Best Practices for
Construction of
Cold Central Plant Recycling and
Cold In-Place Recycling of Asphalt Pavements

Prepared for the
AASHTO TSP-2
by the
Emulsion Task Force (ETF)

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A final review of the document will be provided by the ETF's Messaging and Implementation Subcommittee headed up by Larry Tomkins of Ergon.

Disclaimer

The opinions expressed in this document are those of the authors and do not necessarily reflect the view of the AASHTO TSP-2 ETF or AASHTO Committee on Materials and Pavements (COMP).

Forward

This document titled “Best Practices for the Construction of Cold Central Plant Recycling and Cold In-Place Recycling of Asphalt Pavements” was developed solely to address CCPR and CIR using emulsified asphalt.

The objective of this document is to provide the user with the knowledge and guidance necessary to construct CCPR and CIR pavement that provides the expected service life or life extension. It is a summary of best practices for CCPR and CIR that addresses the following:

- Introduction and Terminology
- Material Requirements
- Preconstruction
- Equipment
- Construction Operations
- Quality Assurance
- Checklists
- Conclusions and Recommendations

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1 INTRODUCTION

Cold In-Place Recycling (CIR) and Cold Central Plant Recycling (CCPR), both considered Cold Recycling (CR) processes, are asphalt pavement rehabilitation methods that reuse existing materials without the application of heat, resulting in benefits such as lower cost, lesser environmental impacts, and reduced construction time compared to non–recycling-focused rehabilitation options. CIR and CCPR can address many asphalt distresses such as raveling, rutting, cracking, and potholes while conserving non-renewable resources and energy.

Although CR technology has existed for several decades, materials and processes have evolved over the years. With these improvements, CR has become a more attractive alternative to traditional mill and fill projects and its use has increased among state/provincial and local agencies to rehabilitate pavements with varying levels of traffic in all climatic zones.

1.1 Terminology

CIR is the on-site recycling process in which the existing asphalt pavement is recycled using a specialized train of equipment potentially including tanker trucks, milling machines, crushing/screening or sizing units, mixers, pavers, and compaction rollers. The CIR process can use up to 100% of the on-site generated reclaimed asphalt pavement (RAP) and an asphalt-based recycling agent (foamed asphalt or emulsified asphalt) with or without a combination of active fillers (e.g., lime, cement, and aggregate) to produce the CIR mixture. The CIR process typically treats to a depth of 75 to 100 mm (3 to 4 inches) but depths up to 150 mm (6 inches) are not uncommon. The CIR mixture is used as a restored pavement layer and then overlaid with a surface treatment or hot/warm mix asphalt (HMA) surface course depending on the structural and functional requirements of the roadway.

CIR is not to be confused with Full Depth Reclamation (FDR). FDR is defined by the Asphalt Recycling and Reclaiming Association (ARRA) as the rehabilitation technique in which the full thickness of the asphalt pavement and a predetermined portion of the underlying materials (base, subbase, and/or subgrade) is uniformly pulverized and blended to provide an upgraded, homogeneous material.

CCPR is the process of recycling millings either from the current or another rehabilitation project (s) or from existing stockpiles of RAP using a mobile recycling plant located at or near the job site. This plant is typically equipped with a screen deck; a pugmill mixing unit; and a mechanism(s) to add water, a recycling agent, and active fillers if needed. The CCPR material is then trucked to the project and placed using conventional paving equipment where it functions as a base or binder layer and is then overlaid with a surface treatment or asphalt overlay. The material can be placed in multiple lifts if needed before the surface course is placed.

1.2 Purpose of Document

The purpose of this document is to summarize the best practices for CIR and CCPR and to identify areas where more research is needed to improve current practices.

1.3 Document Organization

This document is organized in accordance with the Draft Construction Guide Specifications submitted to AASHTO as a product of this research. There are, however, areas where there are departures either to create a better document flow or to avoid replication in multiple sections of the document.

2 MATERIALS

2.1 Reclaimed Asphalt Pavement (RAP)

According to ARRA (2015), RAP is to have the following characteristics when used for CR:

- The RAP material is to be free of contamination of dirt, base, concrete, or other deleterious materials such as silt and clay. Rubberized crack filler, pavement markers, loop wires, thermoplastic markers, paving fabric, and other geosynthetics are to be removed as observed.
- The RAP material is to be reclaimed from the roadway and sized to meet specific contract requirements. The typical specified maximum RAP size ranges from 1.0 to 1.5 inches (25-38 mm). The maximum RAP size is no larger than one-third of the compacted layer thickness.
- The RAP material is to have a consistent gradation. A wet sieve analysis in the field down to an intermediate sieve size indicates the consistency of the RAP and can be used for comparison with the mix design gradation to adjust the asphalt recycling agent rate.
- An example of a RAP crushing and screening unit is shown in Figure 1.

Figure 1. RAP Crushing/Screening Unit (courtesy HRG)

2.2 Asphalt Recycling Agents

Either emulsified asphalt or foamed asphalt is to be used as asphalt recycling agents for CR. The optimum amount of emulsified asphalt or foamed asphalt is determined in accordance with an agency-approved mix design procedure or in accordance with AASHTO PP 86 and AASHTO PP 94, which ensures the CR mixtures have adequate workability and performance. Excess recycling agents can result in an unstable mixture that is subject to rutting and shoving. Too little recycling agent can result in segregation and surface raveling when the road is opened to traffic.

2.2.1 Emulsified Asphalt

Any emulsified asphalt used must be in accordance with AASHTO materials specifications M 140, M 208, and M 316. Upon delivery to the project, check each load of emulsified asphalt delivered for temperature and premature breaking/separation before use. The temperature of each load can be checked using an infrared hand-held digital thermometer or thermometer independent of that fitted to the tanker. Breaking/separation can be checked by a visual sieve test using a No. 20 (0.85 mm) sieve using a field-modified version of AASHTO T 59, Section 12, as shown in Figure 2. Do not heat emulsified asphalt above the supplier's recommendations, generally no more than 160 °F (70 °C).

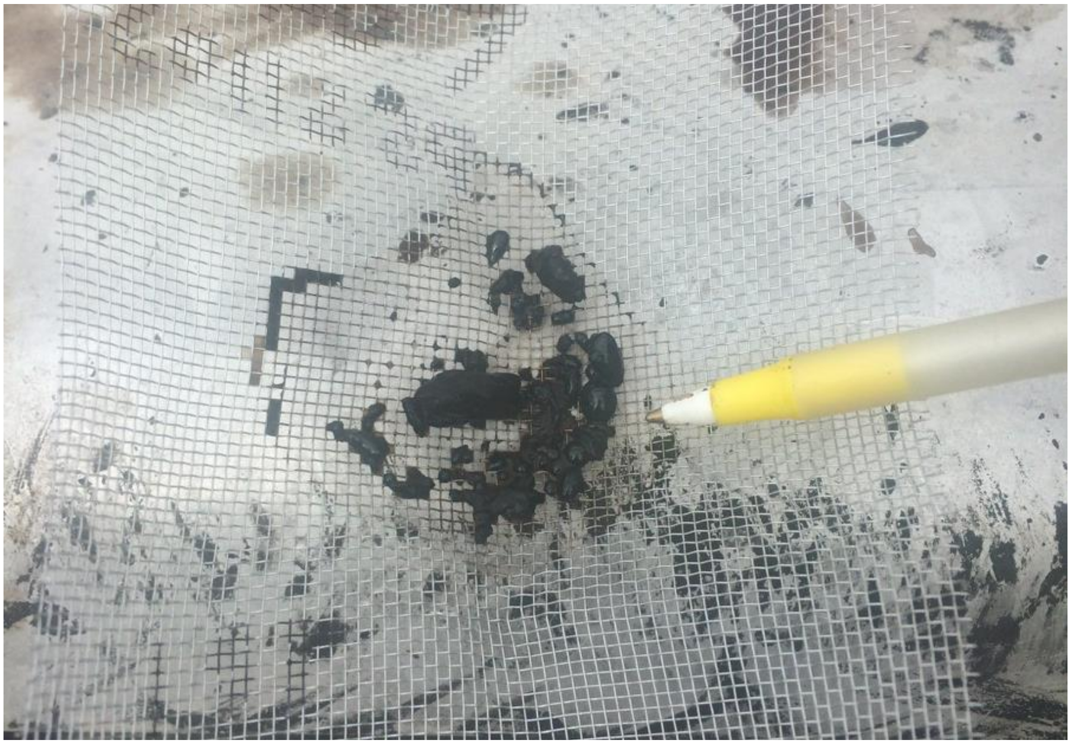

Figure 2. Results from sieve test on emulsified asphalt recycling agent (courtesy ARRA).

2.2.2 Foamed Asphalt

Check that any asphalt binder used for foamed asphalt is in accordance with agency requirements and the mix design. Use the same Performance Grade (PG) asphalt binder for foaming and from the same source as used in the mix design. Verify that the foamed asphalt meets the minimum expansion ratio and half-life requirements in accordance with AASHTO PP 94. All CR equipment must be equipped with a test nozzle on the spray bar or a similar device to allow sampling. The typical testing frequency is once per load of asphalt binder delivered. Ensure the temperature of each load of asphalt cement is within the recommended range for proper foaming. Typically, the asphalt binder must be greater than 320 °F (160 °C) to achieve optimum foaming characteristics. Generally, the temperature of the asphalt binder must not exceed 375 °F (190 °C). Measure the temperature of the asphalt using an infrared measuring device or thermometer independent of that fitted to the tanker. Figure 3 shows the foaming nozzle and test bucket on a Cold Central Plant Recycling plant that is used to check the foaming properties of the binder.

Figure 3. Foaming nozzle and test bucket on a CCPR plant.

2.3 Water

The water used for CR is to be clean and free from deleterious concentrations of acids, alkalis, salts, sugars, and other organics, and chemical or deleterious substances. This is because water containing these substances can cause an adverse effect on the recycling agent or the recycled pavement mixture. If the water is not from a potable supply or is of questionable quality, have it tested to ensure it is suitable? For foamed asphalt, filter water so that on evaporation no deposits or residue is left behind that might clog or impede water flow to the foaming nozzles of the recycling unit.

2.4 Active Filler

When required by the mix design, portland cement, hydrated lime, or lime slurry are used as active fillers to improve CR mixture properties. Apply active fillers at the rate specified in the mix design to ensure that optimal performance of the CR material is achieved. Improper addition of active fillers can result in a structurally weak layer, poor durability, excessive cracking, or a brittle layer.

2.4.1 Portland Cement

Portland cement can be added in either a dry or slurry form and is used in asphalt-based CR mixtures as an active filler. The minimum dry solids content for slurry made from cement is 30%. Ensure any cement used is in accordance with AASHTO materials specifications M 85 and M 240 for Type I or II cement. To prevent the brittle behavior of the mixture, the added cement content is typically less than or equal to 1% by weight of dry RAP. The ratio of residual asphalt in the asphalt recycling agent to dry cement is usually less than 2.5:1 or 2:1 to prevent the brittle behavior of the CR mixture.

2.4.2 Lime

Quicklime or hydrated lime is typically added in a slurry form. The minimum dry solids content for slurry made from lime is 30%. Ensure any quicklime or hydrated lime is in accordance with AASHTO M 216. The added lime content is typically no more than 1% to 1.5% by dry weight of RAP.

2.4.3 Other

Other cementitious or pozzolanic materials such as fly ash have been occasionally used in the past in CR mixes. If an alternative active filler is used, it is important to test its characteristics within the mix design and ensure that it does not compromise the gradation, mix strength, or moisture susceptibility of the mix.

2.5 Corrective Aggregates (Coarse and Fine Aggregates)

Corrective aggregate must meet the gradation and physical property requirements dictated by the mix design and agency specifications for non-surface HMA. Corrective aggregate is most often spread in front of the CIR train or added in appropriate proportions at the CCPR plant. The aggregate addition rate is determined by volumetric distribution using weigh tickets from the haul trucks and the applied area. The milling process may increase the fines content of the mixture above that is determined from crushed cores used in the mix design. The amount depends on many factors including the type of existing aggregates. Therefore, do not add fine aggregates, especially natural sands, to CR mixtures unless the effect on performance is thoroughly evaluated. Adding new fines could lead to a loss of stability, difficulty in coating RAP when the emulsion is used, and increased moisture susceptibility.

There is little guidance in the literature on the use of corrective aggregate and the practice is not common. Croteau and Davidson (2006) reported on situations where it may be advantageous to use corrective aggregate, as shown in Table 1. Gradation ranges are for the aggregate extracted from the RAP or pavement layer to be recycled. The authors also stated that corrective aggregate is often required for RAP with more than 5.5 to 6.0% asphalt before recycling.

Table 1 Use of corrective aggregate based on extracted RAP aggregate gradation (Croteau and Davidson, 2006).

% Passing No. 4 Sieve of extracted RAP aggregate	Action
45-65	No corrective aggregate
65-75	Corrective aggregate if compacted voids are less than 9%
> 75	Corrective aggregate required

3 MIX DESIGN PROCESS

The mix design process is a laboratory procedure that establishes a job mix formula (JMF) for a CR mixture that meets project specifications and helps ensure the performance characteristics required for the long-term service life of the recycled pavement. The contractor usually submits the JMF for approval by the agency unless the JMF is already provided by the agency. Perform the mix design procedure with representative materials to be encountered during the CR process. When the in-place materials change significantly, additional JMFs will be needed. Obtain representative samples of the in-place materials directly from the project site by representative sampling and deliver them to an AASHTO- or agency-approved laboratory experienced in performing CR mix designs. The mix design is used as the baseline measure (or reference) for the rate of recycling agent, water, and active fillers (active filler, and corrective aggregate if required), blended with the RAP to construct the recycled mixture. Although not required by most specifications, the mix design also should indicate the allowable tolerance for the application of recycling agent, water, active filler, and corrective aggregate so as not to jeopardize the performance of the mixture but allow the contractor to adjust the mixture so that it may be placed successfully.

3.1 Sampling Procedures

The sections that follow contain best practices for mix design sampling from the listed AASHTO provisional procedures, ARRA's CR201 and CR202 Recommended Mix Design Guidelines, and the Basic Asphalt Recycling Manual. Mix design sampling is often combined with project selection and evaluation sampling and testing. For example, Dynamic Cone Penetrometer (DCP) testing during sampling is typically performed to assist with thickness design and to determine relative subgrade strengths. Ground Penetrating Radar (GPR) testing can also be conducted to assist in the sampling plan by identifying areas of non-uniform thickness. Therefore, much of the information presented here applies to project selection, sampling, and testing. Additional information regarding project testing, which is often performed during mix design sampling, can be found in Section 4 Project Selection.

3.1.1 Sampling Existing Pavement for CIR and CCPR

Obtain representative samples of RAP to design the CR mixture. The purpose of the samples is to use them for mix design. If pavement thickness is not previously known, the sampling can be used to determine if the thickness of the existing pavement is suitable for the recycle depth proposed. The level of sampling is dependent on many factors including the selected reliability of the design, level of risk, length of the project, and testing required.

Develop a sampling plan that adequately determines the physical properties of the RAP along the length, width, and depth of the project. The gradation of RAP and properties of the mineral aggregate will affect the amount of recycling agent and active fillers and final mixture performance. Therefore, it is important to obtain representative field samples. A visual evaluation can be made along with a review of any available construction and maintenance records to determine whether significant differences in materials will be encountered during recycling. Sections of the roadway with significant differences in materials may be delineated and treated as separate sampling units to ensure representative sampling. A sampling plan often also includes an evaluation of the project cross-sections, etc., which can be determined by testing and visual evaluations.

Samples for mix design and analysis are required for each major difference in observed material types and should not be lumped together in a single mix design. For example, if one area is composed of aged, oxidized, dense-graded asphalt overlay and another area is composed of an open-graded asphalt mixture on top of a less distressed, dense-graded asphalt mixture, two sets of samples are recommended for design and analysis. Another example would be if one area contains a single chip seal and another has multiple seals. With CCPR, if the materials for the entire project can be adequately blended into a single stockpile, separate mix designs are generally not necessary.

After the project is divided into smaller representative segments, obtain samples of the pavement from each representative segment. Representative segments may be defined by homogeneous pavement structures, traffic levels, cut/fill sections, etc. Obtain all samples from the full depth of the pavement to be recycled. If during sampling visual observations indicate greater variation in materials within a segment (i.e., large patches, high binder content mixes, etc.), additional samples may need to be obtained and separated for individual mix designs. Sampling locations and their descriptions are recorded on a sampling log.

Samples are most often obtained as cores or milled RAP from the areas to be recycled. Coring is the traditional method of obtaining field samples. Collect cores that are at least 6 inches (150 mm) in diameter and obtained to the full depth of the pavement (to the underlying base or subgrade soil). This is necessary for CIR as the thickness of the pavement after milling must be evaluated to ensure that the remaining pavement can support the weight of the recycling train. When assessing the possibility of equipment break-through, there is generally little concern if at least 6 inches of aggregate base or 1 inch of asphalt remains, even with low DCP blow counts. If there remains concern about break-through, consider leaving additional aggregate base or pavement thickness (ARRA, 2015).

On retrieval, measure each core to the nearest 1/8 inch (3 mm) and place each in a separate labeled container. Record the date, station, offset, core thickness, depth of asphalt layers to aggregate base, subgrade, or concrete; thickness of individual layers; and type of material in the projected recycled depth in a coring log and provide it to the mix design laboratory.

Samples may be obtained by milling provided the milling machine produces a consistently graded RAP similar to the RAP gradation expected during recycling operations. Small milling machines are not recommended since the consistency of samples between different types of milling machines is highly variable. The gradation of samples obtained by small milling machines is not as coarse, with smaller maximum particle size and more fines, i.e., material passing the No. 200 (0.075 mm) sieve than what is produced by large milling machines typically used during the CR process.

If millings are used, ensure that only millings that represent the pavement to be recycled are collected. If a portion of the existing pavement surface is planned to be milled and removed during construction, mill the pavement in a similar manner and remove the surface before milling for sampling. Mill and sample only to the planned recycle depth. The material may be obtained from one test location for each mix design.

Block sawing is economical for obtaining large samples for mix design purposes when the pavement assessment has shown the pavement materials to be uniform. However, coring allows more sample locations and thus a better cross-section of the area to be recycled.

Obtain at least 350 lb. (160 kg) of usable material for each mix design. Usable material is defined as having representative cores of length equal to (or greater) the recycling depth. Use only that portion of cores or millings to be recycled for mix design purposes.

Based on recommendations from ARRA 2017a and ARRA 2017b, use the following to calculate the minimum number of cores and the recommended sampling frequency for mix design. Equation 1 may be used to determine the minimum number of cores needed for each 350 lb. (160 kg) batch per mix design using an assumed unit weight of 145 lb./ft^3 (2.324 g/cm^3). For different mix design weight requirements or unit weights, the number of cores should be proportional. When using Equation 1, only consider the depth of recycling, any material remaining below the depth of recycling should be trimmed and not used for mix design purposes. The following can be found in ARRA 2017a and ARRA 2017b:

> Equation [1] may be used to determine the number of cores needed for every 350 lbs. (160 kg) per mix design at a core unit weight of 145 pcf (2.324 g/cm^3). For different mix design weight requirements or unit weights of cores, the number of cores should be proportioned. When using equation [1] only consider the depth of recycle. The remaining material below the depth of recycling should be trimmed and not used for mix design purposes.
>
> <u>English Units</u>
>
> $$\text{CMD} = [5{,}311] / [(D^2)\,(\text{CRMD})] \qquad [1a]$$
>
> where:
> CMD = number of cores per the mix design
> D = core diameter (in)
> CRMD = cold recycle milling depth (in)
>
> <u>SI Units</u>
>
> $$\text{CMD} = [83{,}881{,}233] / [(D^2)\,(\text{CRMD})] \qquad [1b]$$
>
> where:
> CMD = number of cores per the mix design
> D = core diameter (mm)
> CRMD = cold recycle milling depth (mm)
>
> For example, if a 3-inch (75-mm) depth of recycling is proposed and the pavement has a unit weight of 145 pcf (2.324 g/cm^3) then the following number of 6-inch (150-mm) diameter cores are needed:
>
> $$\text{CMD} = [5{,}311] / [(6)^2(3)] = 49.2 \text{ or } 49 \text{ cores}$$
>
> $$\text{CMD} = [788{,}881{,}233] / [(150)^2(75)] = 49.7 \text{ or } 50 \text{ cores}$$
>
> Cores should be obtained using a pattern that results in a representative sample of the pavement to be recycled including at or near lane lines, within and between wheel paths, at the pavement edge, and within shoulders if shoulders are to be recycled. ARRA (CR201 & CR202) recommends the roadway be sampled using either staggered/offset sampling (as illustrated in Figure 4 [modified from ARRA 2017a and ARRA 2017b]) or crossroad sampling with no offset (as illustrated in Figure 3). In the figures below D is the sampling distance and L is the offset distance with the offset distance L typically being equal to D/2. With staggered or offset sampling the cores are obtained in one lane at a prescribed sampling rate of D and offset a distance L in the adjacent lane. With crossroad sampling, all cores across both lanes are obtained at a prescribed sampling rate of D with no offset between lanes.

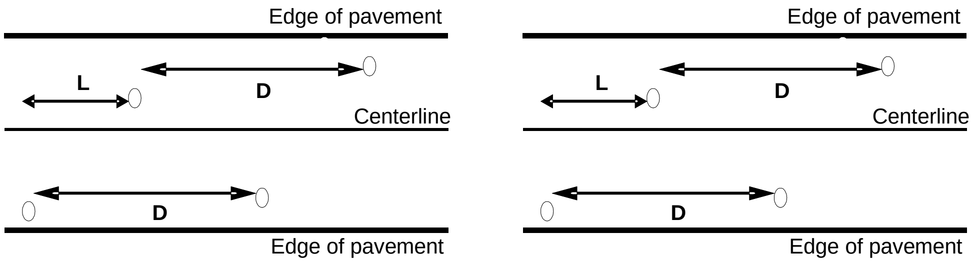

Figure 4 Staggered (offset) sampling, left, and crossroad sampling, right.

ARRA recommends the following minimum rate of coring:

Highways or Airports
 D – 1-mile maximum (1.6 km)
 L – 0.5 mile maximum (0.8 km)
 At least 15% of the cores should be in the shoulder if the shoulder is getting recycled.
 At least 25% of the cores should be on or within 3 feet (1 m) of the centerline.

Arterial and Industrial Streets
 D – 2,000 feet maximum (600 m)
 L – 1,000 feet maximum (300 m)

At least 25% of the cores should be in the shoulder if it is getting recycled or within 3 feet (1 m) of the gutter.
At least 25% of the cores should be on or within 3 feet (1 m) of the centerline.

Residential Streets
Streets less than 250 feet long (75 m), one core when grouped with other streets to obtain the quantity of material required for mix design.

Streets 250 feet to 500 feet (75 m to 150 m) long, two cores when grouped with other streets to obtain the quantity of material required for mix design. One within 3 feet (1m) of the gutter the other within 3 feet (1 m) of the centerline.

Streets over 500 feet (150 m) long, three cores when grouped with other streets to obtain the quantity of material required for mix design. One within 3 feet of the gutter (1 m), one within 3 feet (1 m) of the centerline, and the third between the two.

3.1.2 Sampling for CCPR

For this Best Practices Guide, three types of CCPR are defined depending on where the RAP or millings are obtained and where they will be placed as a CCPR mix: (1) *Same Project CCPR*, where the RAP is milled, hauled to a centrally located CCPR plant, and returned as a CCPR mix to the same location; (2) *Imported Project CCPR*, where the RAP is milled from one location, hauled to a centrally located CCPR plant, and taken as a CCPR mix to a different location; and (3) *Imported Stockpile CCPR*, where millings from an existing stockpile are processed at a CCPR plant and the CCPR mix is hauled to the project location.

For the Same Project and Imported Project CCPR, sampling can occur from the in-place roadway as discussed in Section 3.1.1, but if the project timeline permits, it is better to obtain actual stockpile samples for the mix design. The Imported Stockpile CCPR sampling is performed from existing stockpiles.

When sampling from a stockpile, obtain approximately 350 lb. (160 kg) of RAP for the mix design and at least 30 lb. (14 kg) more if asphalt content, recovered binder properties, or aggregate properties of the RAP are desired. To ensure the stockpile samples accurately represent the materials in the stockpile, remove the stockpile crust in accordance with AASHTO R 97, section 5.2.7, and then sample the RAP in accordance with AASHTO R 97.

In most cases, a RAP stockpile is not fractionated (i.e., separated by sizes) but rather consists of a single pile meeting a maximum RAP size. The RAP can be fractionated into two or three sizes for better batch-to-batch mixture uniformity throughout the recycling project, as shown in Figures 5 and 6. Good RAP crushing operations, coupled with good stockpile management, assure increased uniformity of daily RAP stockpile gradations.

Figure 5 Fractionating RAP (Courtesy ARRA)

Figure 6 Fractionating RAP (Courtesy ARRA)

3.1.3 Shipping

If the material sampled from the field must be shipped, protect them from damage during shipping by using sturdy containers (plastic or metal buckets, small strong plastic tubs, or concrete cylinder molds) shipped individually (if few in number) or together on a pallet. Include sample identification information on all sample containers. Do not use cardboard boxes as they can break down due to the weight of the samples and moisture content from coring. Include a copy of the sampling log, protected in a sealed container and/or delivered electronically, with the shipment of samples. Common containers include plastic 5-gallon buckets with sealed lids or metal/plastic 50-gallon drums.

3.1.4 Repairing Sample Holes

The technique used to repair sampling locations depends on the process used to obtain the sample. For larger milled areas on higher volume roadways, a small paver may be needed to repair adequately. For smaller cored holes, filling with a high-quality cold patch material or HMA is most often used. Add and compact the repair material in multiple lifts to achieve good compaction throughout the thickness of the repair, with the final lift being flush with the existing pavement. Clean the roadway of all loose debris. For core holes, use a tamping rod or Marshall hammer (having a round head of equal or lesser diameter than the core hole diameter) to compact the patch material. Insufficient compaction of the repair will eventually lead to a depression at the pavement surface.

3.2 Mix Design Procedures

Although many agencies have their mix design procedures for CR mixtures, it is recommended that mix designs follow either AASHTO or ARRA procedures. ARRA's mix design procedures are found in CR201 for emulsified asphalt and CR202 for foamed asphalt (ARRA 2017) The AASHTO procedures can be found in PP 86 and MP 31 for emulsified asphalt and PP 94 and MP 38 for foamed asphalt. The ARRA and AASHTO procedures are similar in many aspects.

The AASHTO and ARRA mix design procedures recommend RAP be batched to the gradation expected during recycling. An alternative and more common procedure (especially for CIR) is to perform the mix design using two of the three recommended gradations in the AASHTO or ARRA procedures. Using multiple gradations allows the designer to bracket the gradations anticipated in the field and allows the contractor to adjust recycling agent content during production based on knowledge from the mix design process.

Specimens for mix design are usually produced using either the Superpave Gyratory Compactor or Marshall Hammer. Specimens are compacted to 30 gyrations with a gyratory compactor or 75 blows per face using Marshall compaction. Most mix design procedures include testing specimens for initial and cured strength and resistance to moisture damage. Some mix design procedures include testing raveling resistance and resistance to thermal cracking (cold climates only). An alternative to testing the thermal cracking resistance is to require that the binder in the recycling agent meets the bending beam requirements of AASHTO M 320 for the project location.

3.2.1 AASHTO Mix Design Procedures

Ensure that the emulsified asphalt or foamed asphalt used for the CR mix design complies with AASHTO Specifications PP 86 and MP 31 or PP 94 and MP 38. According to these specifications, a CR mix design incorporates the following steps:

- Obtain samples from the existing pavement or existing RAP stockpile, as required.
- Determine sample binder content and gradation of extracted aggregate.
- Determine aged binder properties, if desired.
- Crush materials to produce RAP and check gradation versus specification.
- Select the type and grade of asphalt recycling agent.
- Select the type and amount of active filler and corrective aggregate, if required.
- Prepare and test specimens.
- Establish the JMF.
- Establish limits for field adjustments to recycling agents and water contents as necessary.

3.2.2 Binder Content Determination and Extracted Aggregate Gradation

When determining the binder content and aggregate gradation from samples of RAP used for CR, only characterize the layer to be recycled. Determine the binder content using an ignition furnace in accordance with AASHTO T 308 or extraction procedure in accordance with AASHTO T 164. Determine the recovered aggregate gradation in accordance with AASHTO T 30 as there may be interest in particle shape testing, though there are no current guidelines for acceptable angularity and other aggregate properties. Measuring the RAP binder content during mix design is important as it can be used to verify the amount of asphalt recycling agent added during production by subtracting the binder content of the RAP before adding any asphalt recycling agent from the binder content of the CR mixture (both determined using the ignition oven).

If there are concerns about binder stiffness due to using a stockpile where plant waste material or a stockpile/pavement where a new pavement and thus unaged RAP (i.e., soft RAP binder) are being used, the binder may be extracted and tested for its performance grade properties. Tests on recovered binder generally include penetration at 77 °F (25 °C) (AASHTO T 49) and/or the absolute viscosity at 140 °F (60 °C) (AASHTO T 202). The use of dynamic shear rheometer testing (AASHTO T 315) to determine shear modulus (G*) and phase angle (δ) for evaluation of existing binder properties is under study. There are currently no guidelines on what performance grade and subsequent criteria are appropriate for the RAP binder, and characteristics are generally only used for informational purposes, if at all.

3.2.3 Recycling Agent

The correct selection of the type and grade of recycling agent is necessary for the proper performance of CR projects. With regards to recycling agent selection, it is recommended to allow contractors to use whichever recycling agent (i.e., emulsified asphalt or foamed asphalt) they are most comfortable using, and that demonstrates they can be used to meet the desired properties during the mix design. Emulsified and foamed asphalt have been shown to have similar performance (NASEM 2017). Use of the recycling agent the contractor is most comfortable with usually will yield higher construction quality. The mix design process will assist the designer with the selection of the type and appropriate amount of recycling agent.

3.2.4 Active Filler and Corrective Aggregate

Active filler is often used to improve the strength, rutting resistance, and moisture resistance of CR mixtures, and corrective aggregates are occasionally used to adjust the gradation of CR mixtures. Active fillers consist of Portland cement (Type I or Type II), lime, fly ash, and other pozzolanic or cementitious materials. Portland cement is typically limited to no more than 1% by weight of the mixture to prevent brittle behavior. The *Basic Asphalt Recycling Manual* recommends a maximum ratio of residual asphalt to Portland cement of 3:1 (ARRA 2015); however, 2:1 to 2.5:1 is most often seen in practice. When lime is used as the active filler, it is typically added at a rate of 1% to 1.5% by weight of the RAP (ARRA 2015). The mix design will assist the designer with determining the need for and selecting the appropriate type and amount of active filler and corrective aggregate.

3.2.5 CR Specimen Preparation and Testing

Specimen preparation and testing should follow the requirements of AASHTO PP 86 and PP 94 or ARRA’s CR201 or 202. Specimens are batched to the desired RAP gradation and different masses based on the requirements of the mix design tests. Water is added to the RAP before the addition of foamed asphalt to simulate the water content typically added at the milling head, 1.5% to 2.5%. Additional water may be required to optimize compacted density and mixture properties.

For most emulsified asphalt recycling agents, additional water will be required for adequate coating and to aid in the compaction of the materials. The amount of water required for coating is usually greater than that needed to facilitate compaction. It is recommended that the coating of the RAP particles be checked to ensure sufficient mixing water is included. For foamed asphalt recycling agents, additional water is not required for coating but is typically required to aid in compaction.

Before the mixing of the RAP with the recycling agent, water, and any active fillers, the RAP is brought to the desired mixing temperature of 77 ± 9 °F (23 ± 5 °C). Using a bucket mixer, hand mixer, or laboratory scale pug mill, mix the emulsified asphalt recycling agents with the RAP, water, and any active fillers at the manufacturer’s recommended temperature (typically ambient). Using a bucket mixer, hand mixer, or laboratory scale pug mill, mix foamed asphalt recycling agents with the RAP, water, and any active fillers at the optimum temperature to achieve the required expansion ratio and half-life. The designer will need to provide a method to produce foamed asphalt that is similar to what will be used during production.

After mixing, specimens are compacted immediately at an ambient temperature of 77 ± 9 °F (23 ± 5 °C) using specified compaction energy or effort. Typical compaction efforts are 75 blows per face with a Marshall hammer in accordance with AASHTO T 245 or 30 gyrations using a Superpave Gyratory Compactor in accordance with AASHTO T 312.

CR mixtures must lose their excess water, or cure, to develop their maximum strength. After compaction emulsified asphalt samples are most often cured at 140 ± 2 °F (60 ± 1 °C) to a constant mass and for no more than 48 hours; foamed asphalt samples are cured at 104 ± 2 °F (40 ± 1 °C) to a constant mass and for no more than48 hours. After curing, specimens are cooled until they reach an internal temperature of 77 ± 9 °F (23 ± 5 °C), usually overnight.

The current practice of strength and moisture sensitivity testing consists of assessing either Marshall Stability in accordance with AASHTO T 245, or the indirect tensile strength in accordance with AASHTO T 283. Stability tests are most often used for mixtures with emulsified asphalt recycling agents with indirect tensile strength testing for mixtures with foamed asphalt recycling agents. Before strength and moisture resistance testing, determine the bulk density of each compacted and cured specimen in accordance with AASHTO T 166. The raveling test (ASTM D7196) is also recommended to evaluate breaking and initial curing for CR mixtures using emulsified asphalt as the recycling agent. Although not a part of the AASHTO or ARRA procedures, the thermal cracking potential of CR mixtures using emulsified asphalt as the recycling agent, a bending beam test may be performed in accordance with AASHTO M 320, or a thermal cracking test performed in accordance with AASHTO T 322 and has been used by a few agencies.

3.2.6 Job Mix Formula

The JMF identifies the optimum recycling agent content, type and grade of asphalt recycling agent, mix water content, and any active filler type and quantity, if used. The JMF also reports the laboratory-compacted density at the recycling agent and moisture content that exhibits the best coating and meets the other performance requirements for mixtures using emulsified asphalt as the recycling agent. The JMF will report the laboratory compacted maximum density at the optimum recycling agent content and moisture content that meets the other performance requirements for mixtures using foamed asphalt as the recycling agent.

3.2.7 Field Adjustments

Adjustments to the JMF will be required as conditions warrant during production. Field personnel experienced in CR construction shall have the authority to make slight adjustments in mix water, recycling agents, and active filler contents based on field conditions.

3.2.9 Optional High-temperature Evaluation

ARRA CR201 includes a procedure to evaluate reduced emulsified asphalt recycling agent content on mix properties due to higher construction temperatures. At higher temperatures, the RAP binder will be less viscous and will allow compaction to a higher density. At higher density, less emulsified asphalt recycling agent is often required to pass the mix design tests. If recycling agent contents are not reduced accordingly, flushing and or mix instability could occur, especially with higher traffic levels. ARRA's optional high-temperature validation procedures quantify the effect of higher temperatures and lower recycling agent contents on performance.

The higher temperature validation consists of reducing the optimum emulsified asphalt recycling agent content by 0.25 to 0.50 percent and mixing and compacting samples at 104 ± 4 °F (40 ± 2 °C). Compaction molds are pre-heated to 104 ± 4 °F (40 ± 2 °C) as well. Six specimens are prepared for strength and moisture sensitivity testing and tested as in the original mix design. Two samples at the medium RAP gradation are prepared for the raveling test (ASTM D7196). Immediately after compaction, the specimens are conditioned at 77 ± 2 °F (25 ± 1 °C) at 50% relative humidity before testing as described in Section 3.2.6. Procedures and calculations are performed in accordance with ASTM D7196. Samples tested for optional high-temperature validation should meet the same requirements as outlined in the specifications at ambient temperatures.

4 PROJECT SELECTION

As discussed previously, CR can be used as a form of pavement rehabilitation or pavement preservation for existing deteriorated pavements or used in the construction of new lanes or new pavement structures. For existing pavements, it is important to consider the pavement condition from both a network-level and a project-level perspective. From a network perspective, the pavement condition and available budget are typically used as a guide to select the appropriate recycling technique as shown in Figure 7.

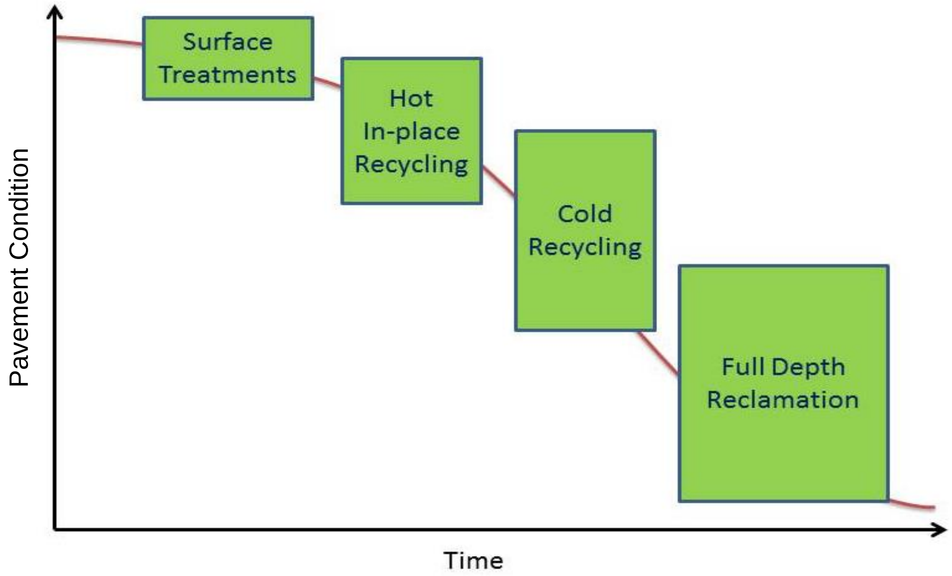

Figure 7 Appropriate pavement recycling techniques based on pavement condition (courtesy of ARRA).

The following steps, outlined in the *Basic Asphalt Recycling Manual* (ARRA 2015), are normally used to further refine the selection from a project-level perspective:

- Assess the type and amount of distress in the pavement.
- Collect and review existing historical information on original construction and subsequent maintenance activities.
- Evaluate the thickness and structural capacity of the existing pavement (often by falling weight deflectometer [FWD] testing).
- Determine the physical properties of the existing pavement materials.
- Determine the cause or causes of the distress.
- Assess geometric requirements.
- Select several potential maintenance or rehabilitation techniques based on the collected information.
- Undertake an economic analysis, including initial and life-cycle costs, of the potential maintenance or rehabilitation techniques.
- Select the most cost-effective maintenance or rehabilitation technique.

In addition, agencies are beginning to explore life-cycle assessments to consider the environmental costs of pavement projects. These types of analyses are not common currently but could be used in the near future to assist with project and treatment selection.

Pavements having major structural issues originating with the pavement foundation will not be good candidates for CR techniques. For pavements with extensive and deep deterioration, the use of FDR or FDR combined with CCPR will result in a longer-lasting pavement structure. Whatever the pavement deterioration mechanism, the cause of the distress (rather than its symptoms) must be addressed. FDR will usually be a cost-effective option if the structural issue comprises more than 10-15% of the surface area of the pavement, otherwise, localized patching combined with a CR technique may be more cost-effective.

4.1 Pavement Distress Evaluation

It is important to assess properly the pavement being considered for CR. Ideally, the pavement will have adequate structural support and adequate drainage. Cracked pavements that are structurally sound and have well-drained bases are the best candidates for rehabilitation using CR techniques. The pulverization of the bound asphalt layers removes the cracks, preventing them from reflecting to the surface. If all cracking cannot be addressed, it is generally accepted that approximately 70% of the existing pavement thickness should be recycled to greatly delay the return of reflective cracking (ARRA 2015). When possible, recycling the paved shoulders can help mitigate the propagation of cracks into the adjacent recycled lane. Any failure due to inadequate drainage also needs to be addressed.

Table 2 lists the pavement distresses that can be best addressed using CR. Unless the cause or causes of the pavement distress are addressed during the recycling process, the distress will be mitigated but they will not be eliminated. The expected design life, performance during the design life, and future maintenance requirements are related to the depth of CR treatment and the type and thickness of the surface course (asphalt overlay or surface treatment).

Table 2 CR Applicability (modified from ARRA 2015)

Pavement Distress		Applicability
Surface Defects	Raveling	Yes
	Potholes	Yes
	Bleeding	Yes
	Skid Resistance	Yes
Deformations	Shoulder Drop Off	No
	Rutting - Wear	Yes
	Rutting - Mix Instability	Possible, verify with a mix design and may require the use of active filler or corrective aggregate
	Rutting - Deep Structural	Possible, ensure that structural requirements can be met, which may require a thicker asphalt surfacing or the use of CCPR plus FDR to stabilize the pavement foundation.
	Corrugations	Yes
	Shoving	Possible, verify with a mix design and may require the use of active filler or corrective aggregate
Load Associated Cracking	Fatigue – Bottom Up	Possible, ensure that structural requirements can be met, which may require a thicker asphalt surfacing or the use of CCPR plus FDR to stabilize the pavement foundation.
	Fatigue – Top Down	Possible, ensure CR treatment depth exceeds the depth of cracking
	Edge	Possible, use CR to address shoulder support by providing a wider lane
	Slippage	Possible, ensure CR treatment depth exceeds the depth of slippage
Non-Load Associated Cracking	Block	Yes
	Longitudinal	Yes
	Transverse	Yes
	Reflective	Yes
Combined Cracking	Joint Reflection	Possible, CR can increase the time until cracking reappears
	Discontinuity	Yes
Base/Subgrade Deficiencies	Swells, Bumps, Sags Depressions	Possible, CCPR plus FDR may be a better choice depending on the condition, CIR may not correct the issue but may delay the reoccurrence
Roughness	Ride Quality	Yes
Other Criteria	All Levels of Traffic	Yes, given that a proper structural design is included
	Rural	Yes
	Urban	Yes, geometric constraints may dictate the use of certain equipment or the use of CIR versus CCPR
	Stripping	Possible, verify with a mix design and may require the use of active filler or corrective aggregate
	Poor Drainage	No, poor drainage must be addressed before completing CR or any other rehabilitation method to ensure adequate performance

The Indiana DOT's 2013 Design Manual (INDOT 2020) contains a guidance flowchart for selecting pavement recycling techniques, part of that information is shown in Figure 8. The figure shows that the Indiana DOT considers CIR applicable for pavements with low to severe cracking and for stripped HMA layers and is applicable for any traffic level, amount of rutting, or International Roughness Index (IRI). The Indiana DOT states that CIR replaces aged, oxidized, or raveled surfaces.

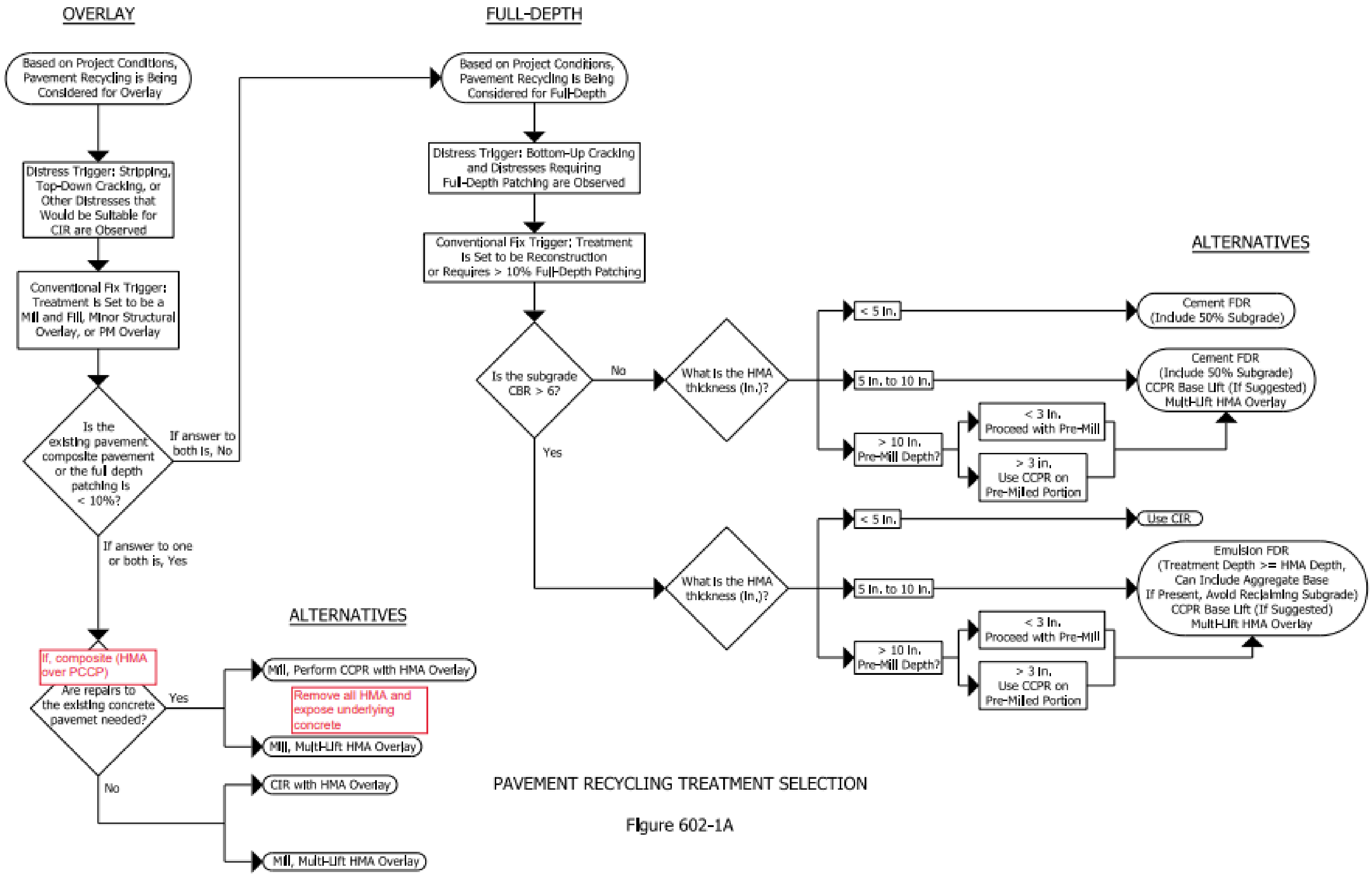

Figure 8. Indiana Department of Transportation flowchart for guidance on selecting pavement recycling techniques (from INDOT 2020)

4.2 Structural Considerations

4.2.1 Treatment Depth

The location of the distresses to be addressed and the thickness of the existing pavement affect the treatment depth. CR treatment depths are generally from 3 to 4 inches (75 to 100 mm) with depths as thin as 2 inches (50 mm) possible with good underlying support and depths up to 5 inches (125 mm) or more, provided proper compaction can be achieved. Ideally, the treatment depth for CIR shall extend through any deteriorated asphalt layers. This is especially true for delaminated or poorly bonded asphalt layers to help prevent the removal of large chunks during the milling process. For CCPR, paved layer thicknesses are often 3 to 4 inches (75 to 100 mm) per lift with thicknesses as thin as 2 inches (50 mm) and up to 8 inches (200 mm) in a single pass reported in the literature (Diefenderfer et al. 2015). To place thicker layers with either CR process, heavier rollers are needed to ensure adequate compaction throughout the CR layer. If smoothness is a concern, the CR layer can be profile milled after compaction. To achieve even greater depths, combinations of CIR and CCPR are possible, or multiple layers of CCPR can be placed.

If the treatment depth is equal to the total asphalt pavement layer thickness, there is an increased risk that portions of the underlying unbound materials may be incorporated into the mixture when the CIR process is used. A small portion of a high-quality granular base can be incorporated without concern; however, caution needs to be exercised before incorporating any fine-graded or plastic materials as these can adversely affect mix properties. Incorporation of unbound granular materials into the CIR mixture can be successfully undertaken to a limited extent, but the amount of incorporated unbound granular materials must be consistent to prevent mix problems such as under- and over-asphalted sections. If the presence of unbound material is expected, it should be considered during the mix design process. The upper limit of unbound granular materials is approximately 25% by weight of RAP. If the unbound granular base content is more than 25%, the overall costs may increase due to the higher recycling agent demand. Mixing RAP with underlying materials is generally classified as FDR. Although reclaimers are traditionally used in FDR, some contractors are beginning to use single-unit CIR trains due to the full lane-width recycling capability (Roads and Bridges, 2020).

4.2.2 Traffic Levels

CR techniques have been routinely used on low-volume pavements but have found success in higher-volume interstate-type pavements in recent years. As long as adequate materials and a structural design are used, the materials can support any range of traffic levels. Examples of high-traffic level applications are provided in Table 3.

Table 3 Example CR projects having high traffic levels

Location	Route	Year Constructed	Recycling Process(es) Used	Approximate Traffic Level as of 2022, ESALs
Virginia	I-81	2011	CCPR, FDR (right lane), CIR (left lane)	24 million (right lane) 4 million (left lane)
Alabama	NCAT Test Track, Section S12	2012	CCPR, FDR	30 million (discontinued with no cracking or distress concerns)
Alabama	NCAT Test Track Section N3	2012	CCPR	20 million (discontinued with no cracking or distress concerns)
Alabama	NCAT Test Track, Section N4	2012	CCPR	35 million (first cracks at 29.7 million ESALs)

4.2.3 Structural Assessment of Existing Pavement Prior to Recycling

Before recycling, the structural capacity of the existing pavement should be assessed. This task is performed to help determine the required thickness of the recycled layers and the new surface layers(s). The most used methods to assess the structural capacity of existing pavement are DCP, lightweight deflectometer (LWD), or FWD testing. DCP testing is most often used on unbound materials and is suitable to test subgrade or aggregate base layers. Correlations are used with DCP testing to convert the number of blows per unit of depth to an approximate stiffness value of the layer. Table 4 provides an example of DCP values that could be used to assess subgrade support for CR operations, agencies are encouraged to develop their values based on local experience.

LWD and FWD testing are examples of deflection testing where the properties of the layer(s) are assessed based on measured deflections at the surface from an applied load. LWD testing is useful for unbound layers but may quickly go out of range when testing a bound layer such as asphalt or a stiff stabilized layer. FWD testing is used more often by agencies and consists of either a towed trailer or a truck-mounted unit. Since LWD and FWD testing relies on the thickness of the layers, GPR testing is often done before, or at the same time as, deflection testing. GPR is a nondestructive technique that is used to determine layer thicknesses, subsurface anomalies, and the extent of different pavement structures. Following GPR testing, it is common to collect cores to verify the findings of GPR testing, especially in areas where interpreting the GPR data may be difficult. Assessing the structural capacity of the existing pavement is an important step in achieving a long-lasting rehabilitation design.

Table 4 Example DCP values (Matthews, 2013 ARRA Semi-Annual Meeting).

DCP	Acceptable	Marginal	Poor
Each Set of 10 Blows	<6 inches <150 mm	6 to 10 inches 150 to 250 mm	>10 inches >250 mm
Inches per Blow Mm per Blow	0.6 15	0.6 to 1.0 15 to 25	>1.0 >25

4.2.4 Overlay Thickness Design

Pavements with major or extensive structural and/or base failures will not be good candidates for CR. Other recycling methods such as FDR or CCPR combined with FDR are better options. Whichever technique is chosen, the sources/causes of any isolated structural problems within the pavement must be identified and corrected. If structural/base failures are less than 10%-15% of the project area, it may be economically feasible to remove and repair the failed areas by deep asphalt patching or aggregate base and asphalt patching before undertaking CR. If aggregate base is used within the patch, it should only be used to the same elevation as aggregate based in the surrounding pavement to ensure that water will not be trapped within the repair area.

Pavements having major structural issues originating with the pavement foundation will not be good candidates for CR techniques. For pavements with extensive and deep deterioration, the use of FDR or FDR combined with CCPR will result in a longer-lasting pavement structure. Whatever the pavement deterioration mechanism, the cause of the distress (rather than its symptoms) must be addressed. FDR will usually be a cost-effective option if the structural issue comprises more than 10-15% of the surface area of the pavement, otherwise, localized patching combined with a CR technique may be more cost-effective.

There are several ways in which the thickness of the asphalt surface layer(s) used on top of a CR layer can be determined. One way is to place multiple asphalt layers on higher-priority routes and single asphalt layers (or even surface treatments) on lower-priority routes. This method relies on trial and error to ensure the desired service life of the pavement. Another method is to develop a series of catalog designs that define the surface layer(s) thickness based on a combination of underlying support and traffic level. The catalog may be developed based on a combination of experience and engineering design and can be very effective once the input parameters are determined and used to develop the initial minimum thickness values. For a designed approach, a pavement design can be completed using project-specific inputs into a design program such as the *1993 AASHTO Guide for the Design of Pavement Structures* or *AASHTOWare Pavement ME Design* (commonly referred to as the '93 Guide and Pavement ME, respectively). Even when using a designed approach, refinement of the design based on experience will be needed.

The *1993 AASHTO Guide for the Design of Pavement Structures* assists the designer with calculating the thickness of a pavement structure that is expected to carry a given amount of traffic, at a desired level of serviceability, for a defined period. Using these inputs, a required Structural Number is calculated. If the required Structural Number is less than a calculated Structural Number for a given design (calculated as the sum of a structural layer coefficient multiplied by the thickness for each layer) then a design is considered acceptable.
Most agencies use typical structural layer coefficient values for commonly used materials. The structural layer coefficient for CR materials used by agencies usually ranges from 0.25 to 0.35 with many using 0.30 to 0.35 (NASEM 2017). ARRA recommends a structural layer coefficient for CR mixes of 0.35 (www.roadresource.org). Research sponsored by the Virginia DOT has suggested that values ranging from 0.36 to 0.44 may be appropriate (Diaz-Sanchez et al. 2017, Diefenderfer et al. 2015).

The *AASHTOWare Pavement ME Design* process is used to analyze a pavement structure by calculating the pavement response using mechanistic principles and predicting the distress mechanisms by empirical transfer functions. NCHRP Report 863 (*Project 9-51 Material Properties of Cold In-Place Recycled and Full-Depth Reclamation Asphalt Concrete for Pavement Design*) offers example CR materials properties that can be used with Pavement ME. The study found that CR mixes have dynamic modulus values ranging from approximately 250,000 to 850,000 psi at 70°F and 10 Hz (1720 to 5850 MPa at 22°C) and rutting properties that are equivalent to and sometimes better than HMA base mixes (NASEM 2017). As of the writing of this Best Practices Guide, the transfer functions used to predict distresses within pavements using CR materials are not yet well defined.

4.3 Other Factors that Impact Project Selection

4.3.1 Utilities

Before recycling, locate all utilities within the pavement cross-section and perform any utility upgrades. Lower any manholes before CIR so that they are deeper than 2 inches below the planned depth of the recycled layer. After recycling and surface course placement, the manhole can be located, material excavated, and raised to the surface. If utilities cannot be lowered, mill around the utility before recycling. In the case of CIR, place the millings in front of the CIR train and around the utility cover; this may require some handwork. CCPR can be paved similarly to how HMA mixtures are paved around utilities.

4.3.2 Surface Treatments and Specialty Mixtures

Surface treatments and specialty mixes can be included in a CR mixture but they must be considered in the mix design process since they can vary in aggregate type and binder content. This is why it is important to have good sampling procedures that capture all materials in the pavement, even if multiple designs must be performed, as described in Section 3.1. If the surface treatment or specialty mix adversely affects the mix design, the layer can be removed by milling before recycling.

4.3.3 Paving Fabrics, Geosynthetics, and Crack Seal

If rubberized crack filler, pavement markers, loop wires, thermoplastic markers, or other similar materials are present in the RAP, they should be removed, if possible, before recycling. If it is not possible to remove these materials, it is important to verify that they will not adversely affect the mix design performance. If paving fabrics are present in the bound layers, the recycling should extend either below the paving fabric layer or to no less than 1 inch above the paving fabric as to prevent delamination. Paving fabric and crack seal material pieces greater than 2 inches should also be removed; evenly mix such materials if they remain.

4.3.4 Patches

The presence of large or frequent surface patches increases the variability of the existing pavement and decreases the homogeneity of the resulting CR materials. The presence of large or frequent patches may also be an indication of poor subgrade conditions. Weak pavement structures and failing subgrades can lead to CR equipment break-through, or reduced compaction of the CR mixture due to excessive pavement deflection under compaction equipment. This can lead to raveling during the curing period, rutting after placement of the surface course, or long-term performance problems related to fatigue of the CR layer. If there are structural or drainage issues, or excessive patches, FDR or reconstruction of the pavement may be required.

4.3.5 Lane Widths Greater than Maximum Width of Cold Recycler

To recycle a lane wider than the maximum recycling width of the cold recycler (typically 8 ft to 12 ft and up to 14.5 ft with an extension), a secondary or smaller milling machine can be used to mill the additional width and deposit the material in front of the cold recycler (Figure 9). Once the material is recycled and then deposited into the paver, the paver can then be used to pave the full width of the lane.

Figure 9 Recycling the shoulder plus full lane width by using a second milling machine. (courtesy ARRA)

4.3.6 Recycling Existing Paved and Granular Shoulders

When recycling existing paved shoulders with CCPR, the width of the shoulder is generally not a concern since the limits of operations are governed by the maximum width of milling and/or paving. When recycling existing shoulders with CIR, the width of the shoulder lane will influence how the recycling work is attempted. If the existing paved shoulder is less than approximately 4 feet (1.2 m) wide, it can typically be recycled in a single pass along with the adjacent driving lane. This additional width can be accommodated by using milling machine extensions, a supplemental milling machine, or multiple passes of a single milling machine. If the existing paved shoulder is greater than approximately 4 feet (1.2 m) wide, it may require more than one pass of the CIR process. In this case, the shoulders are usually treated first and the second pass of the CIR equipment is used to treat the adjacent driving lane so that joints are located on or near the lane lines.

When recycling granular shoulders, CIR has been successfully used where the existing granular material is incorporated into the recycled mixture to widen the pavement. To achieve success, the shoulder must have sufficient granular material with a limited amount of fines and be of very low plasticity, the shoulder must have sufficient strength to support the CIR equipment, and the amount of uncoated granular material should be less than approximately 25% by weight of dry RAP.

4.3.7 Traffic Control

Using CR techniques to rehabilitate pavements can minimize disruptions to traffic and inconvenience to users due to shorter construction times when compared to other pavement maintenance/rehabilitation methods. CR techniques can also be performed during off-peak hours (such as at night) to further reduce traffic impacts; however, these production adjustments may result in reduced productivity and may require additional attention to the selection of recycling agents and active fillers.

CIR equipment width also needs to be considered when selecting appropriate CIR projects. The cold recycler can occupy 1 to 1.5 lane widths within the construction zone. Recycling multi-lane divided roadways usually does not pose significant issues. When recycling two-lane undivided roadways, one-way traffic through the work zone is most often accommodated by flaggers and/or pilot vehicles. Additional difficulties arise when recycling two-lane undivided roadways having narrow lanes, particularly if there is little to no paved shoulder. The accommodation of large/wide trucks or oversized loads will need to be considered. If detouring these vehicles is not possible, CCPR may be a better option given that only typical asphalt paving equipment is present in the work zone.

CR techniques are also applicable at intersections and approaches to driveways and business entrances; however, appropriate planning is required. For CIR, due to the speed of the process, intersections and approaches are not impacted for very long. Crossing traffic is usually controlled by flaggers and lane demarcation devices. In certain circumstances, the CIR contractor may be able to shorten sections of the recycling train (if used) to limit the impact on traffic.

4.3.8 Curing

Direct sunlight will assist in the initial curing of the CR layer. Projects or areas within a project that receive more shade will experience longer curing times. Extended traffic control time, for a day or more, may be required to ensure extensively shaded areas do not ravel when opened to traffic. Similar curing conditions/problems can occur if work is being undertaken in cold, damp conditions typical of late fall or early spring weather, or when there are pavement areas with poor drainage or higher than average moisture contents. In these types of conditions, the use of active fillers such as lime or cement can prove beneficial. These active fillers usually accelerate strength gain thereby reducing the curing time sufficiently to permit the areas to be opened to traffic sooner. Foamed asphalt recycling agents are sometimes found to have a shorter curing time and can be less sensitive to shaded conditions.

4.3.9 Fluff

Fluff is the term used to describe the increase in the volume of a recycled layer as compared to the original asphalt pavement. This increase in volume (up to 10%-12%) is caused by the recycled layer having a lesser density (approximately 130-136 lb./ft^3) as compared to the original asphalt pavement (approximately 140 to 146 lb./ft^3). This is not generally a concern for CCPR as CCPR mixes are placed to a final compacted thickness and the contractor will adjust the amount of material placed to match the planned layer thickness. However, for CIR, inadequate consideration of fluff can lead to an increase in the final elevation of the recycled layer as compared to the original pavement. For CIR projects where fluff cannot be accommodated, alternatives include either pre-milling or profile milling after the recycling operation has been completed. Other options include discharging excess material into waiting dump trucks during construction or can be used to widen the paved roadway by filling a narrow trench created ahead of the CR machine.

4.4 Treatment Combinations

To perform a deep rehabilitation of thick asphalt pavement, it may be desirable to combine recycling techniques. Although FDR and CCPR comprise the most often used combination of recycling techniques, it is possible to combine CIR and CCPR. CIR and CCPR might be used together to complete a deep rehabilitation of the asphalt layers. Once the CCPR treatment depth is removed by milling, a CIR machine can be used to treat the bottom portions of the asphalt layers. Following the CIR process, the milled material can be returned using a CCPR process to make a thick recycled pavement structure. This combined process might be economical if hauling material to the CCPR plant is costly (either due to longer distances or longer haul times) or undesirable due to environmental considerations (considering emissions related to hauling).

5 EQUIPMENT

5.1 Milling Machine

A milling machine is most often used to remove the upper portions of an existing asphalt pavement either in a pre-mill step before CIR operations or to provide the RAP required for a CCPR process. The milling machine’s treatment width ranges from a few feet to well over a full lane width of a typical highway pavement. Different widths are accommodated by either different-sized cutting drums or bolt-on extensions. For CR projects, choose the size of the milling machine to remove the material width and depth as specified for a particular project.

Milling machines generally operate their cutting drums in the “up-cut” direction, that is the cutting drum is rotating counterclockwise when the machine is traveling from left to right. Downward pressure is applied to hold broken pieces of pavement in place using a pressure plate or shoe. This pressure plate keeps larger pieces in place, to prevent making large slabs, until they can be broken up by the cutting drum. The particle size distribution of the RAP produced by milling machines can be influenced, but not controlled, by the forward speed of the machine and the rotational speed of the drum. Generally, lower forward speeds and higher drum speeds will produce a finer gradation. To provide a smoother pavement, most milling machines can be equipped with non-contact ultrasonic sensors and automatic grade and slope control systems, or total machine control systems.

The RAP produced by milling machines is most often discharged to waiting dump trucks using onboard conveyors, as shown in Figure 10, or deposited into windrows.

Figure 10 Milling machine depositing RAP into haul trucks. (courtesy ARRA)

5.2 Haul Trucks

Haul trucks are used to haul RAP, asphalt, CCPR materials, etc. to and from a paving project. Depending on the size of the project, haul trucks may range from trucks having a steering axle plus a single drive axle to having up to 4 or 5 axles behind a steering axle. The most common haul truck is one having a single steering axle and a tandem drive axle. Hydraulic lift beds made from steel or aluminum are typical. Do not use release agents in the lift beds as they can adversely affect the recycled materials. The number of haul trucks used on a project will vary depending on availability, haul time, and quantity of materials.

5.3 Active Filler Spreading and Slurry Storage Equipment

When used on CIR projects, active filler spreader equipment can apply dry active fillers (such as lime or cement) to the surface of the pavement before recycling at a prescribed weight per unit area, as shown in Figure 10. For proper application, the spreader equipment should have the ability to meter the amount of active filler applied based on the forward speed of the vehicle. Apply the dry active filler only for the distance of work that can be accomplished in a single day of recycling. During windy weather or when adjacent to high-speed traffic, minimize the distance between the active filler spreader and the recycling equipment to prevent fugitive dust; however, other dust control measures may be needed. One example to reduce the amount of fugitive dust is to pre-wet the roadway before spreading or to wet the top of the spread dry active filler. Do not wet cementitious active fillers far ahead of the recycling equipment such that the hydration reactions are completed before being incorporated into the CIR material.

When a lime or cement slurry is being used on a project, it is important to ensure that the storage equipment contains agitators. Agitators are important for maintaining the suspension of the slurry

Figure 11 Applying active filler (cement) ahead of a multi-unit CIR train. (courtesy ARRA)

5.4 Cold Recycling Equipment

Depending on the specifics of the project, several options exist for equipment to produce the CR material. For CIR projects, single-unit and multi-unit trains can be used to mill the existing pavement, size the RAP (multi-unit trains only), add the asphalt recycling agent, and deposit the recycled material into a windrow or discharge using a conveyor. For CCPR projects, a mobile cold recycling plant can be used to add the asphalt recycling agent (and any other active fillers if used) to the RAP and to discharge the product into waiting haul trucks. Limited experience is presented in the literature on using HMA plants to produce CCPR mixtures with minor modifications to the plant (Bowers and Powell 2021). To successfully produce CCPR in a HMA Plant, the greatest consideration is the internal temperature of the asphalt plant which must be at or near ambient temperature. Because of this, it is unlikely a plant operator would be able to switch between hot mix and CCPR production during the same day using currently available equipment. In addition, the CCPR production quantities will be less than the maximum production of hot mix through the same plant.

Regardless of the CR process, it is important to ensure that large “chunks” or slabs of material are not present within the mixture. This is best achieved by using materials screens, typically having a 1.5-inch sieve opening, for CCPR mixes. Multi-unit trains contain a screening deck and crusher to reduce any oversized materials. Single-unit trains do not contain screening decks and any oversize RAP that is observed at the surface should be removed or placed in front of the unit to resize. If scabbing is observed during CIR, it is important to adjust the recycling depth to ensure a consistent gradation.

5.4.1 CIR Single-Unit Trains

A CIR project can be completed using a single-unit train to perform the recycling operation. A single-unit train includes a down-cut (rotating clockwise when moving from left to right) cutting head to remove a portion of the existing pavement to the required depth and cross-slope. The RAP produced is blended with the asphalt recycling agent, added at the cutter head, and any active fillers are applied ahead of the train. The RAP gradation can be influenced by the rotational speed of the cutting head and the forward speed of the train. Single-unit trains do not contain screening or crushing units so the ability to influence the particle size distribution is limited. Other equipment may include an asphalt recycling agent tanker truck that is usually pushed by the single-unit train.

The advantages of using the single-unit train include a shorter length of equipment and a high degree of maneuverability. In addition, single-unit trains can easily process up to one lane mile per day with longer passes routinely reported. For a single-unit train, the quantity of asphalt recycling agent added is based on the treatment volume (including width, depth, and anticipated forward speed). Since the rate is calculated volumetrically, the degree of process control is reduced than if the active filler rate were based on the actual weight of the material to be recycled. Examples of single-unit CIR trains are shown in Figures 12 and 13.

(a) **(b)**

Figure 12 Single unit CIR Trains (courtesy ARRA)

Figure 13 Single Unit CIR Train (courtesy HRG)

5.4.2 CIR Multi-Unit Trains

CIR projects can also be completed using a multi-unit train. Multi-unit CIR trains include a large full-width milling machine, a trailer-mounted screening/crushing unit, and a trailer-mounted pugmill mixer (or a combined screening/crushing/pugmill unit). The milling machine removes the thickness of the existing asphalt pavement to be recycled and this RAP is sized by the screening/crushing operation. Appropriately sized material is sent on to the mixing unit whereas oversized material is returned to the crushing unit. The properly sized material is mixed with the asphalt recycling agent in the pugmill unit and the resultant mixture is deposited into a windrow (for pickup and placement into a paver hopper) or conveyed directly to a paver hopper.

The amount of asphalt recycling agent is determined by a belt scale that weighs the amount of RAP delivered to the pugmill. The primary advantage of the multi-unit train includes a higher level of process control related to the asphalt recycling agent quantity and the maximum RAP particle size. Disadvantages include a longer equipment train and less maneuverability than the single-unit train option. Examples of multi-unit CIR trains are shown in Figures 14, 15, and 16.

Figure 14 Multi-unit train (courtesy ARRA)

Figure 15 Multi-unit CIR Train (Courtesy HRG)

Figure 16 Multi-unit train (courtesy ARRA)

5.4.3 CCPR Mobile Cold Recycling Plants

CCPR materials can be produced using a mobile cold recycling plant. The mobile plant is usually located on or near a paving project or at a nearby contractor's facility. RAP obtained from milling the paving project, or from existing stockpiles, is combined with an asphalt recycling agent and any active fillers (if used) and mixed in the mobile plant's continuous pug mill. The CCPR material is discharged into either stockpiles or directly into waiting haul trucks.

The mobile cold recycling plant usually consists of a single cold feed bin/hopper, mixing pugmill, separate tanks for the asphalt recycling agent and water, and a silo or tank for any active fillers (if used). If corrective aggregates or RAP fractionation is desired, add or fractionate before introduction to the cold feed bin or use separation chambers on the cold feed bin. A belt scale is used to accurately dose the asphalt recycling agent, water, and any needed active fillers. The plant should also be equipped with positive displacement pumps to automatically shut off the supply of asphalt recycling agents, water, and active fillers if the pug mill mixer is empty. An example of a mobile CCPR plant is shown in Figures 17 and 18. The processing unit from a multi-unit train, in a stationary mode, is also used to produce the CCPR mix, as shown in Figure 19.

Figure 17 CCPR plant.

Figure 18 CCPR Plant (Courtesy HRG)

Figure 19 Processing unit from multi-unit train producing CCPR mix (ARRA 2015)

5.5 Paving Equipment

CR mixtures are most often placed using conventional asphalt paving equipment. The main exception is that a materials transfer vehicle is not used as it can easily become clogged with the CR mixture.

When placing CIR materials, the material is delivered to the paver either directly from the cold recycler by an onboard conveyor or by a pickup machine from a windrow. If utilizing a pickup device, it should be capable of removing and transferring the entire windrow of recycled mix in a single pass and a track paver with a minimum power of 170 HP is recommended. If the material is delivered by conveyor, do not cycle the hopper wings periodically as this practice can introduce segregation into the paved mixture. Depending on the depth of the CIR layer, a paver hopper insert might be required to hold a larger quantity of material from the conveyor. The paver screed should be controlled by electronic grade and cross-slope control and be of sufficient size and power to spread the recycled material in one continuous pass, without segregation, to the specified width and thickness. Do not heat the screed as this will clog the screed and tear the mat. When placing CCPR materials, the haul trucks normally dump the CCPR mixture directly into the paver hopper.

5.6 Compaction Equipment

ARRA (2015) recommends three rollers, at least one pneumatic tire roller, and at least one double drum vibratory roller. The third roller is at the contractor’s option. The pneumatic tire roller should have a minimum mass of 22 tons, and the vibratory roller a minimum mass of at least 10 tons. The pneumatic tire roller helps to orient the recycled RAP particles to achieve maximum compaction. The vibratory roller enhances the overall compaction of the recycled mat, and can also be used in static mode for finishing. To prevent the pickup of recycled material, ensure all rollers have working spray systems. The minimum width of the main compaction rollers should be 65 inches. Use the same size and inflation pressure on all tires on the pneumatic tire roller for maximized compaction effort.

Figure 20 **Minimum 22 ton Pneumatic Tire Roller (Courtesy HRG)**

Figure 21 **Minimum 10 ton Vibratory Roller (Courtesy HRG)**

Minimum 22 ton Pneumatic Tire Roller

If the CR mixture is being placed on a wet but stable base, it may be helpful to turn off the vibratory setting of the roller so that excess water is not pulled up into the recycled base. There is currently no guidance on what constitutes a “wet” base, so the contractor or engineer must make that judgment. If excess water is pulled into the recycled mat, it will be important to allow for the water to evaporate from the mat for curing purposes before trafficking or surfacing.

5.7 Fog Sealing and Fine Aggregate Spreading Equipment

Fog sealing and fine aggregate (typically sand) spreading are not required if traffic will not be allowed on the recycled layer before surfacing. If the recycled layer is fog-sealed and traffic is expected, a fine aggregate used as a blotting material is needed to prevent the pickup of the recycled material. Apply the fog seal, at a diluted (typically 1:1 with water) application rate of 0.05 to 0.15 gal/yd^2 (0.23 to 0.68 l/m^2). Apply the fine aggregate blotting material to the fog-sealed surface, using an aggregate spreader, at a typical rate of 2 to 3 lb./yd^2 (1.08 to 1.63 kg/m^2).

6 CONSTRUCTION OPERATIONS

6.1 Just-in-Time Training (JITT) / Preconstruction Personnel Meeting

Personnel involved with the construction and quality control of CR from both the Contractor and Agency should complete a just-in-time training (JITT) course before the start of CR operations. The JITT is an important element of the paving process to ensure that proper procedures are followed to construct a high-quality CR pavement. Generally, the trainer conducting the JITT should have completed a minimum of 5 CR projects and be familiar with the specifications for the current project. The JITT is most often held 5 to 14 days before construction. It is equally important that agency inspection staff and appropriate field personnel from the CR contractor (e.g., recycling foreman, QC staff, etc.) both attend. Typically, the JITT should include a discussion on typical production and compaction processes and challenges, along with corrective actions. The training session also provides an opportunity for open discussion between the contracting personnel and agency personnel to address any questions before construction.

The course instructor is typically provided by either the contractor or the agency and should be acceptable to both the contractor and the agency. The instructor should be experienced in mix design, construction, and field quality control test methods associated with CR projects.

6.2 Roadway Preparation and Pavement Removal

All vegetation, pavement markers and markings, and debris should be removed from and along the edges of the pavement that is being recycled. The pavement should be free of contamination. Correct any areas having soft subgrade or drainage issues before CR operations because they can lead to several problems including increased curing time, inadequate density, or long-term pavement stripping issues.

Planned cross-slope adjustments exceeding 0.5% need to be completed before recycling since greater adjustments are not achievable using the recycling unit.

6.3 Weather Limitations

Weather is an important factor to consider for CR mixes. It is typically recommended to only produce CR mixtures when the RAP temperature (not pavement or air temperature) is at least 50 °F (10 °C) unless otherwise approved by the agency. Depending on the recycling agent, and if active fillers are used, the minimum temperatures may also need to be adjusted upwards. Some emulsified asphalt may require higher temperatures, such as 60 °F (16 °C) and rising. This is why it is important to measure the RAP temperature rather than the ambient or pavement surface temperature.

In the case of a foamed asphalt recycling agent, “stringers” may be produced if the mix is produced at too low of a temperature. If stringers occur, the foam is not being distributed evenly throughout the mix matrix, and thus the mix will not perform as designed. For emulsified asphalt recycling agents, placing the mixture in cold temperatures could significantly delay the curing of the material. CR operations are not to be performed when overnight ambient temperatures are forecast to be less than 35 °F (2 °C) for any part of the overnight period. Both foamed and emulsified asphalt recycling agents can be used for night paving, but the contractor must work with the emulsion supplier to ensure that the emulsion will break in the absence of sunlight and the warmer daytime temperatures, especially if the mat must be trafficked or surfaced soon after placement (e.g., the next morning).

CR may be adversely affected by precipitation by slowing the emulsion break time, pumping during compaction (caused by having too much water), washing dry active fillers off the pavement, etc. The contractor can demonstrate the performance of the recycled asphalt pavement by showing the material density and other properties are not affected and that the recycled layer can be covered within the time required by the agency.

6.4 Construction Process

6.4.1 Equipment Calibration and Verification

The mixing equipment should be calibrated annually and monitored throughout the year to ensure the accuracy of the material rates being delivered. During construction, a 10% tolerance of the actual delivery rates by volumetric distribution is normally sufficient to verify the equipment remains properly calibrated.

Perform the calibration by delivering known quantities of RAP, asphalt recycling agent, and water through the recycling equipment to verify that the materials are delivered to the accuracy specified.

The recycling agent meter must be able to accurately measure the amount of recycling agent to within a tolerance of ± 2.0% of the specified rate by weight of RAP and the CIR recycler or CCPR plant must be capable of automatically adjusting the flow rate to compensate for any variation in the amount of RAP being introduced into the mixing equipment. During production, check the application rate by evaluating the weight or volume of recycled material against the weight or volume of the recycling agent used for a single tanker. If outside the 10% tolerance, the equipment should be recalibrated.

6.4.2 Milling Depth

Check the milling depth by measuring along the longitudinal joint in 100-ft intervals. It is important to ensure that there are no uncontrolled variations such as rising or dipping, as these may indicate a hydraulic problem.

Note that cold recycled material will not compact to the same milling depth, as the RAP will fluff approximately 10-12% after milling and asphalt recycling agent injection, depending on material, methods, and environmental factors. Agencies may specify treatment thickness as either a milled depth or as a compacted CIR thickness. Specifying a milled depth is a best practice because it keeps the Contractor from having to estimate the correct milling depth to account for the increased volume.

6.4.3 Application and Application Rates

If corrective aggregate and/or active filler are required, they should be spread uniformly on the existing pavement ahead of the milling operation within a tolerance of ± 10% of the specified rate. Spread dry cement using either a cyclone or screw-type calibrated spreader truck. Spread corrective aggregate in consistent and uniform windrows using belly dump trucks or tailgated with end dump trucks and spread to a uniform thickness with a motor grader or mechanical spreader. Application rates should be measured by using a tarp or pan test and verifying the yield of each load of active filler. An example of measuring the active filler application rate using the pan test is shown in Figure 22.

Figure 22 Measuring the application rate of active filler using a pan test. (courtesy ARRA)

Cement or lime slurry may be added directly to the mixing chamber or sprayed over the cutting teeth of the milling machine. The slurry must apply the active filler within a tolerance of ± 0.1% of the specified rate.

Mill and pulverize the existing pavement to the specified maximum particle size and blend with the desired rate of recycling agent, water, and active fillers (if required) as indicated by the mix design. Judiciously make any changes to the target moisture, recycling agent, or active filler content due to changing gradation, materials, or other environmental factors and inform the engineer of any recommended changes. It is expected that mixtures using emulsified asphalt will exhibit a degree of coating on most particles and be free of pooling emulsion and balls of fines. It is expected that mixtures using foamed asphalt will visually exhibit appropriate dispersion of foamed asphalt throughout the entire mixture and be free of any clumps of binder or "strings" of asphalt binder.

6.4.4 Placement

The recycled mix (including the recycling agent, water, and active fillers [if needed]) is either placed in a windrow on the pavement and loaded into the paver with a pickup device (Figure 23) or placed directly into the paver hopper (Figure 24). The recycled mix must be spread uniformly across the planned width using a screed in one continuous pass, exercising care to avoid segregation, tearing, or scarring of the final compacted surface. This includes minimizing handwork and preventing a buildup of materials on the edges of the screed.

Figure 23 CCPR Mix Being Delivered to Paver via Windrow (Courtesy HRG)

Figure 24 CCPR Mix Being Directly Delivered to Paver (Courtesy HRG)

For projects where a thick layer is being recycled, the contractor may need to adjust the paver to incorporate the larger volume of materials. This may include using a paver hopper insert and a series of vibrators to ensure the recycled materials continue to flow to the conveyor belt. Also, if no paver hopper insert is used, the paving contractor should not cycle the wings of the paver hopper during the placement of the material.

6.4.5 Compaction

CR materials commonly require higher compaction effort to achieve density, which will not be at the same air voids or voids in the total mix (VTM) as an HMA. Typical VTM for CR mixtures ranges from 8 to 16%. This is due to the nature of the mixture, which is compacted at lower temperatures, contains oxidized asphalt binder, and less lubrication effect from the binder compared to an HMA, and has higher internal friction between particles.

6.4.5.1 Test Strip

It is recommended that a Test Strip be placed as part of the first day of production rather than several days before production. The reason for this is that waiting for acceptance tests delays the work of the contractor and requires them and their equipment to remain idle until test results are completed. In addition, quality control tests, including density and gradation, are quickly obtainable.

To produce a Test Strip, the Contractor should construct a minimum 500-foot (150 m) long section, one lane wide at the design depth, at an approved location. Testing should occur only in the last 200 feet. The construction procedures intended for the entire project should be used. According to ARRA (2015), the purpose of the Test Strip is to:

a) Demonstrate that the equipment, materials, and processes proposed can produce a recycled pavement material layer that conforms to specification requirements;
b) Determine the optimal rates and any necessary adjustments for recycling agent, water, and any active fillers (if used); and
c) Determine the rolling pattern (roller sequence, manner, etc.) necessary to obtain the desired density.

If the Test Strip is not acceptable in accordance with agency specifications, the process shall be repeated until an acceptable test strip is produced. Test strips that do not meet specification requirements shall be reworked, recompacted, or removed and replaced at the Contractor's expense. Once the test strip is accepted by the agency, the Contractor should use the same equipment, materials, and construction methods for the remainder of recycling operations unless adjustments made by the Contractor are approved by the agency. If adjustments are made, the Contractor should be required to produce a new test strip.

To verify the percent passing the maximum sieve size, collect a sample of pulverized material. Changes in gradation can also serve as an indicator of any adjustments that need to be made to the recycling agent and/or moisture contents. It is recommended to establish the maximum compacted density using a rolling versus density chart that shows the progress of densification for each roller pass. This will also establish the maximum obtainable density, which can be used as the target density during production. The maximum obtainable density is the “break over point," measured using a nuclear density gauge in accordance with AASHTO 301 or T355. While establishing the break-over point, measure the density at the same location after each pass. The number of roller passes that result in the highest density without causing any cracking of the mixture is defined as the rolling pattern. It is also important to recognize that a wet pavement density is used due to the nuclear density gauge's inability to accurately measure the moisture content in an asphalt-stabilized mixture.

Using the break-over point method to determine when the maximum density is achieved is recommended because rapid results can be obtained while accounting for field variables such as gradation changes in the CR mixture, temperature changes, etc. Other methods to establish the target density that have been used include indicating a percentage of the maximum density from the laboratory mix design (not recommended) and the use of a field Proctor test. There are challenges and benefits to all methods. The challenge with using a percentage of maximum density from the laboratory mix design is that CR laboratory gradation is an estimate of the field gradation and will likely vary throughout the project and may not give an indication of the maximum obtainable density. CR mixes are not typically designed using a proctor test and the proctor test may or may not capture the maximum obtainable density. Dry densities are occasionally used with laboratory mix design and proctor target densities. However, this requires determining the moisture content of a field sample. This typically delays test results several hours to 1 day, although a correction factor can be determined and applied to subsequent density tests. The break-over curve using wet densities is the most common method of determining a target density.

6.4.5.2 Primary Compaction

Primary compaction may be affected by many different environmental and material factors such as temperature, humidity, gradation of the RAP, and recycling agent type, among others. Begin compaction of foamed CR mixes immediately after placement. Begin compaction on CR mixes using emulsified asphalt as the emulsion begins to "break," or turn from brown to black. This may take a few minutes to up to a few hours depending on the emulsion formulation and weather conditions. It is important, however, to make sure not to begin compaction too long after the breaking of the emulsion has begun because a crust can form on top of the recycled mat, making compaction more challenging and may result in mat defects such as checking or cracking.

Use the rolling pattern and target density established during the Test Strip for primary compaction, and continually monitor density compliance with the specification in accordance with AASHTO T 310 or T 355. Breakdown rolling often uses one or two passes with the double drum vibratory roller (operated in static mode) as a means to prevent edge distortion and significant distortion from the pneumatic roller, as well as help to improve the final smoothness of the mat. Additional compaction then often occurs using a pneumatic tire roller or double drum vibratory roller. Finish rolling is performed to remove roller marks with the double drum roller in static mode. Use sprayed water on all rollers during compaction as a means to keep the CR mixture from sticking and apply at a rate that keeps the rollers/tires clean. Do not stop and start rollers on an uncompacted portion of the recycled mat.

To begin the compaction process, roll the longitudinal joint of the pavement following the rolling pattern established in accordance with the Test Strip. Overlap passes of the roller with initial passes starting on the low side and moving to the high side; ensure all passes are parallel to the pavement centerline. Ensure the drive drum of the double drum vibratory roller is in the forward position or nearest the paver. The exception for this is on steep grades where, due to potential tearing and shoving of the mat, the position may be reversed. Ensure that lines and grades are maintained along the edges of the pavement and that the final CR mat is free of blemishes, ruts, bumps, indentations, and segregation, and agrees with the cross slope and profile as required by the project.

If challenges are meeting the target density, or if there are major distortions, checking, or cracking of the mat, discontinue rolling and establish a new target density. This can also be indicative of potential changes in material or material support. Determine a new target density and rolling pattern in accordance with the methods described for the Test Strip. If the base support is high in moisture content consider not using vibratory compaction as it may cause water from the base to be pulled up into the CR mixture, delaying the time to cure and thus time to traffic or surfacing. If the moisture content is too high at the beginning of compaction, minor cracking, and displacement can occur. Steps to take beyond waiting for further curing/moisture escape are turning off the vibratory mode on the roller to see if static rolling results in the same challenges. If so, apply passes using the pneumatic rolling followed by passes with the double drum vibratory roller. Continue this procedure until there is no longer any displacement of the recycled mat while rolling.

6.4.5.3 Secondary Compaction

Secondary compaction can be performed on CR that uses an emulsified asphalt as its recycling agent. Begin secondary compaction after the initial cure is complete, sometimes this may be as little as two hours after primary compaction depending on weather and material conditions. Secondary compaction can remove minor consolidation in the wheel paths caused by traffic, as well as potentially achieve additional density. It is recommended that secondary compaction be applied during the warmer part of the day when the pavement surface temperature is greater than 80 °F. If the pavement temperature never reaches 80 °F before surfacing, consider suspending secondary compaction.

Establish a new roller pattern and target density for secondary compaction using the same procedures as described in the Test Strip section. Use the same rollers used for primary compaction. Attempt a minimum of four roller passes while establishing the new target density and roller pattern. If there is any cracking in the mat, cease secondary compaction immediately.

Do not attempt secondary compaction for mixtures using foamed asphalt as the recycling agent or for mixtures containing an active filler. The active filler will begin hydrating once it comes in contact with water and secondary compaction risks breaking any bonds that have formed within the mix matrix, thus reducing the stiffness benefit that can come with an active filler.

6.4.6 Field Adjustments

Small adjustments to the water content, asphalt recycling agent content, and active fillers content are expected during CR placement. Not only can the materials to be recycled vary depending on their age, previous maintenance, construction practices, etc.. Changes in pavement temperature during milling can also influence the gradation of the RAP throughout the day. Use the proportions developed during the mix design procedure as a starting point for construction since the actual conditions in the field will differ from those in the laboratory. Rigid adherence to the original mix design can result in less than optimum performance. Make any adjustments to the mix design judiciously and changes should be made by experienced personnel. The contractor must inform the agency of any recommended changes to the mix design proportions, and any suggested changes greater than allowable limits must be approved by the agency.

6.4.7 Curing

The compacted CR mixture must adequately cure before surfacing or opening to traffic. The goal of curing is to achieve the necessary mix of stability to prevent rutting and raveling under traffic or subsequent paving operations. The rate at which curing progresses is variable and depends on several factors including ambient temperature, humidity, wind speed, precipitation, moisture content of the recycled layer, level of compaction, asphalt recycling agent used, and presence of active filler among others. Typical curing periods can range from a few hours to a few days. Although many agency specifications require a wait time or a measured moisture content to assess curing, NCHRP Report 960 details the development of a test to assess when a recycled layer is ready for trafficking or surfacing (NASEM 2021).

6.4.8 Opening to Traffic

In addition to ensuring adequate stability, curing of the mix can prevent pickup or raveling of the surface due to the adhesion of the recycling agent to the tires of the passing vehicle. If there is a concern, a fog seal and a fine aggregate blotter course are recommended to prevent pickup. It is also important to ensure that water adequately drains from the recycled layer. If drainage is poor, it must be addressed as this will likely lead to deterioration of the pavement. Soft subgrade issues can also lead to depressions of the mat under traffic and must be addressed.

Before placing the surface course, it is important to repair any damage done to the mat from construction or other traffic. If damage is caused by poor pavement drainage or subgrade, make sure to address those problems in addition to repairing the mat as they may ultimately lead to pavement failure. The AASHTO Construction Guide Specifications for CIR and CCPR recommend subgrade repair as a separate contract item, any additional drainage work discovered during trafficking should also be a separate contract item. Appropriate repair techniques are listed in Table 5:

Table 5 CR damage mitigation approaches (adapted from ARRA 2015).

Damage	Mitigation
Isolated areas of minor raveling or scuffing.	Sweep and monitor. Determine if fog sealing or re-fog sealing is necessary to protect.
Isolated areas of major raveling, scuffing, or tearing.	Maintain better traffic restrictions in areas that are not cured. Sweep and monitor. Determine if fog sealing or re-fog sealing is necessary to protect. Fill or remove and replace deep damaged areas with asphalt mixture (CR mix, asphalt mix, etc.) before the surface course.
Large-scale areas of raveling, scuffing, or tearing in straight traffic areas.	Re-recycle or remove and replace with asphalt mixture (CR mix, asphalt mix, etc.).
Dimpling due to parked vehicles and equipment	Fill with asphalt mixture (CR mix, asphalt mix, etc.) before the surface course.

Permanent deformation within wheel path areas due to secondary compaction by traffic	Fill with asphalt mixture (CR mix, asphalt mix, etc.) or micro surfacing in the low areas or cold mill to provide a smooth surface.
Permanent Deformation and shoving due to unstable mixture.	Investigate pavement structure in conjunction with the mix design lab. Depending on investigation, remove and replace affected areas with asphalt mixture (CR mix, asphalt mix, etc.) or re-recycle supplementing with uncoated coarse aggregate and/or recycling agent as necessary.

The Short-Pin Raveling Test, outlined in NCHRP Research Report 960, was developed as a rapid field test to determine when the recycled layer can be trafficked. The test includes counting the number of blows to drive a test fixture into a recycled pavement layer and measuring an applied torque to indicate when the layer can be trafficked. Table 6 provides the preliminary threshold values recommended by the research. More information, including a Proposed AASHTO Standard Method of Test specification, can be found in NCHRP Research Report 960 (NASEM 2021).

Table 6 Short-pin raveling test minimum values (NASEM 2021)

Test	**Minimum Value (Average of 3 tests)**
Number of Blows	7.1
Torque, ft-lb	20.2

6.4.9 Placement of Wearing Surface and Smoothness

Different state specifications have different requirements on when to place the surface course. Many use a specific curing time (Section 6.5.7) or a moisture content of 3.0% or less within the recycled layer. Curing time and moisture content targets before placing the wearing surface have typically been specified based on experience and can sometimes be limiting in terms of application location. There are numerous examples of CR mixes being overlaid within hours of placement.

The Long-Pin Shear Test, outlined in NCHRP Research Report 960, was developed as a rapid field test to determine when the recycled layer can be surfaced. The test includes counting the number of blows to drive a test fixture into a recycled pavement layer and measuring an applied torque to indicate when the layer can be surfaced. Figure 25 shows the test being conducted in the field and Table 7 provides the preliminary threshold values recommended by the research. More information, including a Proposed AASHTO Standard Method of Test specification, can be found in NCHRP Research Report 960 (NASEM 2021).


(a) (b)

Figure 25. (a) Dynamic Cone Penetrometer weight being used to drive the long-pin shear device into the cold recycled mat while counting the number of blows and (b) torque being applied to the long-pin shear device and recorded.

Table 7. Long-pin shear test values (NASEM 2021)

Test	**Minimum Value (Average of 3 tests)**
Number of Blows	19.3
Torque, ft-lb	62.9

Once the mat is approved for surfacing, use a power broom to remove any loose particles. If smoothness is a concern and a thin overlay or surface treatment is being placed on the surface, profile milling can be performed on the finished CR surface. If the overlay is of adequate thickness to be micro-milled, then it is recommended to micro-mill the surface or the intermediate asphalt layer before surfacing. See Figure 26.

Figure 26 CCPR After Scarification Milling (Courtesy HRG)

If an asphalt mix is being placed as the surface course, apply a tack coat in accordance with AASHTO MP 36 and AASHTO PP 93 to the recycled layer. It is not uncommon for some of the tack coat to absorb into the mat, a byproduct of the higher air voids of the mixture, though it shall not completely absorb the tack. A tack coat is typically applied at a minimum rate of 0.05 gal/yd^2 (0.2 l/m^2) for CR mixes. Although the use of hot asphalt binder as a tack is permitted, it is important to ensure that it has cooled before allowing any trucks to drive on the surface to prevent pickup of the CR layer.

7 QUALITY ASSURANCE PROGRAM

7.1 Quality Control

To assist the Contractor with delivering a quality product to the agency, it is recommended that the Contractor establish, implement, and maintain a Quality Control (QC) Plan that describes all equipment, materials, production, workmanship, and processes during construction. Included in a QC Plan are the contractor qualifications and personnel having assigned quality assurance responsibilities. A QC Plan program also includes a description of preconstruction activities such as CR mix design, site preparation, material handling and transportation, and stockpiling, as well as procedures that will be used for sampling, testing, inspection, monitoring, documentation, and corrective action during transport, stockpiling, placement, and finishing operations. The QC Plan is project-specific and needs to be reviewed and approved by the agency before the start of construction. The QC Plan can be used by both the Contractor and the Agency as a starting point if any disputes regarding materials quality arise. The Agency may use failure to comply with the QC Plan as a reason to shut down production until the Contractor’s operations comply.

7.1.1 QC Personnel

Within the QC Plan, The Contractor should list the QC personnel who will provide process and quality control sampling and testing during the CR mix production and construction.

QC personnel typically include a QC Plan Manager, QC Technicians, and other Contractor staff. The QC Plan Manager is the person responsible for the execution of the QC Plan and may act as a liaison between the Contractor and the Agency. This person must be on the job and have the authority to stop or suspend construction operations. QC Technicians are those Contractor staff who are responsible for conducting QC tests and inspections to implement the QC Plan. Additional Contractor staff who should be included in the QC Plan include the project foreman and potentially equipment operators.

The QC personnel listed in the QC Plan must complete the Just-in-Time Training before construction. The contractor must provide the names, contact information, and qualifications of all QC personnel.

7.1.2 QC Laboratory

The QC Laboratory is the entity where off-field quality testing occurs. The QC Laboratory must be an agency-approved laboratory for all tests within the relevant scope of testing. The Contractor needs to document, in the QC Plan, that the testing and sampling equipment and measuring devices meet the requirements of the specified standards and test methods. Records of the calibration and maintenance of all sampling, testing, and measuring equipment, and all documents required by the accreditation or agency program are to be kept by the QC Laboratory.

7.1.3 Compaction Testing

Compaction intends to densify the CR materials, using heavy rollers, to as high a density as achievable based on in-situ conditions. A Target Density is established using a test strip as described in Section 6.4.5.1.

During production, the density of the compacted CR material is measured with a nuclear density gauge in accordance with AASHTO T 310. See Figure 27. Typically required densities are given as a percentage of the Target Density and range from 97% to 103% of the Target Density. If two successive density tests are either below or above this range, a new Target Density will need to be established using a new test strip as described in Section 6.4.5.1.

Figure 27 Nuclear Density Testing (Courtesy HRG)

7.2 Agency Acceptance

To provide acceptance of the constructed product, the Agency must ensure the Contractor has constructed the project in accordance with the specifications. The Agency will conduct acceptance sampling, testing, and inspections in accordance with AASHTO R 10. If QC results are to be used for acceptance, the Agency may conduct verification testing. Table 8 provides recommended agency acceptance properties, methods, frequencies, and criteria for the construction of CR pavements.

Table 8 Recommended agency acceptance test properties, methods, frequencies, and criteria.

Property	Method	Minimum Frequency	Criteria
Density	AASHTO T 310 or AASHTO T 355	Once per 1000 ft	97-103% of the target density
Gradation*	AASHTO T 27	At least once in the first 250 ft of each day and then once per 2500 ft thereafter	100% passing max particle size
Cut Depth**	Agency Method	At least once in the first 250 ft of each day and then once per 500 ft thereafter	±0.25 inch of planned depth
Cross Slope**			±0.1% of the planned percent cross-slope

Surface Tolerance			Less than 3/8 inch using a 10-ft straight edge
Recycling Agent	Read Meter	At least once in the first 250 ft of each day and then twice per 1000 ft thereafter	±0.25% of the planned percent recycling agent content
Active Filler	Agency Method	Measure at the beginning of each load using the tarp test and calculate the yield with each load	±0.1% of the planned percent active filler
Corrective Aggregate			Within ±10% of the target corrective aggregate

*Measure gradation of the CR materials on unburned materials (i.e., do not use the ignition furnace), and due to frequency of testing may or may not include recycling agent.

**For CIR only.

***If the cross-slope adjustment is greater than 0.25% on a particular sublot, use either depth or cross-slope as an acceptance parameter for that sublot only.

8 RECOMMENDED REFERENCES AND SOURCES

Several additional references and sources are beneficial to review for insight into the CR processes, design, production, construction, and performance. Some recommended references and courses are as follows:

- AAHSTO Transportation Curriculum Coordination Council (TC3) course, *Cold In-Place Recycling (CIR)*
- Asphalt Recycling and Reclaiming Association, *Basic Asphalt Recycling Manual*
- Asphalt Recycling and Reclaiming Association, CR101 Recommended Construction Guidelines For Cold In-place Recycling (CIR) Using Bituminous Recycling Agents
- Asphalt Recycling and Reclaiming Association, CR102 Recommended Construction Guidelines For Cold Central Plant Recycling (CCPR) Using Bituminous Recycling Agents
- Asphalt Recycling and Reclaiming Association, CR201 Recommended Mix Design Guidelines for Cold Recycling Using Emulsified Asphalt Recycling Agent
- Asphalt Recycling and Reclamation Association, CR202 Recommended Mix Design Guidelines for Cold Recycling Using Foamed (Expanded) Asphalt Recycling Agent
- Federal Highway Administration, Tech Brief: Overview of Project Selection Guidelines for Cold In-place and Cold Central Plant Pavement Recycling, FHWA-HIF-17-042
- Federal Highway Administration, Sustainable Pavement Program: In-place and Central-Plant Recycling of Asphalt Pavements in Virginia, FHWA-HIF-19-078
- National Highway Institute course, *Asphalt Pavement In-Place Recycling Techniques*, Course Number: FHWA-NHI-131050
- National Cooperative Research Program (NCHRP) Research Report 960 Proposed AASHTO Practice and Tests for Process Control and Product Acceptance of Asphalt-Treated Cold Recycled Pavements, 2021.
- RoadResource.org
- Wirtgen GmbH, *Cold Recycling: Wirtgen Cold Recycling Technology*

9 REFERENCES

1. Asphalt Reclaiming and Recycling Association (ARRA) (2015) *Basic Asphalt Recycling Manual.* 2015.
2. Asphalt Recycling and Reclaiming Association (ARRA) (2017a) CR101 Recommended Construction Guidelines For Cold In-place Recycling (CIR) Using Bituminous Recycling Agents, 2017.
3. Asphalt Recycling and Reclaiming Association (ARRA) (2017b), CR102 Recommended Construction Guidelines For Cold Central Plant Recycling (CCPR) Using Bituminous Recycling Agents, 2017.
4. Indiana Department of Transportation (INDOT) (2020). *Indiana Design Manual – 2013,* Chapter 602 Project Categories and Pavement Types, p.29, 2020.
5. Matthews, D. (2013). "Controlling Quality – What Matters for Performance of In-Place Recycling." Presentation at the ARRA Semi-Annual Meeting, Dallas, TX, Nov. 13, 2013.
6. Diefenderfer, B.K, Bowers, B.F., and Apeagyei, A.K. (2015) Initial Performance of Virginia's Interstate 81 In-Place Pavement Recycling Project. Transportation Research Record: Journal of the Transportation Research Board, Washington, D.C. 2015, No. 2524, pp. 152-159.
7. Road Resource, www.roadresource.org
8. A No-Cost Design Change and First-Try Use of Foamed Asphalt Yields a Brand New Road Near Clemson University. (2020) Roads and Bridges Magazine. Available at: https://www.roadsbridges.com/asphalt-recycling/article/10652431/a-no-cost-design-change-and-first-try-use-of-foamed-asphalt-yields-a-brand-new-road-near-clemson-university. Accessed June 28, 2022.
9. National Academy of Sciences, Engineering, and Medicine (NASEM) (2017), *Material Properties of Cold In-Place Recycled and Full-Depth Reclamation Asphalt Concrete.* Washington, DC: The National Academies Press. https://doi.org/10.17226/24902.
10. Diaz-Sanchez, M. A., Timm, D. H., and Diefenderfer B. K. (2017). Structural Coefficients of Cold Central-Plant Recycled Asphalt Mixtures. Journal of Transportation Engineering, American Society of Civil Engineers, Vol 143, No. 6. https://doi.org/10.1061/JTEPBS.0000005.
11. Bowers and Powell (2021) Use of a Hot-Mix Asphalt Plant to Produce a Cold Central Plant Recycled Mix: Production Method and Performance. Transportation Research Record: Journal of the Transportation Research Board, Washington DC, 2021, DOI: 10.1177/03611981211017904.
12. National Academies of Sciences, Engineering, and Medicine (NASEM) (2021). *Proposed AASHTO Practice and Tests for Process Control and Product Acceptance of Asphalt-Treated Cold Recycled Pavements.* Washington, DC: The National Academies Press. https://doi.org/10.17226/25971.