017.
20. *Recommended Quality Control Sampling and Testing Guidelines for Full Depth Reclamation (FDR) Using Cementitious Stabilizing Agents.* FDR302, Asphalt Recycling and Reclaiming Association, Glen Ellyn, IL, 2017.
21. *AASHTO MP 31-17 Standard Specification for Materials for Cold Recycled Mixtures with Emulsified Asphalt*, American Association of State Highway and Transportation Officials, Washington, DC, 2019.
22. *AASHTO MP 38-18 Standard Specification for Mix Design of Cold Recycled Mixture with Foamed Asphalt.* American Association of State Highway and Transportation Officials, Washington, DC, 2019.
23. *AASHTO PP 86-17 Standard Practice for Emulsified Asphalt Content of Cold Recycled Mixture Design*. American Association of State Highway and Transportation Officials, Washington, DC, 2019.
24. *AASHTO PP 94-18 Standard Specification for Determination of Optimum Asphalt Content of Cold Recycled Mixture with Foamed Asphalt.* American Association of State Highway and Transportation Officials, Washington, DC, 2019.
25. *Proposed AASHTO Practice and Tests for Process Control and Product Acceptance of Asphalt-treated Cold Recycled Pavements.* NCHRP Report 960, National Academy of Science, 2020.
26. *Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects.* FP-14, United States Department of Transportation, Federal Highway Administration, Washington, DC, 2014.
27. *Project Development and Design Manual.* Federal Highway Administration, Washington, DC, 2013.
28. Cross, S.A, *Cold In-Place Recycling (CIR).* FHWA Report No. FHWA-CFL/TD-13-00x, Federal Highway Administration, Washington, DC, 2013.
29. *Determination of Optimum Emulsified Asphalt Content of Cold In-Place Recycled Mixtures.* FLH-T-524, Federal Lands Highways, Washington, DC.
30. *Determination of Optimum Emulsified Asphalt Content of Full Depth Reclamation Cold In-Place Recycled Mixtures*. FLH-T-524, Federal Lands Highways, Washington, DC.
31. *Determination of Optimum Emulsified or Foamed Asphalt Content of Full Depth Reclamation Mixtures.* FLH-T-522, Federal Lands Highways, Washington, DC.
32. *INDOT Design Manual–2013, Chapter 602.* Indiana Department of Transportation, Indianapolis, IN, last update October 6, 2021.
33. *Standard Specifications 2022*. Indiana Department of Transportation, Indianapolis, IN, 2022.

34. ITM 593. *Asphalt Emulsion Supplier Program.* Indiana Department of Transportation, Indianapolis, IN, 2021
35. ITM 592. *Mix Design Procedure for Cold Recycled (CR) Asphalt with Emulsion.* Indiana Department of Transportation, Indianapolis, IN, 2021.
36. ITM 594. *Mix Design Procedure for Full Depth Reclamation (FDR) with Asphalt Emulsion.* Indiana Department of Transportation, Indianapolis, IN, 2020.
37. ITM 595. *Mix Design Procedure for Full Depth Reclamation (FDR) with Cement.* Indiana Department of Transportation, Indianapolis, IN, 2020
38. Flora, William. *Rehabilitation of Low-Volume Roads Using FDR*. Purdue Road School 2020, Purdue University, West Lafayette, IN, 2020.
39. McKeen, G.R. *Cold Institute Recycling Evaluation.* Alliance for Transportation Research, Albuquerque, NM, 1996.
40. *New Mexico Department of Transportation Design Manual.* New Mexico Department of Transportation, Santa Fe, NM, 2020.
41. *Standard Specifications for Highway and Bridge Construction 2019 Edition.* New Mexico Department of Transportation, Santa Fe, NM, 2019.
42. Standard Specifications for Highway and Bridge Construction, Section 412: *Hot In-Place Recycling of Asphalt Pavement (Remixing) 2019 Edition*. New Mexico Department of Transportation, Santa Fe, NM, 2019.
43. *Standard Specifications for Highway And Bridge Construction, Section 413: Single-Machine Hot In-Place Surface Repaving 2019 Edition*, New Mexico Department of Transportation, Santa Fe, NM, 2019.
44. *Special Provisions for Section 301-A: Full Depth Reclamation - Foamed Asphalt Stabilized Base.* New Mexico Department of Transportation, Santa Fe, NM, 2020.
45. *Special Provisions for Section 301-B: Cold Central Plant Recycling (CCPR)-Foamed Asphalt Stabilized Base.* New Mexico Department of Transportation, Santa Fe, NM, 2019.
46. *Special Provisions for Section Section 415-A: Cold In-Situ Recycling (Cir) Of Existing Surfacing.* New Mexico Department of Transportation, Santa Fe, NM, 2021.
47. *Special Provisions for Section, 415-B: Preconstruction Personnel Training.* New Mexico Department of Transportation, Santa Fe, NM, 2021.
48. *AASHTO M 320, Standard Specification for Performance-Graded Asphalt Binder.* American Association of State Highway and Transportation Officials, Washington, DC, 2017.
49. *AASHTO T 59, Standard Method of Test for Emulsified Asphalts*. American Association of State Highway and Transportation Officials, Washington, DC, 2016.
50. *AASHTO M 323, Standard Specification for Superpave Mix Design.* American Association of State Highway and Transportation Officials, Washington, DC, 2017.
51. *Special Provisions for Section 410: Stockpiled Surface Treatment Aggregate ½" Department-Furnished Reclaimed Asphalt Pavement (RAP).* New Mexico Department of Transportation, Santa Fe, NM, 2019.
52. Cortes, D.D., P. Bandini, and R. Rascon-de-Lira. *Determine Binder and HMA/WMA Aging Rates and Their Effects on Mixture/Pavement Cracking Resistance*. New Mexico Department of Transportation, Research Bureau, Report No. NM14MSC-03-009, Albuquerque, NM, 2014.
53. *Pavement Report 2019*. New York State Department of Transportation, Albany, NY, 2019. Available online:

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https://www.dot.ny.gov/divisions/engineering/repository/2019%20Pavement%20Report.pdf, accessed 12/27/2021.

54. FOB (free on board) definition, Available Online: https://en.wikipedia.org/wiki/FOB_(shipping), accessed 12/28/2021.
55. *Comprehensive Pavement Design Manual*. New York State Department of Transportation, Albany, NY, 2000, Portions Revised through September 2021, https://www.dot.ny.gov/divisions/engineering/design/dqab/cpdm, accessed 12/27/2021.
56. *Cold Recycling Mix Design, Materials Management Plan, and Additional Quality Control Requirements*. Materials Method 416-1, New York State Department of Transportation, Albany, NY, 2021.
57. *Hot Mix Asphalt Recycling Using Recycling Agents.* Standard Specifications, Volume 4, New York State Department of Transportation, Albany, NY, January 1, 2022.
58. *NYSDOT Materials Procedure (MP) 417-01- Calibration of Metering System for Recycling Equipment.* New York State Department of Transportation, Albany, NY, January 1, 2022.
59. Bland, F.S. Jr. *Pavement Reclamation in District Four*. South Carolina Department of Transportation, Columbia, SC, 2004.
60. Scullion, T., J. Uzan, S. Hilbrich and P. Chen. *Thickness Design Systems for Pavements Containing Soil-Cement Bases*. Portland Cement Association, Skokie, IL, 2008.
61. *Standard Method of Test for Sampling, Preparing and Testing of Cement Modified Recycled Base Compression Specimens in the Laboratory.* SCDOT Designation: SC-T-26, South Carolina Department of Transportation, Columbia, SC, 2017.
62. *AASHTO T 99-19, Standard Method of Test for Moisture–Density Relations of Soils Using a 2.5-kg (5.5-lb) Rammer and a 305-mm (12-in.) Drop.* American Association of State Highway and Transportation Officials, Washington, DC, 2019.
63. *Supplemental Technical Specification for Cement Modified Recycled Base.* SCDOT Designation: SC-M-306, South Carolina Department of Transportation, Columbia, SC, 2021.
64. *Standard Method of Test for Field Determination of Maximum Dry Density and Optimum Moisture Content of Soils by the One-Point Method.* SCDOT Designation: SC-T-29, South Carolina Department of Transportation, Columbia, SC, 2008.
65. *Quality Acceptance Sampling & Testing Guide.* Section 106, South Carolina Department of Transportation, Columbia, SC, 2021.
66. Campbell, M.L. *Field Evaluation of In-Place Recycling with Portland Cement.* South Carolina Department of Transportation, Columbia, SC, 2013.
67. *Manual of Instructions.* Virginia Department of Transportation, Richmond, VA. Available online:https://www.virginiadot.org/business/materials-download-docs.asp.Accessed: 12/27/2022.
68. Tanyu, B.F, S. Ullah, and E. Akmaz. *Optimizing Reclaimed Asphalt Pavement (RAP) Content in Unbound Base Aggregate*. Virginia Transportation Research Council, Charlottesville, VA, 2021.

APPENDIX A - SAMPLING, TESTING AND ACCEPTANCE REQUIREMENTS

Table A. 1. CIR and CCPR Sampling, Testing and Acceptance Requirements.

Material or Product (Subsection)	Type of Acceptance (Subsection)	Characteristic	Category	Test Methods Specifications	Sampling Frequency	Point of Sampling	Split Sample	Reporting Time	Remarks
Source									
Asphalt binder	Measured and tested for conformance (106.04)	Quality	–	AASHTO M 140, AASHTO M 208, & Subsection 702.02	1 per type and source of material	Asphalt supplier	Yes	Minimum 30 days before production	–
Design									
Emulsified asphalt mix design	Measured and tested for conformance (106.04)	All	–	Subsection 310.03 & FLH T 524	1 per submitted mix design	Existing roadway	Yes	Minimum 30 days before production	For Type A compaction only
Production Start-up (control strip)									
Emulsified asphalt mixture	Measured and tested for conformance (106.04)	Gradation	–	AASHTO T 27	3 minimum	Before emulsion addition	No	Upon completing test	–
		Bulk specific gravity (density)	–	FLH T 524	1 minimum	Loose mix in windrow	"	”	For Type A compaction only
		Density	–	ASTM D2950 & Subsection 310.07(b)	Subsection 310.07(b)	In-place after compaction	"	"	"
		Depth of cut	–	–	3 minimum	Both ends of milling drum	"	"	–

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Table A. 1. CIR and CCPR Sampling, Testing and Acceptance Requirements. (Continued)

Material or Product (Subsection)	Type of Acceptance (Subsection)	Characteristic	Category	Test Methods Specifications	Sampling Frequency	Point of Sampling	Split Sample	Reporting Time	Remarks
Production									
Emulsified asphalt material	Measured and tested for conformance (106.04)	Bulk specific gravity (density)	–	FLH T 524	1 per change in material	Loose mix in windrow	No	Upon completion of test	For Type A compaction only
		Density	–	ASTM D2950 & Subsection 310.07(b)	1 per 2000 yd^2 (1700 m^2)	In-place after compaction	"	End of shift	"
		Depth of cut	–	–	1 per 500 ft (150 m)	Both ends of milling drum	"	"	–
	Process control (153.03)	Gradation	–	AASHTO T 27	Minimum 1 per 3500 yd^2 (3000 m^2)	Before emulsion addition	No	Upon completion of test	–
		Indirect tensile strength(1)	–	AASHTO T 283 (as modified by FLH T 524)	1 per 3500 yd^2 (3000 m^2)	"	"	4 days	"
Emulsified asphalt material	"	Application rates	–	Calculation of yield rate, Subsection 310.08	Minimum 1 per tank load	–	"	"	–
Finished Product									
Cold recycled asphalt base	Measured and tested for conformance (106.04)	Surface tolerance	–	Straightedge measurement, Subsection 310.09(c)	Continuously, after compaction	Finished recycled base surface	No	24 hours	–

[1] Transport samples immediately to a field material laboratory for indirect tensile strength compaction. Compact within 1 hour of sampling.

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Table A. 2. FDR Cement Sampling, Testing and Acceptance Requirements.

Material or Product (Subsection)	Type of Acceptance (Subsection)	Characteristic	Category	Test Methods Specifications	Sampling Frequency	Point of Sampling	Split Sample	Reporting Time	Remarks
Mix Design									
Full depth reclamation (FDR) with cement mixture	Measured and tested for conformance (106.04)	All	–	Subsection 305.03	1 per submitted mix design	Existing roadway	Yes	Minimum 30 days before production	–
Production Start-up (control strip)									
FDR with cement material	Measured and tested for conformance (106.04)	Gradation	–	AASHTO T 27	3 minimum	Behind reclaimer before compaction	No	Upon Completion of test	Minus 2-inch (50-mm) sieve requirement only
		Moisture-density (max density)	–	AASHTO T 134	1 minimum	"	Yes	"	Minimum 4 points per proctor
		Moisture content (in-place)	–	AASHTO T 255	3 minimum	In-place after compaction	No	"	–
		Density	–	AASHTO T 310 or other approved methods	Subsection 305.05(b)	"	"	"	–

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Table A. 2. FDR Cement Sampling, Testing and Acceptance Requirements (continued).

Material or Product (Subsection)	Type of Acceptance (Subsection)	Characteristic	Category	Test Methods Specifications	Sampling Frequency	Point of Sampling	Split Sample	Reporting Time	Remarks
Production									
FDR with cement material	Measured and tested for conformance (106.04)	Moisture-density (maximum density)	–	AASHTO T 134	1 per change of material	Behind reclaimer before compaction	Yes	Before using in work	Minimum 4 points per proctor
		Density	–	AASHTO T 310 or other procedures	1 per 2,000 yd^2 (1,700 m^2)	In-place after compaction	No	End of shift	–
	Process control (153.03)	Gradation	–	AASHTO T 27	Minimum 1 per 3500 yd^2 (3000 m^2)	Behind reclaimer before compaction	"	Upon completion of test	Monitor % passing 2-inch and No. 4 sieves
		Moisture content (in-place)	–	AASHTO T 255 or other approved methods	"	In-place after compaction	"	"	–
		Unconfined compression strength (7-day)	–	Table 305-1	Minimum 1 per day	Behind reclaimer before compaction	"	7 days	7-day cure
Finished Product									
FDR with cement material	Measured and tested for conformance (106.04)	Surface tolerance & grade	–	Subsection 301.06	Determined by the CO	Completed FDR surface	No	Before placement of next layer or as requested	–

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Table A. 2. FDR Cement Sampling, Testing and Acceptance Requirements (continued).

Material or Product (Subsection)	Type of Acceptance (Subsection)	Characteristic	Category	Test Methods Specifications	Sampling Frequency	Point of Sampling	Split Sample	Reporting Time	Remarks
Mix Design									
Full depth reclamation (FDR) with cement mixture	Measured and tested for conformance (106.04)	All	–	Subsection 305.03	1 per submitted mix design	Existing roadway	Yes	Minimum 30 days before production	–
Production Start-up (control strip)									
FDR with cement material	Measured and tested for conformance (106.04)	Gradation	–	AASHTO T 27	3 minimum	Behind reclaimer before compaction	No	Upon Completion of test	Minus 2-inch sieve requirement only
		Moisture-density (max density)	–	AASHTO T 134	1 minimum	"	Yes	"	Minimum 4 points per proctor
		Moisture content (in-place)	–	AASHTO T 255	3 minimum	In-place after compaction	No	"	–
		Density	–	AASHTO T 310 or other approved methods	Subsection 305.05(b)	"	"	"	–

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Table A. 2. FDR Cement Sampling, Testing and Acceptance Requirements (continued).

Material or Product (Subsection)	Type of Acceptance (Subsection)	Characteristic	Category	Test Methods Specifications	Sampling Frequency	Point of Sampling	Split Sample	Reporting Time	Remarks
Production									
FDR with cement material	Measured and tested for conformance (106.04)	Moisture-density (maximum density)	–	AASHTO T 134	1 per change of material	Behind reclaimer before compaction	Yes	Before using in work	Minimum 4 points per proctor
		Density	–	AASHTO T 310 or approved procedures	1 per 2,000 yd^2 (1,700 m^2)	In-place after compaction	No	End of shift	–
	Process control (153.03)	Gradation	–	AASHTO T 27	Minimum 1 per 3500 yd^2 (3000 m^2)	Behind reclaimer before compaction	"	Upon completion of test	Monitor percent passing 2-inch, No. 4 sieves
		Moisture content (in-place)	–	AASHTO T 255 or approved methods	"	In-place after compaction	"	"	–
		Unconfined compression strength (7-day)	–	Table 305-1	Minimum 1 per day	Behind reclaimer before compaction	"	7 days	7-day cure
Finished Product									
FDR with cement material	Measured and tested for conformance (106.04)	Surface tolerance & grade	–	Subsection 301.06	Determined by the CO	Completed FDR surface	No	Before placement of next layer or as requested	–

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Table A. 3. FDR Asphalt Sampling, Testing and Acceptance Requirements.

Material or Product (Subsection)	Type of Acceptance (Subsection)	Characteristic	Category	Test Methods Specifications	Sampling Frequency	Point of Sampling	Split Sample	Reporting Time	Remarks
Source									
Emulsified asphalt	Measured and tested for conformance (106.04)	Quality	–	Subsection 702.02	1 per type & source of material	Asphalt supplier	Yes	Minimum 30 days before production	–
Asphalt binder (foamed)	"	"	–	Subsection 702.01 & Table 306-2	"	"	"	"	–
Mix Design									
Full depth reclamation (FDR) with asphalt mixture	Measured and tested for conformance (106.04)	All	–	Subsection 306.03 & FLH T 522	1 per submitted mix design	Existing roadway	Yes	Minimum 30 days before production	–

Table A. 3. FDR Asphalt Sampling, Testing and Acceptance Requirements. (continued)

Material or Product (Subsection)	Type of Acceptance (Subsection)	Characteristic	Category	Test Methods Specifications	Sampling Frequency	Point of Sampling	Split Sample	Reporting Time	Remarks
Production Start-up (control strip)									
Asphalt binder (foamed)	Measured and tested for conformance (106.04)	Binder temperature	–	Subsection 306.09	1 minimum	Temperature gauge(3)	No	Upon completing test	–
		Half-life & expansion ratio	–	Table 306-2 & FLH T 522	"	Test nozzle on reclaimer	"	"	–
FDR with asphalt material	Measured and tested for conformance (106.04)	Gradation	–	AASHTO T 27	3 minimum	Behind reclaimer before compaction	No	"	Minus 2-inch sieve requirement only
		Moisture-density (wet density)(1)	–	AASHTO T 180, Method D	1 minimum	"	"	"	–
		Moisture content (in-place)	–	AASHTO T 255	3 minimum	In-place after compaction	"	“	–
		Density	–	AASHTO T 310	"	In-place after compaction	"	"	Report wet density
	Visual inspection (106.02)	Homogeneous mixing	–	Subsection 306.05(b)	Subsection 306.05(b)	Behind reclaimer before compaction	"	"	–

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Table A. 3. FDR Asphalt Sampling, Testing and Acceptance Requirements (continued).

Material or Product (Subsection)	Type of Acceptance (Subsection)	Characteristic	Category	Test Methods Specifications	Sampling Frequency	Point of Sampling	Split Sample	Reporting Time	Remarks
				Production					
FDR asphalt material	Measured and tested for conformance (106.04)	Moisture-density (wet density)(1)	–	AASHTO T 180, Method D	1 per change in material	Behind reclaimer before compaction	No	Before using in work	–
		Density	–	AASHTO T 310	1 per 2000 yd^2 (1700 m^2)	In-place after compaction	"	End of shift	Report wet density
	Process control (153.03)	Gradation	–	AASHTO T 27	Minimum 1 per 3500 yd^2 (3000 m^2)	Behind reclaimer before compaction	No	Upon completion of test	–
		Moisture content	–	AASHTO T 255	1 per lane mile (lane kilometer)	"	"	"	–
		Homogeneous mixing	–	Subsection 306.05(b)	Minimum 1 per 3500 yd^2 (3000 m^2)	"	"	"	–
		Binder content of mix	–	Calculation (yield rate)	Minimum 1 per tank load	–	"	"	–
		Indirect tensile strength (2)	–	AASHTO T 283 (as modified by FLH T 522)	1 per 15000 yd^2 (12,540 m^2)	"	"	4 days	–

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Table A. 3. FDR Asphalt Sampling, Testing and Acceptance Requirements (continued).

Material or Product (Subsection)	Type of Acceptance (Subsection)	Characteristic	Category	Test Methods Specifications	Sampling Frequency	Point of Sampling	Split Sample	Reporting Time	Remarks
Production (continued)									
Asphalt binder (foamed)	Process control (153.03)	Binder temperature	–	Subsection 306.09	1 per tank load	Temperature gauge [3]	No	Upon completing test	–
		Half-life & expansion ratio	–	Table 306-2 & FLH T 522	"	Test nozzle on reclaimer	"	"	–
Finished Product									
FDR with asphalt material	Measured and tested for conformance (106.04)	Surface tolerance & Grade	–	Subsection 301.06	Determined by the CO	Completed FDR surface	No	Before placement of next layer or as requested	–

[1] At least 5 points per proctor.
[2] Immediately after collecting sample, transport to a field material laboratory and compact for indirect tensile strength testing.
[3] Measure asphalt binder temperature with a calibrated thermometer.