TechBrief

The Asphalt Pavement Technology Program is an integrated national effort to improve the long-term performance and cost-effectiveness of asphalt pavements. Managed by the Federal Highway Administration through partnerships with State highway agencies, industry, and academia, the program's primary goals are to reduce congestion, improve safety, and foster technology innovation. The program was established to develop and implement suggestions, methods, procedures, and other tools for asphalt pavement materials selection, mixture design, testing, construction, and quality control.

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# Asphalt Pavement Recycling Technologies

*This Technical Brief summarizes techniques successfully used by State DOTs and Federal Lands Highway Divisions to implement use of cold asphalt and hot in-place asphalt recycling technologies.*

*The contents of this document do not have the force and effect of law and are not meant to bind the public in any way. This document is intended only to provide clarity to the public regarding existing requirements under the law or agency policies.*

## Introduction

State Departments of Transportation (DOT) and other agencies are facing greater pressure to integrate sustainability into pavement construction and reduce material costs at the same time.(1) The asphalt industry recycles over 99 percent of reclaimed asphalt pavement (RAP); the majority of it is recycled back in asphalt pavement.(2) This has been driven by the desire for cost-effective alternatives to virgin asphalt binder initially. In some urban areas, RAP supply exceeds demand, resulting in stockpiles of excess RAP; in some rural areas available supply of RAP can be less than demand.(3) Hauling excess RAP from urban to rural areas is not a sustainable practice. This challenge can be addressed using a portable cold central recycling plant or cold in-place or hot in-place recycling techniques. These technologies can also be used in urban areas to increase recycling rates. A National Asphalt Pavement Association (NAPA) 2021 construction season survey stated that 25 companies collectively indicated that they used over 4.8 million tons of RAP by performing in-place recycling processes during the 2021 construction season.(2)

This TechBrief focuses on these sustainable asphalt pavement recycling techniques (APRT): cold in-place recycling (CIR), full depth reclamation (FDR), cold central plant recycling (CCPR), and hot in-place recycling (HIPR).

Cold recycling is a method of reconstructing any flexible pavement where the need arises from structural failures. CIR is 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.(1) FDR is 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 is 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 or additives (if required), mixed, then replaced.(1) With CCPR, the recycled material is milled from a roadway and brought to a centrally located recycling plant that incorporates the recycling agents into the material.(4)

The objective of this effort was to learn more about successful practices and lessons learned for implementation of APRT.

### Benefits of Using Asphalt Pavement Recycling Techniques (APRT)

These sustainable APRT offer many potential benefits versus other rehabilitation or reconstruction techniques that mitigate or eliminate distresses in existing pavement including:

- Cost savings, reduced energy consumption, conservation of natural resources, and user delays.
- Reuse of some or all of the existing pavement materials, plus pavement geometry (profile and cross-slope) may be corrected while preserving overhead clearances and improving pavement structural capacity and pavement performance.

Other benefits can include reducing the large quantities of RAP previously stockpiled in some parts of states by using CCPR; not generating RAP surplus by using CIR, FDR, and HIPR; increased speed of construction; and making deeper repairs in a pavement structure than would be made with conventional mill and fill alternatives providing a substantial structural pavement foundation.

## Virtual Site Visits

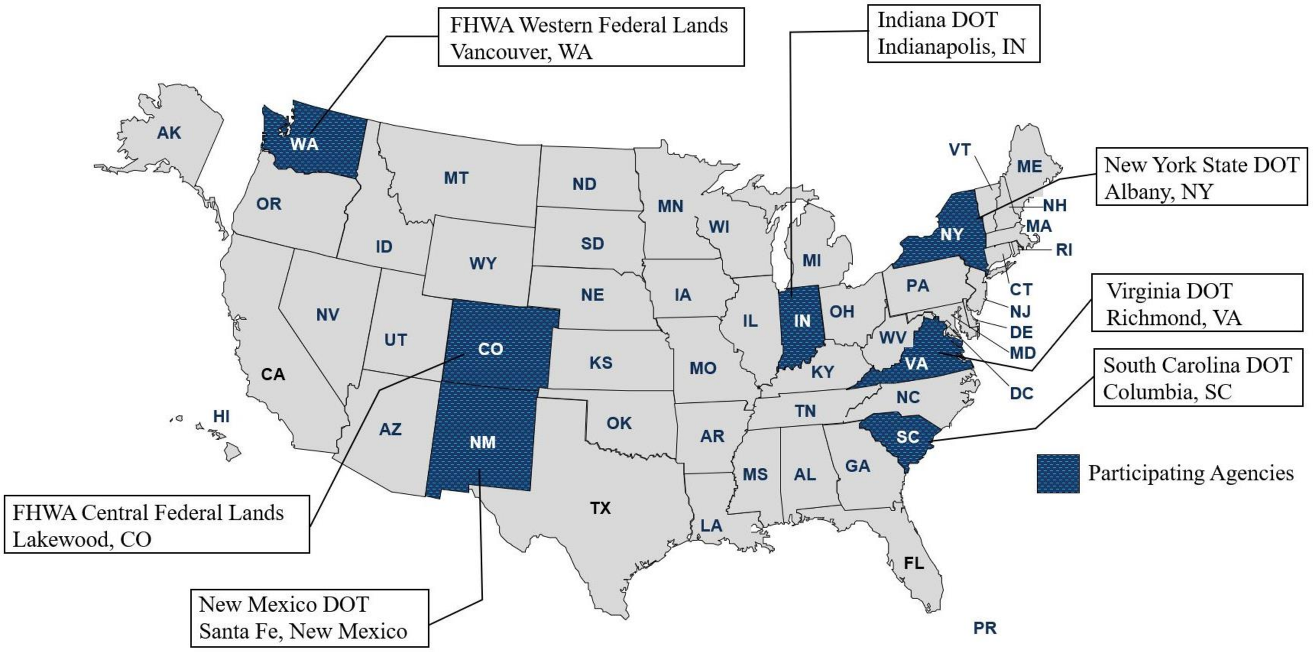
Interviews of State DOTs and FHWA Federal Lands Highway Offices, were used to learn more about successful practices and recommendations for implementing recycling technologies. The interviews included: project/recycling technology selection criteria, structural pavement design, materials and mix design, field construction and acceptance, and agency stated best practices and lessons learned.

Figure 1 shows that the participating agencies were geographically dispersed across the U.S. and include Central Federal Lands (CFL), Western Federal Lands (WFL), Indiana DOT (INDOT), New Mexico DOT (NMDOT), New York State DOT (NYSDOT), South Carolina DOT (SCDOT), and Virginia DOT (VDOT). Federal Lands Highway (FLH) will be used to collectively refer to CFL and WFL. Table 1 shows a summary of recycling techniques used by each agency. NMDOT uses all four techniques, SCDOT only uses FDR, and the other agencies use three. Table 2 shows the number of years of agency experience with the APRT and they range from as few as three up to 50 depending on the APRT. Several agencies indicated interest in using more CCPR in the future.

Table 3 shows approximately what percentage each of the recycling techniques represents, relative to the agency's total of CIR, CCPR, FDR and HIPR recycling programs. The reported percentages are typical over a multiple year period.

**Table 1. Recycling techniques used by each agency.**

| Recycling Technique | FLH | INDOT | NMDOT | NYSDOT | SCDOT | VDOT |
|---|---|---|---|---|---|---|
| CIR | Yes | Yes | Yes | Yes | No | Yes |
| CCPR | Yes | Yes | Yes | Limited | No | Yes |
| FDR | Yes | Yes | Yes | No | Yes | Yes |
| HIPR | No | No | Yes | Yes | No | No |




Source: University of Nevada Reno

**Figure 1. Map of participating State DOTs and Federal Lands Offices.**

**Table 2. Years of agency experience using recycling technologies.**

| Recycling Technique | FLH | INDOT | NMDOT | NYSDOT | SCDOT | VDOT |
|---|---|---|---|---|---|---|
| CIR | 50 | 5-10 | 3 | $20^+$ | n/a | $10^+$ |
| CCPR | 15 | 5-10 | 8 | $5^+$ | n/a | $10^+$ |
| FDR | 40 | 5-10 | 9 | n/a | 7 | $13^+$ |
| HIPR | 50 | n/a | $20^+$ | $15^+$ | n/a | n/a |

**Table 3. Percentage of recycling program by agency and recycling technique.**

| Recycling Technique | FLH | INDOT | NMDOT | NYSDOT | SCDOT | VDOT |
|---|---|---|---|---|---|---|
| CIR | 6% | 38% | 10% | 50 to 65% | 0% | 20% |
| CCPR | 6% | 12% | 40% | <1% | 0% | 18% |
| FDR | 88% | 50% | 50% | 0% | 100% | 62% |
| HIPR | 0% | 0% | n/a | 35 to 50% | 0% | 0% |

## Quantifying Recycling Technique Cost, Performance, and Sustainable Benefits

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. Recently, Life Cycle Assessment (LCA) has been used to quantify the environmental aspects of pavements. In FHWA Technical Brief HIF-22-033, "Life Cycle Assessment of Pavements," LCA was described as "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."(4) Robinette and Epps successfully used LCCA and LCA in 2010 to illustrate and quantify economic and environmental aspects of in-place asphalt recycling techniques.(5) The LCCA showed cost savings and the LCA showed reduced environmental impacts compared to traditional reconstruction techniques.

Recently completed NCHRP Synthesis 569, Practice and Performance of Cold In-Place Recycling and Cold Central Plant Recycling stated, "The reported service life of cold recycled pavements ranges from 20 to 34 years when the cold recycled mix is used in conjunction with an overlay. The service life is somewhat shorter and more variable when chip seals are used as the wearing surface. Poor drainage can reduce the service life by 30% or more," and "Cold recycling with an overlay can reduce the cost of a project by 40% to 60% compared to a conventional mill and fill. Greenhouse gas emissions can be reduced by about 50% compared to a conventional mill and fill."(6) Structural pavement performance and life cycle assessment analyses on two CIR and two CCPR pavements in Alabama indicated that energy consumption was reduced 56 to 64 percent, and greenhouse gas emissions were reduced 39 to 46 percent compared to new asphalt pavements.(7)

There are many options available for rehabilitating a pavement, and selection of the most appropriate and cost-effective approach is an important engineering decision during the project development phase. FLH have established through life-cycle cost analysis that cold recycled asphalt techniques have lower life-cycle costs than conventional construction methods when local materials and contractors are available. This analysis is also supported by pavement management system models. This information is used to explain 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 has reported overall good performance with the cold asphalt recycling techniques. Techniques used to assess performance include visual observations, pavement management data and light weight deflectometer (LWD). Direct comparisons of conventional rehabilitation and recycling rehabilitation are difficult to find. A reasonable sample size for comparison simply is not available. However, recycled sections are performing well as illustrated in Figure 2, which shows pavement condition rating (PCR) versus time in years for FLH CIR and FDR projects. An overall PCR is based on a combination of surface condition rating (SCR), that includes rutting, cracking (transverse, longitudinal, and alligator), patching/potholes, and roughness condition index (RCI) which is based on International Roughness Index (IRI). Asphalt PCR is calculated weighting SCR at 60 percent and RCI at 40 percent. A PCR of 95-100 is Excellent/New, 85-94 is Good, 61-84 is Fair, and 60 or below is Poor. Every CIR constructed by CFL is still in service with some having up to 35 years of service. According to FLH, as illustrated in Figure 2, CIR and FDR surfaced with five inches of HMA are performing particularly well, while FDR surfaced with three inches of HMA is more variable, though still performing well overall.(8)

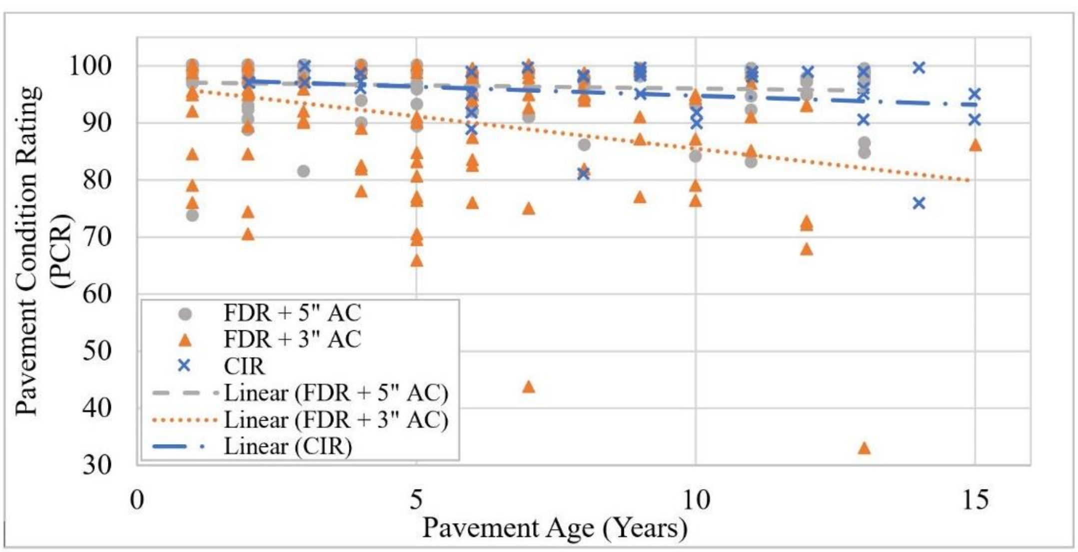



**Figure 2. Pavement performance versus time.(8)**

An analysis of the structural performance and cost associated with FDR compared to conventional rehabilitation was performed by INDOT.[9] Subgrade and surface deflection data showed significant improvements in structural capacity with the FDR construction. Figure 3 shows that the FDR cost is saving 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 recycling would be significantly less than for a replacement project. INDOT indicated a key point is FDR projects provide a new structural foundation that should provide better long-term performance for the investment.

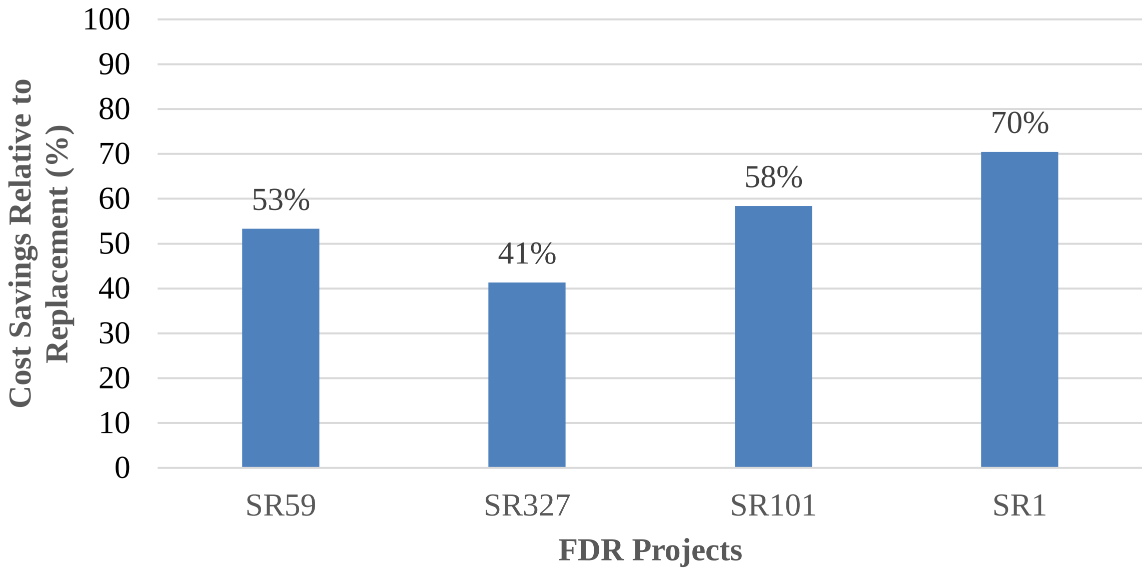



**Figure 3. INDOT percent cost savings per lane mile for FDR versus replacement.**

NMDOT reported overall good performance with cold asphalt recycling and HIPR techniques. Two districts indicated maintenance activities, timing, and frequency for recycled pavements were similar to control mixes. NMDOT is collecting cost and performance data over time that can be used to communicate the successful use of recycling and sustainable benefits in the future. The time for construction of FDR was reported to be reduced significantly when compared to reconstruction, hence reducing user impacts and safety risks.

NYSDOT reported overall good performance with the cold asphalt recycling techniques, and 30 to 40 percent initial cost savings over the conventional alternatives (i.e., overlay or mill and overlay). 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.

SCDOT reported good overall performance of cement modified recycled base (CMRB) (i.e., FDR with cement) and indicated that there are initial cost benefits with using it for roads needing additional structure or greater amounts of patching. SCDOT reported 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 select CMRB over a traditional mill and fill alternative 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 is considered a perpetual base, requiring only resurfacing after the design life.

VDOT reported overall good performance with the cold asphalt recycling techniques. Techniques used to assess performance include visual observations, falling weight deflectometer (FWD), and instrumentation in pavements. 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. VDOT sections on the National Center for Asphalt Technologies (NCAT) test track show that the recycled sections are a perpetual pavement. A perpetual pavement is a three-layer, flexible pavement design and construction concept that produces a deep-strength asphalt pavement resistant to structural fatigue distress for a long time period (e.g. 50 years). At this point in time, it is difficult to draw comparisons with 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.

VDOT recently conducted a study to quantify potential environmental benefits of recycled asphalt pavement projects considering three restorative maintenance projects, two of which include CIR, as well as five reconstruction projects that included FDR with asphalt, FDR with cement, CCPR, and FDR with lime stabilized base.(10) When the system boundaries were from cradle-to-laid (excluded service life) it was reported that pavement recycling projects used for interstate reconstruction and primary route restorative maintenance resulted in lower carbon footprint than those with non-recycling designs. The cradle-to-laid boundary was selected for comparison because when the entire life cycle was included, the authors indicated that approximately 98 percent of the total carbon footprint was associated with pavement–vehicle interaction that occurs during the use phase.

## Summary of Observations by Category

Each State DOT involved in this review has a methodology to successfully use APRT. Over time, project/recycling technology selection criteria, structural pavement design methodology, materials and mixture design requirements, and construction and acceptance specifications have been developed by each agency. Highlights from each participating agency on these topics follow.

### Project/Recycling Technology Selection Criteria

When an agency uses APRT, it is important that policy, materials selection, mixture design, and construction specifications clarify how to use them for successful pavement performance. FHWA Tech Brief HIF-17-042, Overview of Project Selection Guidelines for Cold In-place and Cold Central Plant Pavement Recycling, indicates that applying the right treatment to the right road at the right time can result in significant agency cost savings stretching agency dollars. (11)

FLH has a Project Design and Development Manual (PDDM) that provides FLH staff and contractors detailed guidance on selection of projects for using recycling technologies.(12) A chapter contains guidance on preliminary pavement 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 alternatives recommended.
- Recommended follow-up testing or additional information gathering.

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.(13) Figure 4 is a helpful INDOT Pavement Recycling Treatment Selection Flowchart. In summary, existing pavement type, roadway classification/traffic level, required patching, and FDR subgrade CBR are criteria used to identify and select recycling technologies for use.

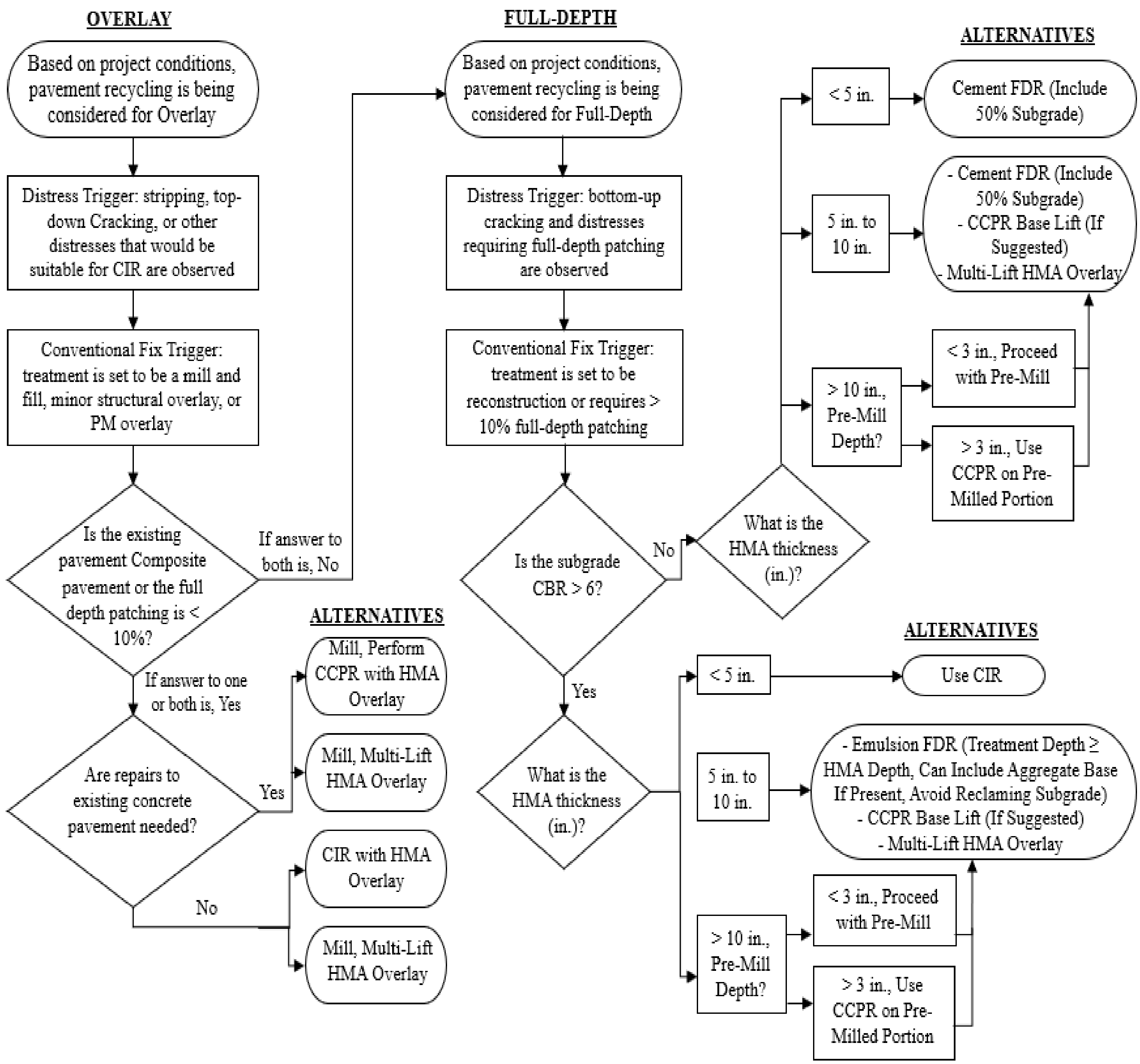



**Figure 4. INDOT Pavement Recycling Treatment Selection Flowchart.(14)**

NMDOT recommendations are not specifically based on roadway classification, traffic level, geographic location or climatic region. Recycling techniques have been used on Interstate pavements including Interstate 25 (I-25) and Interstate 40 (I-40).

The NYSDOT Comprehensive Pavement Design Manual (CPDM) provides designers with a single-source of current NYSDOT policy and guidance to pavement designs for projects falling under the jurisdiction of the NYSDOT.(14) The CPDM Chapter 3: Pavement Evaluation and Treatment Type Selection Process is focused on the process to be used for treatment selection. 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). Figure 5 is NYSDOT's cold asphalt recycling guide for conditions in the CPMD. Chapter 3 of the CPDM shows relationships among pavement treatments, funding sources, work type (i.e., preservation, rehabilitation, new construction, or reconstruction), processing, and implementation. It states requirements for minimum service lives, pavement evaluation, treatment selection, and life cycle cost analysis for 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 a preservation treatment with no traffic restrictions on its use. NYSDOT indicated that it and other public agencies in the state specify HIPR.

Chapter 5 of the CPDM; Appendix 5A, Pavement Rehabilitation Manual, Volume II: Treatment Selection; includes guidelines for each treatment NYSDOT uses, including sections on Conditions for Use, Constructability, Performance, Expected Failure Modes, and Expected Service Life. The procedure for treatment selection includes 10 steps leading to selection of the best treatment strategy based on existing pavement condition, treatment alternatives, design life, and estimated cost.

SCDOT indicated that the driving factor on rehabilitation/reconstruction for the majority of routes that would use CMRB (i.e., FDR with cement) is based on lowest initial cost due to the existing condition or required structure of the road, as well as feasibility of using CMRB in the construction process given existing pavement cross section and Management of Traffic (MOT) requirements. Selection is between CMRB and traditional mill and fill. Individual investigations for routes deemed to be potential candidates for other treatments need to be performed. A decision to switch from mill and fill to CMRB would be based on depth of distresses and existing versus required structural needs. When patching exceeds 15 to 20 percent, then CMRB is very commonly selected because it is more cost-effective, and it results in a uniform pavement structure. With CMRB, only one lane is constructed at a time and opened at the end of the day. Thus, traffic is indirectly considered since extended lane closures are only used for major projects. CMRB is not performed on concrete pavements.

The VDOT has a Materials Manual of Instructions (MOI) that provides detailed guidance on selection of projects for using recycling technologies.(15) Section 608, Chapter VI of the MOI includes multiple criteria and directs the pavement engineer to consider recycling when more than four inches of milling will be needed to remove deteriorated pavement. If recycling is not chosen, justification as to why it was not selected is to be included in the project pavement design report.

Finally, NCHRP Synthesis 569, Practice and Performance of Cold In-Place Recycling and Cold Central Plant Recycling, provides limited information on pavement traffic levels associated with the use of cold asphalt recycling technologies. Based on a survey, "A total of 40 agencies responded… Most cold recycling programs pave less than 50 lane-miles per year. Cold recycling is frequently used on roadways with annual average daily traffic (AADT) under 10,000, but more experienced agencies use cold recycling on roadways with AADTs between 10,000 and 25,000." (6)

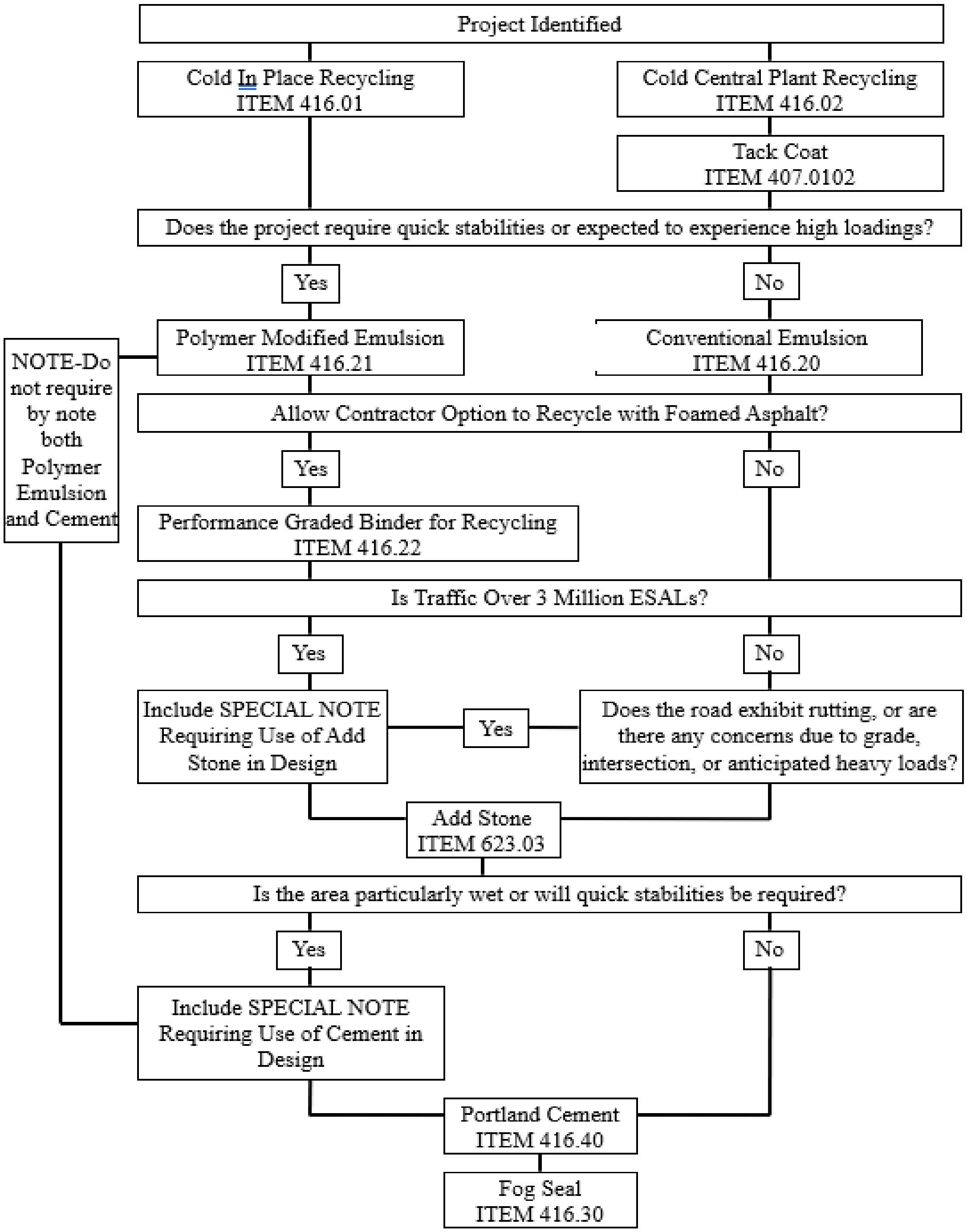



**Figure 5. NYSDOT Cold Recycling Treatment Selection Flowchart.[(15)]**

## Structural Pavement Design

Most participating agencies involved in this effort use the AASHTO[1] Guide for Design of Pavement Structures 1993.[(16)] Table 4 shows layer coefficients or modulus used by agencies. FLH uses the AASHTO[1] Guide for Design of Pavement Structures 1993 with the other inputs (e.g., terminal serviceability, reliability, etc.) unchanged, and dynamic modulus used to develop or validate layer coefficients.[(18)] Light weight deflectometer (LWD) was used for validation of FDR (mechanical) and FDR (cement) layer coefficients.

[1] Use of this AASHTO guide is not a Federal requirement.

**Table 4. Layer coefficients or moduli used for pavement designs.**

| Technology | FLH Layer Coefficients | INDOT Resilient Modulus | NMDOT Layer Coefficients | NYDOT n/a | SCDOT Layer Coefficients | VDOT Layer Coefficients |
|---|---|---|---|---|---|---|
| CIR | 0.28-0.30 | 75-100ksi | 0.35 | n/a[1] | n/a | 0.35 |
| CCPR | 0.25-0.30 | 75-100ksi | 0.35 | n/a | n/a | 0.35[2] |
| FDR with Asphalt | 0.20-0.25 | 75-100ksi | 0.30 | n/a | n/a | 0.25 |
| FDR with Cement | 0.15-0.22 | 75-100ksi | n/a | n/a | 0.26 | 0.25 |

[1]NYSDOT typically has very thick pavements, so formal structural design is not performed.
[2]CCPR is not modeled per the AASHTO[1] Mechanistic Empirical Pavement Design Guide, an 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.(13)

INDOT develops pavement designs using the AASHTO[1] Mechanistic-Empirical Pavement Design Guide with details in Chapter 601 of the INDOT Design Manual.(13) Designers of INDOT projects obtain location specific PG grade and mixture type inputs for each district. The software does not directly handle recycled materials so INDOT uses a resilient modulus range of 75 to 100ksi for CIR and FDR.

NMDOT performs pavement designs per the AASHTO[1] Guide for Design of Pavement Structures 1993. Structural layer coefficients for each cold asphalt recycling and HIPR technique were developed based on indirect tensile strength (ITS) tests and verified with FWD back calculation. The NMDOT pavement design procedure integrates the layer coefficients in Table 4.

NYSDOT uses the AASHTO[1] Guide for Design of Pavement Structures 1993. NYSDOT indicated that existing pavement structures are typically very thick, so a formal pavement design is not regularly conducted. If the site investigation identifies localized structural issues, then it is addressed with a planned additional deep section repair.

SCDOT uses the AASHTO[1] Guide for Design of Pavement Structures 1972, with an FDR (CMRB) layer coefficient of 0.26.(19) This has allowed SCDOT to modify both depths and strengths.(20) The same effort led SCDOT to reducing the amount of cement in CMRB and increased thicknesses. The structural design method is considered conservative, and for project specific conditions with high traffic the required structural number may be adjusted based on mechanistic empirical analysis.

VDOT uses the AASHTO Mechanistic-Empirical Pavement Design Guide for new construction (new lane-miles, new alignment, new or existing routes) and for reconstruction on Interstates and Primary routes. Chemically stabilized materials, like FDR, are modeled as a high-quality aggregate base in a flexible system. CCPR is not modeled in the AASHTOWare[1] Pavement ME software. An 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 like mill-and-fill or straight overlays, the AASHTO[1] Guide for Design of Pavement Structures 1993 is used.(17) The following layer coefficients 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.

## Materials and Mix Design

A high-level summary of the agencies' materials and mix design requirements for each recycling technology follows. Specific details on materials and mix design test methods and criteria can be found in Reference 20, Cold Asphalt and Hot In-place Asphalt Recycling Technologies, as well the specifications and test methods referenced for each participating agency.

### *Cold In-place Recycling (CIR)*

Five of the participating agencies use CIR. FLH and NMDOT use engineered emulsions, INDOT uses emulsions, and NYSDOT and VDOT use emulsion or foamed asphalt. NYSDOT also uses polymer modified emulsion. All of the agencies allow portland cement as an active filler, while FLH and NMDOT also allow lime. All agencies have CIR gradation requirements with 100 percent passing the top sieve size of 1.25 to 2.0 inches and they all allow the use of supplement aggregates. All agencies use gyratory compactions for mix design, except VDOT which uses gyratory or 75 blow Marshall compaction. FLH applies 35 gyrations, while FLH, INDOT, NMDOT, and VDOT apply 30 gyrations. FLH uses emulsions indirect tensile strength (ITS) and tensile strength ratio (TSR) tests; Marshall stability, retained stability, and raveling tests are used by INDOT; NMDOT uses ITS, TSR, coating tests, and raveling tests; NYSDOT uses ITS and TSR or retained Marshall stability; and VDOT uses Marshall stability and retained stability. When using foamed asphalt NYSDOT uses ITS and TSR or retained Marshall stability while VDOT uses ITS, TSR, expansion ratio, and half-life.

### *Cold Central Plan Recycling (CCPR)*

Five of the participating agencies use CCPR. FLH, INDOT, NYSDOT and VDOT use the same materials and mix design tests for CCPR that are used for CIR depending on if they are made with emulsion or foamed asphalt. One exception is that for CCPR gradation, 100 percent must pass the 1.5 to 2.0 inch sieve depending on agency. NMDOT only uses foamed asphalt for CCPR, portland cement active filler, 100 percent passing the 1.0 inch sieve, 75 blow Marshall compaction, Marshall stability, ITS, TSR and moisture density relationship (MDR) tests.

### *Full Depth Reclamation with Asphalt (FDR Asphalt)*

Four of the participating agencies use FDR asphalt. FLH and VDOT use emulsion or foamed asphalt with portland cement as an active filler for FDR Asphalt. INDOT only uses emulsion, while NMDOT only used foamed asphalt. For FDR gradation 100 percent must pass 1.5 to 3.0 inch sieves depending on the agency. Gyratory compaction is used by FLH, INDOT and VDOT. FLH applies 35 gyrations, while INDOT and VDOT apply 30 gyrations. NMDOT and VDOT use 75 blow Marshall compaction. VDOT uses Marshall compaction for FDR made with emulsion and gyratory compaction for foamed asphalt FDR. For FDR with emulsion, FLH uses ITS and TSR; INDOT uses ITS dry and ITS wet; and VDOT uses Marshall Stability tests. For FDR with foamed asphalt, FLH uses ITS, TSR, expansion ratio and half life; INDOT uses ITS dry and ITS wet, and VDOT uses ITS, TSR and half life.

### *Full Depth Reclamation with Cement (FDR Cement)*

Four of the participating agencies use FDR cement. FLH, INDOT, SCDOT and VDOT typically use portland cement, while FLH may also use lime and VDOT may also use lime or kiln dust. With FDR cement, lime is sometimes used to help break up heavy clay. For FDR gradation, 100 percent must pass the 1.5 to 3.0 inch sieve depending on the agency with FLH requiring 1.5 inch and NMDOT requiring 3.0 inch. FLH and VDOT use AASHTO T134[1] to define moisture density relationships, while INDOT uses AASHTO T180[1] and SCDOT uses AASHTO T99[1]. All four agencies use unconfined compressive strength (UCS). FLH and INDOT use both minimum and maximum UCS, while SCDOT uses UCS to find the percent portland cement that yields UCS of 600 psi. FLH also uses a freeze thaw mass loss test.

### *Hot In-place Recycling (HIPR)*

NMDOT and NYSDOT utilize HIPR. There are three types of HIPR processes used, heater scarifying, remixing, and repaving.[(4)] NMDOT uses remixing and repaving. Recycling agent is used for both processes, an ARA-1P recycling agent which contains at least 1.5 percent Styrene-Butadiene-Styrene (SBS) polymer. The dose used must restore the aged binder to meet the PG binder grade requirement for the project specific location. NMDOT mix designs are performed with a gyratory compactor using 30 gyrations and design air voids of 4 percent. The Hamburg Wheel Track Test is used to evaluate rutting and moisture sensitivity and ITS is used to assess cracking potential.

NYSDOT uses the HIPR heater scarifying method with recycling agents. 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 but less than 90 percent of the existing HMA prior to heater scarifying recycling activity. A method specification is used for the compaction requirement.

## Field Construction and Acceptance

Each of the participating agencies have unique field construction, quality control and acceptance requirements for each recycling technology. Details and references to specifications and test methods can be found in Reference 21. High-level summaries associated with each recycling technique used by the participating agencies follow.

### *Cold In-place Recycling (CIR)*

All five of the participating agencies using CIR have related quality control or acceptance requirements including CIR gradation, moisture content, emulsion rate, density, thickness, and surface tolerances. NYSDOT also includes asphalt content. Additionally, FLH and NMDOT have ITS requirements. The FLH density requirements are 97 percent of control strip or a method specified number of passes. The INDOT density requirement is 97 to 102 percent of control strip. The NMDOT density requirement is a percent of control strip with payment that is a function of the observed average density. The NYSDOT density requirement is a minimum number of passes and 96 to 110 percent of peak target density. The VDOT density requirement is a percentage of the approved mix design density with payment that is a function of the observed density.

### *Cold Central Plant Recycling (CCPR)*

The CCPR field construction, quality control, and acceptance requirements are essentially the same as the CIR requirements for the agencies, with a few exceptions. INDOT has an additional smoothness requirement and the agencies using foamed asphalt (NMDOT, NYSDOT, and VDOT) may include expansion rate and half life. Density requirements are different for each agency. The FLH density requirement is 97 percent of AASHTO T180[1] wet density. The INDOT density requirement is 95 percent of AASHTO T180[1] maximum density. The NMDOT density requirement is a percentage of the average density from the prior days' production. The VDOT density requirement is a percent of the approved mix design density.

### *Full Depth Reclamation with Asphalt (FDR with Asphalt)*

All four of the participating agencies using FDR have related quality control or acceptance requirements for FDR asphalt that include pulverization depth; FDR gradation, moisture content, emulsion or binder rate, and density. FLH also include expansion rate and half life. NMDOT includes stability and ITS. INDOT and NMDOT also include proof rolling requirements. The FLH density requirement is 97 percent of AASHTO T180[1] wet density. The INDOT density requirement is 95 percent of AASHTO T180[1] maximum density. The NMDOT density requirement is a percentage of the average density from the prior days' production. The VDOT density requirement is a percent of the approved mix design density.

### *Full Depth Reclamation with Cement (FDR with Cement)*

All four of the participating agencies using FDR cement have quality control or acceptance requirements including gradation, moisture content, emulsion or binder rate, and density. FLH, INDOT, and SCDOT also include UCS. NMDOT includes stability and ITS. The FLH density requirement is 95 percent of AASHTO T134[1] maximum density. The INDOT density requirement is 95 percent of AASHTO T180[1] maximum density. The SCDOT density requirement is 95 percent of AASHTO T99[1] maximum density, and the VDOT density requirement is a percentage of the approved mix design density based on AASHTO T134[1].

## Curing and Opening to Traffic for Cold Recycling Technologies

Curing time and opening to traffic are important considerations for CIR and CCPR. Table 5 is an example of a summary of the requirements of the participating agencies for CIR and CCPR. There is less consistency among the agencies in terms of both moisture contents and days compared to other requirements.

**Table 5. CIR and CCPR curing time and opening to traffic criteria.**

| Item | FLH | InDOT[1] | NMDOT | NYSDOT | VDOT |
|---|---|---|---|---|---|
| Traffic | 0 for 2 hours | n/a | 0 for 2 hours | n/a | 0 for 2 hours |
| Moisture Content | ≤ 2.5% | ≤ 3.0% | ≤ 3.0% | n/a | ≤ 50% of OMC |
| Time | Cover within 14 days | ≥ 3 days | ≥ 3 days | Emulsion ≥ 10 days; Foamed Asphalt ≥ 3 days | n/a |

[1]Greater than 3 days and less than 3.0% moisture or cured 10 days without rainfall.

# Agency Reported Successful Practices and Lessons Learned

Over 100 successful practices and over 80 lessons learned were identified by the participating agencies.[(20)] Highlights of these successful practices and lessons learned follow.

## Agency Successful Practices

Successful practices identified by the participating agencies include:

- Requiring preparatory planning meetings, QC plans, just in time training, and use of control or test strips to demonstrate production and construction capability (all agencies).
- Having the equipment sections of specifications clearly define control, metering, and calibration requirements for all materials used with recycling equipment (INDOT, NMDOT, NYSDOT, VDOT).
- Requiring mix designs developed by accredited labs (INDOT, NMDOT, NYSDOT, SCDOT).
- Using recycling techniques to minimize impacts on National Parks prioritizing cold asphalt recycling technologies when designing projects and selecting materials, which is rational as many projects are constructed in remote locations (FLH).
- Specifications having clear material testing and inspection requirements by source, design, production startup (control strip), production, and finished product in tabular form with responsibilities and how the results are used (FLH).
- Having detailed pavement recycling treatment selection flowcharts (INDOT, NYSDOT).
- Having a pay item for the stabilizer helps insure the proper dose is used (INDOT).
- Proof rolling FDR asphalt is a requirement in specifications (INDOT, NMDOT).
- Specifying the cold milling equipment be used to obtain RAP samples for CIR mix design that will be used during construction, and milling the existing pavement surface to the depth it will be removed during construction prior to obtain millings for mix design purposes (NMDOT).
- Collecting cost and performance data as a function of time for communicating successful use of recycling, as well as the sustainable (cost, environmental, societal) benefits (NMDOT).
- Use of a single statewide contract for DOT and municipalities coupled with NYSDOT commitment to consistently have a sizeable APRT program provides municipalities efficiency benefits and a DOT vetted specification (NYSDOT).
- Having identified a patching level at which CMRB (FDR with cement) is more cost effective than patching prior to rehabilitation (SCDOT).
- Having a standing quality improvement committee for recycling with SCDOT, contractor, and FHWA representatives (SCDOT).
- Applying multiple cold asphalt recycling techniques on low and high-volume roads with minimum project length requirements for different cold recycling technologies (VDOT).
- Requiring a qualified technical expert be on site with early recycling projects for some trial sections to start or if first trial section failed, plus requiring certified technicians familiar with recycling on projects with recertification each 5 years (VDOT).
- Using of fixed stabilizer doses for bidding purposes (VDOT).

### Agency Lessons Learned

Lessons learned about recycling technologies by the participating agencies include:

- Holding pre-project planning meetings, requiring QC plans, just in time training, and use of test strips can all minimize risk and lead to better overall project outcomes (all agencies).
- Recognizing that weather conditions can significantly impact recycling production, constructability, and curing; resulting in operational and schedule changes for successful construction (all agencies).
- Performing adequate project investigation to understand site subsurface and pavement variability, geometric constraints, drainage, etc. is essential for recycling type selection, materials designs, and successful project design and construction (FLH, INDOT, NMDOT, SCDOT, VDOT).
- Using multiple recycling technologies on the same project can be successful and cost effective even on high volume projects (INDOT, VDOT).
- Obtaining adequate in-place density is critical to good performance and use of test strips can assist with this (FLH, VDOT).
- Having procurement methods that make it possible for recycling contractors to enter and stay in a market, like alternative bidding and statewide contracts (INDOT, NYSDOT).
- Having annual end of season stakeholder meetings where participants openly discuss challenges and opportunities that can lead to improved materials, test methods, specifications, and construction (NMDOT, NYSDOT, SCDOY, VDOT).
- Using excess portland cement in FDR cement will lead to cracking (NMDOT, SCDOT).
- Edge cracking of FDR cement can be reduced by placing the FDR 6 to 12 inches wider than the planned asphalt pavement (INDOT, SCDOT).
- Recognizing it is possible to re-recycle cold recycled asphalts (NYSDOT).

## Research and Training Needs Identified

The participating agencies identified the following research needs associated with recycling techniques:

- Education as to the benefits of recycling and application of the technologies so that the technologies are broadly embraced (INDOT, VDOT).
- The need to document performance of recycling techniques over performance lives (FLH, INDOT).
- The ability to integrate cold recycling technologies in the PavementME Software and/or improve modulus and layer coefficients for the 1993 AASHTO[1] Pavement Design (INDOT, SCDOT).
- An FDR mix design process optimizing UCS mix design criteria to provide adequate structural capacity without excess shrinkage cracking in FDR (SCDOT).
- Quantifying the variability of performance tests due to inherent in-place recycling techniques so rational design and acceptance criteria can be established for the performance tests (NYSDOT).
- Project selection guidelines (refine traffic levels, thin overlays) for various applications (VDOT).
- Determination of the best surfaces to use with cold recycled technologies including chip seals, micro surfacing, HMA, and white topping (INDOT).
- Having a funding mechanism for cold recycling when a reduced carbon footprint will occur, such that grants to get credit for using these technologies can be obtained (INDOT).
- The ability to determine the rate of RAP aging in stockpiles and ability to measure oxidation in asphalt pavements at highway speeds while collecting pavement condition data (NMDOT).
- Defining moisture levels at which cold recycled asphalt could be opened to traffic (VDOT).

## Summary

The use of CIR, CCPR, FDR and HIPR can provide cost savings while conserving natural resources and significantly reducing cradle through construction related greenhouse gas emission, when compared to conventional rehabilitation or reconstruction of asphalt pavements. Other benefits can include reducing the large quantities of RAP previously stockpiled in some parts of states by using CCPR; not generating RAP surplus by using CIR, FDR, and HIPR; increased speed of construction; and making deeper repairs in a pavement structure than would be made with conventional mill and fill alternatives which can provide a more substantial structure pavement foundation. Recent national work indicates that cold recycled pavement lives of 20 years or more are common, and that using cold recycled pavement can reduce construction costs and greenhouse gas emissions by about 50 percent, compared to conventional mill and overlay.(6)

A range of techniques and criteria used by agencies specifying APRT were identified and summarized. Examples of how participating agencies select cold recycling techniques for use at the project level were presented along with how the agencies address the recycled materials in structural pavement designs. Commonly used materials, mix design procedures, and field construct practices were presented that other agencies might find useful. Agency identified best practices and lessons learned based on experience using the recycling technologies were also highlighted. Collectively, the information indicates that desired performance can be observed with appropriate project selection, design, production, and construction.

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# Asphalt Pavement Recycling Technologies

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