UFC 3-250-07
7 December 2021

UNIFIED FACILITIES CRITERIA (UFC)

STANDARD PRACTICE FOR PAVEMENT RECYCLING

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

UNIFIED FACILITIES CRITERIA (UFC)

STANDARD PRACTICE FOR PAVEMENT RECYCLING

Any copyrighted material included in this UFC is identified at its point of use.
Use of the copyrighted material apart from this UFC must have the permission of the copyright holder.

Use of the name or mark of any specific manufacturer, commercial product, commodity, or service in this UFC does not imply endorsement by the Department of Defense.

U.S. ARMY CORPS OF ENGINEERS

NAVAL FACILITIES ENGINEERING COMMAND

AIR FORCE CIVIL ENGINEER CENTER (Preparing Activity)

Record of Changes (changes are indicated by **1**\ ... /**1**/)

Change No.	Date	Location

This UFC supersedes UFC 3-250-07, dated 16 January 2004.

FOREWORD

The Unified Facilities Criteria (UFC) system is prescribed by MIL-STD 3007 and provides planning, design, construction, sustainment, restoration, and modernization criteria, and applies to the Military Departments, the Defense Agencies, and the DoD Field Activities in accordance with USD (AT&L) Memorandum dated 29 May 2002. UFC will be used for all DoD projects and work for other customers where appropriate. All construction outside of the United States is also governed by Status of Forces Agreements (SOFA), Host Nation Funded Construction Agreements (HNFA), and in some instances, Bilateral Infrastructure Agreements (BIA.) Therefore, the acquisition team must ensure compliance with the most stringent of the UFC, the SOFA, the HNFA, and the BIA, as applicable.

UFC are living documents and will be periodically reviewed, updated, and made available to users as part of the Services' responsibility for providing technical criteria for military construction. Headquarters, U.S. Army Corps of Engineers (HQUSACE), Naval Facilities Engineering Command (NAVFAC), and Air Force Civil Engineer Center (AFCEC) are responsible for administration of the UFC system. Defense agencies should contact the preparing service for document interpretation and improvements. Technical content of a UFC is the responsibility of the cognizant DoD working group. Send recommended changes with supporting rationale to the respective service proponent office by the following electronic form: Criteria Change Request. The form is also accessible from the Internet sites listed below.

UFC are effective upon issuance and are distributed only in electronic media from the following source:

- Whole Building Design Guide web site http://DoD.wbdg.org/.

Refer to UFC 1-200-01, *DoD Building Code (General Building Requirements)*, for implementation of new issuances on projects.

AUTHORIZED BY:

CHRISTINE T. ALTENDORF, PhD, P.E., SES
Chief, Engineering and Construction
U.S. Army Corps of Engineers

R. DAVID CURFMAN, P.E., SES
Chief Engineer and Assistant Commander of Design and Construction
Naval Facilities Engineering Systems Command

NANCY J. BALKUS, P.E., SES, DAF
Deputy Director of Civil Engineers
DCS/Logistics, Engineering &
Force Protection (HAF/A4C)
HQ United States Air Force

MICHAEL McANDREW
Deputy Assistant Secretary of Defense (Construction)
Office of the Assistant Secretary of Defense (Sustainment)

UNIFIED FACILITIES CRITERIA (UFC)
REVISION SUMMARY SHEET

Document: UFC 3-250-07, *Standard Practice for Pavement Recycling*

Superseding: This UFC supersedes UFC 3-250-07, *Standard Practice for Pavement Recycling*, dated 16 January 2004.

Description: This UFC documents and explains standard operating practices for recycling pavement materials and using the material in pavement structures. These practices apply to roads, airfields, and construction platforms having a stabilized surface layer.

Reasons for Document: This update brings the document in compliance with UFC 1-300-01, *Criteria Format Standard*. Editorial changes were to improve readability, correct typographical errors, update outdated references, and clarify standard practices.

Impact: Cost impact is negligible; improved guidance typically results in improved performance and reduced lifecycle cost.

Unification Issues: None

TABLE OF CONTENTS

FIGURES

TABLES

CHAPTER 1 INTRODUCTION

1-1 PURPOSE AND SCOPE.

This UFC documents the standard practices for recycling pavement materials and using recycled materials in the Department of Defense (DoD) and the National Aeronautics and Space Administration (NASA) pavement structures. It covers recycling methods permitted on DoD and NASA pavements. It provides requirements for the selection of recycling methods as well as the design of pavement cross sections using the recycled materials and recycling methods.

1-2 APPLICABILITY.

These standard practices apply to DoD and NASA pavements. These practices apply to roads, airfields, and construction platforms having a stabilized surface layer. Do not use, plan to use, or bid on a project while planning to use any materials or methods on or in DoD or NASA pavements that are not outlined in this or any other applicable UFC or UFGS without prior approval of the Pavements Discipline Working Group (DWG) and contracting officer and Designer of Record (DOR).

1-3 GENERAL BUILDING REQUIREMENTS.

Comply with UFC 1-200-01, *DoD Building Code (General Building Requirements).* UFC 1-200-01 provides applicability of model building codes and government unique criteria for typical design disciplines and building systems, as well as for accessibility, antiterrorism, security, high performance and sustainability requirements, and safety. Use this UFC in addition to UFC 1-200-01 and the UFC and government criteria referenced therein.

1-4 BEST PRACTICES AND OTHER CONTENT.

Appendix A is reserved for future use.

1-5 SUPPLEMENTAL RESOURCES.

Appendix B contains a list of supplemental resources and references not used herein.

1-6 GLOSSARY.

Appendix C contains a list of acronyms, abbreviations, and definitions

1-7 REFERENCES.

Appendix D contains a list of references used in this document. The publication date of the code or standard is not included in this document. Unless otherwise specified, the most recent edition of the referenced publication applies.

1-8 BACKGROUND.

Pavement recycling reuses pavement materials from existing pavement. Pavement recycling may remove and reprocess existing pavement materials at a central plant and then incorporate them into a new pavement structure, or it may involve reprocessing or modification of existing material in-place and making them part of a new pavement. Recycling is an economical and feasible alternative to using all virgin materials for pavement rehabilitation, reconstruction, and new construction. This is especially true at remote sites. The primary advantages are in reduced cost and time savings, reduced environmental impact, conservation and protection of natural resources, and ability to maintain existing pavement lines and grade.

Recycling presents many advantages for the rehabilitation of fatigued and deteriorated airfield and roadway pavements. Technical advances (since the adoption of early recycling concepts in the 1970s) in terms of materials and mixes, construction methods, and equipment, make recycling a viable solution for rehabilitation or reconstruction. Recycling of pavement materials plays a significant role in sustainable development and reuse of materials.

This UFC contains guidance from a variety of documents, to include:

- Asphalt Recycling and Reclaiming Association (ARRA) *Basic Asphalt Recycling Manual*, 2015.
- Federal Highway Administration (FHWA) *Pavement Recycling Guidelines for State and Local Government,* 1997.
- FHWA National Highway Institute (NHI) *4R Participant's Manual* (Course 131008), *HMA Pavement Evaluation and Rehabilitation Reference Manual* (Course 131063), *PCC Pavement Evaluation and Rehabilitation Reference Manual* (Course 131062), and *Asphalt Pavement Recycling Technologies Manual* (Course 131050).
- Permanent International Association of Road Congresses (PIARC) *Pavement Recycling Guidelines,* 2003.
- Airfield Asphalt Pavement Technology Program (AAPTP) *Use of Reclaimed Asphalt Pavements* and *Development of Guidelines for Rubblization July 2008*.
- Innovative Pavement Research Foundation (IPRF) *Evaluation, Design, and Construction Techniques for Airfield Concrete Pavement Used as Recycled Material for Base,* 2006.
- Federal Aviation Administration (FAA) Advisory Circulars and Engineering Briefs.
- Transportation Research Board (TRB) Recycling Reports.

Key DoD documents used in preparing this manual are:

- UFC 3-250-01, *Pavement Design for Roads and Parking Areas*
- UFC 3-250-04, *Standard Practice for Concrete Pavements*
- UFC 3-260-02, *Pavement Design for Airfields*
- UFC 3-260-03, *Airfield Pavement Evaluation*
- UFC 3-260-16, *O&M Manual: Standard Practice for Airfield Pavement Condition Surveys*
- UFC 3-270-08, *Pavement Maintenance Management*
- UFGS 32 01 16.70, *Cold-Mix Reused Asphalt Paving*
- UFGS 32 01 16.71, *Cold Milling Asphalt Paving*
- UFGS 32 01 16.74, *In-Place Hot Reused Asphalt Paving*
- UFGS 32 01 16.75, *Heater Scarifying of Asphalt Paving*
- UFGS 32 11 16.16, *[Base Course for Rigid] and [Subbase Course for Flexible][Subbase Course for Pervious] Paving*
- UFGS 32 11 23, *Aggregate Base Course*
- UFGS 32 11 36.13, *Lean Concrete Base Course*
- UFGS 32 12 15.13, *Asphalt Paving for Airfields*
- UFGS 32 12 16.16, *Road-Mix Asphalt Paving*
- UFGS 32 13 13.06, *Portland Cement Concrete Pavement for Roads and Site Facilities*
- UFGS 32 13 14.13, *Concrete Paving for Airfields and Other Heavy-Duty Pavements*
- TSPWG 3-260-03.02-19, *Airfield Pavement Evaluation Standards and Procedures*
- TSPWG M 3-250-04.06-2 *Alkali-Aggregate Reaction in Portland Cement Concrete (PCC) Airfield Pavements*
- TSPWG 3-250-07.07-6, *Risk Assessment Procedure for Recycling PCC Suffering from Alkali-Aggregate Reaction in Airfield Pavement Structures*

Always consider recycling materials when repairing or rehabilitating existing pavements. The remaining sections of this chapter provide guidance for industry-wide recycling practices. To determine the latest restrictions/limitations on using recycled materials on DoD projects consult the following UFGS documents:

32 01 13 64
32 01 16.70
32 01 16.71

32 01 16.74
32 01 16.75
32 12 15.13 and 32 12 16.16 for asphalt recycling applications
32 13 14.13 and 32 13 13.06 for concrete recycling applications

Do not alter or waive UFGS requirements without prior approval of the Pavements DWG Representative. Chapters 4 through 5 detail the current restrictions/limitations.

1-9 JUSTIFICATION FOR RECYCLING.

Recycling pavement materials is a feasible approach to rehabilitate distressed pavements. Reclaimed materials can reduce the cost of rehabilitation or reconstruction and provide other benefits. Therefore, consider using recycled materials when repairing, rehabilitating, or reconstructing existing pavements. The following are reasons for using reclaimed pavement materials:

- *Environment.* Prior to the inception of recycling techniques, reconstructing old pavements consisted of removing, stockpiling, or disposing of old pavement materials. Recycling can reuse these pavement materials and often offers a cost reduction compared to purchasing virgin materials. Recycling eliminates the disposal problem and conserves natural resources. Some recycling methods reduce greenhouse gases and save energy (Mueller, 2008).
- *Material availability and cost.* The supply of natural material is limited. Even though there is presently an abundant supply of aggregates in the US, the distribution of these sources does not always coincide with the project location. The amount of asphalt and high-quality aggregate available for construction is limited. The high cost of aggregates and asphalt binder increase the unit cost of pavement and encourages the use of recycled materials. The rising cost of fuel and equipment operations encourages recycling, especially for longer haul distances.
- *Technology and equipment.* The increased interest in recycling pavements drives technology and equipment development for recycling that improve performance and reduce cost when utilizing recycled materials. While there are problems peculiar to recycling, the number and complexity of these problems has declined significantly in recent years.
- *Performance*. Studies show that properly designed recycled mixes perform as well as virgin mixes. Experience of different states in the U.S. indicates that, in most cases, the performance of the recycled asphalt pavements is comparable to asphalt pavements constructed with virgin materials. Successfully incorporating recycled asphalt requires; good project selection criteria, proper mix design and good quality control and acceptance (QC/QA) criteria as is with asphalt mixtures using virgin materials.

- *Recycling of non-pavement materials.* Several materials in recycled pavements come from non-pavement sources including reclaimed asphalt shingles, crumb rubber, plastics, and many other products. While widely used elsewhere, this manual does not cover their use.
- *Improved structural capacity*. Except for asphalt surface recycling, all other recycling methods can improve the structural capacity of pavements through the improvement of material properties, increased layer thickness, and/or the addition of a structural layer.
- *Maintain geometry of pavement surface.* Recycling can help maintain pavement surface geometry. This is important in relation to existing curbs and gutters, maintaining clearances underneath bridges or other structures, and in other areas where the design requirements require matching the elevation of adjacent structures.
- *Construction at remote sites.* In some instances, recycling is a necessity such as for pavements at remote sites and/or island bases, where local aggregate materials are not available or are extremely expensive to crush, screen, and mine.

1-10 RECYCLING METHODS AND MATERIALS.

The processes, technologies, and equipment for pavement recycling have greatly improved since the early adoption of recycling techniques in the 1980s. The following sections describe basic recycling methods used in the United States (ARRA, 2001; Kandhal and Mallick, 1997; Bozkurt et al., 2002; Buncher and Jones, 2006; ARRA and FHWA, 2015) along with the applicable UFGS and other documents covering the construction requirements for DoD airfield and roadway pavements.

1-10.1 Asphalt Pavement Recycling.

1-10.1.1 Cold milling (CM).

Cold milling is the controlled removal of an existing pavement to some desired depth. CM is used to correct the surface profile and/or cross-slope or to remove a pavement surface exhibiting distresses such as raveling, top down cracking, rutting, bleeding, and polished aggregate. Overlay the milled surface with hot mix asphalt (HMA), apply a surface treatment, or use as a temporary surface for immediate correction of friction problems (UFGS 32 01 16.71). Construction contracts often state that the milled pavement material is the property of the contractor, who may stockpile and process the material as reclaimed asphalt pavement (RAP) for a future project.

1-10.1.2 Hot recycling (HR).

Hot recycling is the process in which RAP is combined with virgin aggregate, asphalt binder, and/or recycling agents in a central plant blending and mixing operation to produce HMA paving mixtures. The primary benefit of HR is to offset the high cost of virgin asphalt binder. Allow the use of HR on all DoD pavements except the surface course for airfields. Other DoD airfield mixtures may contain RAP such that the amount of asphalt binder from RAP does not exceed 20 percent of the total asphalt content in the recycled asphalt mixture. DoD roadway mixtures may contain RAP such that the amount of asphalt binder from RAP does not exceed 30 percent of the total asphalt content in the recycled asphalt mixture. (UFGS 32 12 15.13 *and UFGS 32 12 16.16*).

1-10.1.3 Hot in-place recycling (HIR).

Hot in-place recycling is the process of heating and softening the existing pavement to allow it to be scarified/milled to a specified depth and combined in-place with virgin aggregate, asphalt binder, and/or HMA. HIR is then re-laid to serve as a base or intermediate course under a new HMA overlay. In some cases, HIR is used as the final wearing surface. HIR is comprised of three specific types:

1-10.1.3.1 HIR-I, Surface Recycling.

In HIR-I, Surface Recycling, the top 0.75 to 2.0 inches (19 to 50 mm) of the existing pavement surface is heated, scarified, combined with new asphalt binder, and re-laid for the purpose of minor mix improvement/modification. Surface recycling can be single-pass or double-pass. In single-pass, the recycled mix is re-laid and serves as the final wearing surface (mix heated-scarified material with new asphalt binder or recycling agent to produce in-place hot recycled mixture). HIR-I is typically used on roadways with low traffic volume (UFGS 32 01 16.75 and UFGS 32 01 16.74).

1-10.1.3.2 HIR-II, Remixing.

In HIR-II, Remixing, the existing pavement is heated, loosened, combined with virgin aggregate and new asphalt binder or new HMA, and re-laid for significant mix improvement and modest pavement strengthening. Remixing can be single stage or multiple stage. In single stage remixing, heat and scarify the pavement to a specified depth in one pass, mix with additional virgin aggregate and asphalt binder, relay mix, and compact. In the double pass method of remixing, the first pass of remixed material is covered with a layer of HMA prior to compaction (UFGS 32 01 16.75 and UFGS 32 01 16.74).

1-10.1.3.3 HIR-III, Repaving.

In HIR-III, Repaving, heat, loosen and combine the pavement surface with virgin asphalt binder and re-lay in tandem with an HMA overlay to strengthen and restore the surface profile and/or friction characteristics. Repaving is surface recycling with an integrally applied thermally bonded overlay (Kandhal and Mallick, 1997). Repaving is single-pass or double-pass. The single-pass method uses one unit equipped with two screeds. In-place material is recycled and repaved with the first screed. New HMA is dumped into the front of the unit, conveyed past the first screed, placed atop the recycled mix, and paved with the second screed. The double-pass method uses two separate units. The first unit recycles and repaves using its own screed. The second unit is a conventional asphalt paver that places and spreads new HMA on top of recycled layer (UFGS 32 01 16.75 and UFGS 32 01 16.74).

1-10.1.4 Cold Recycling.

1-10.1.4.1 Cold in-place recycling (CIR).

Cold in-place recycling is the process of milling and sizing RAP, in-place mixing of RAP with recycling additive and new aggregate (either in the milling machine cutting chamber or in a mix paver) to produce a recycled cold mix, and then placing and compacting the recycled cold mix, typically in a single pass. Use CIR to restore the profile or cross-slope of the existing surface or to mitigate surface and base layer distresses. HMA overlays are required for airfields and higher volume roads (UFGS 32 01 16.71; UFGS 32 01 16.70).

1-10.1.4.2 Cold central-plant recycling (CCPR).

Cold central-plant recycling combines stockpiled RAP with virgin aggregate, recycling additives, and water at a central plant to produce recycled cold mix for use as a new base course. Like CIR, use CCPR to restore the profile or cross-slope of the existing surface or to mitigate surface and base layer distresses. CCPR is generally a viable alternative when stockpiles of high-quality RAP are available or when it is not possible to recycle the pavement in-place (ARRA, 2015). An HMA overlay is required for airfields and higher volume roads (UFGS 32 01 16.70).

1-10.1.4.3 Full-depth reclamation (FDR).

Full-depth reclamation is a process in which all of the asphalt pavement section and a predetermined amount of underlying base material is integrally mixed, treated, and re-laid in-place using a reclaiming machine to produce a stabilized base course. Add asphalt emulsion or portland cement as part of the process. Type C fly ash and lime-fly ash are also used to as chemical stabilization agents in FDR. FDR eliminates existing distresses and restores structural capacity by creating a stronger, higher load-carrying base and is recommended for pavements having a base or subgrade problem. FDR is generally used on low volume roads (Kandhal and Mallick, 1997, UFGS 32 01 16.70*).*

1-10.2 Portland Cement Concrete (PCC) Pavement Recycling.

1-10.2.1 Slab Fracturing (SF).

The process consists of in-place recycling involving breaking or cracking of the existing PCC pavement to prevent reflection cracking in an HMA overlay. SF comprises the following three specific types:

1-10.2.2 Crack and Seat.

Slabs of a jointed plain concrete pavement (JPCP) are fractured into small segments 2 to 6 feet (0.6 to 1.8 m) in length, which are then seated firmly into place in preparation for an HMA overlay.

1-10.2.2.1 Break and Seat.

Fracture slabs of a jointed reinforced concrete pavement (JRCP) into small segments 1.5 to 4 feet (0.5 to 1.2 m) long, with reinforcing steel adequately ruptured/sheared to ensure discontinuity among the fracture pieces. Seat the pieces firmly into place in preparation for an HMA overlay.

1-10.2.2.2 Rubblization.

The rubblization process breaks and pulverizes slabs of JPCP, JRCP, and continuously reinforced concrete pavement (CRCP) into small, discontinuous pieces which no longer act as slabs, but rather function as a high quality granular base. At the slab surface, sizes range from sand-sized particles to 6 inches (150 mm). At the slab bottom sizes are 6 to 15 inches (150 to 375 mm). The rubblized PCC is compacted prior to receiving an HMA overlay. Rubblization is the most widely used slab fracturing process since it best prevents reflective cracking.

1-10.2.3 Recycled Concrete Aggregate.

Recycled concrete aggregate is the product of PCC demolition and removal and off-site processing (i.e., crushing, sizing, and steel removal) of broken concrete into aggregate for use in unbound layers, lean concrete base, or PCC surfacing. (UFGS 32 11 23; UFGS 32 11 20, *[Base Course for Rigid] [and] [Subbases for Flexible] Paving*; UFGS 32 11 36.13; UFGS 32 13 14.13.

There are a number of variations of each method using various additives and different equipment. Moreover, a wide array of construction techniques is possible in terms of the depth of existing pavement removal, the thickness of the recycled material layer, and the type and thickness of cover layer (e.g., chip seal, HMA surface course), if used.

Table 1-1 provides a summary of the basic recycling methods used on asphalt-surfaced pavements while Table 1-2 provides a summary of PCC pavement recycling methods.

1-11 DESIGN CONSIDERATIONS IN RECYCLING.

To achieve satisfactory results by recycling requires an evaluation of the available materials and proper mix design. Additionally, determine the structural adequacy of the existing pavement and design calculations to ensure that the recycled pavement section suffices for the anticipated traffic levels.

Consider the functional aspects of pavement performance in the selection of recycling treatments. In cases where the recycled mix serves as the wearing course, the mix must be capable of (a) placement to the required level of smoothness, (b) providing adequate long-term friction, and (c) providing long-term durability to environmental and traffic effects. The sections below provide brief discussions of these critical aspects of recycling and present relevant DoD specifications and guidance documents corresponding to pavement recycling methods.

Table 1-1 Summary of Asphalt Pavement Recycling Applications

Type	Treatment Equipment	Product	Central Plant or In-Place	Placement and Compaction Equipment	Use
Cold Planing/ Milling (CM)	Milling machine[1]	RAP for Hot or Cold recycling (HR/CR)	N/A	N/A	Controlled removal of the existing pavement to the desired depth
Hot Recycling (HR)	Milling machine[1] or ripper crusher to produce RAP[2]	HMA with RAP	Central plant	Conventional paver and rollers	Some RAP can generally be used in all HMA pavements, except as a surface course on airfields
Hot In-Place Recycling, Type I—Surface Recycling (HIR-I)	Heater-scarifier or hot rotary milling machine	Recycled HMA	In-place	Screed attached to recycling equipment and conventional rollers	Surface course or base course. HMA overlay required on airfields
Hot In-Place Recycling Type II—Remixing (HIR-II)	Heater-scarifier or hot rotary milling machine	Recycled HMA	In-place	Screed attached to recycling equipment and conventional rollers	Typically used as surface course but can serve as base course. HMA overlay required on airfields
Hot In-Place Recycling Type III—Repaving (HIR-III)	Heater-scarifier or hot rotary milling machine	Recycled HMA integrally laid with new HMA overlay	In-place	Screed attached to mixer and conventional rollers	Surface course, except on airfields and high volume roads.
Cold In-Place Recycling (CIR)	Milling machine	Recycled asphalt mixture	In-place	Screed or auger/screed system, or conventional asphalt paver, rollers	Base course
Cold Central Plant Recycling (CCPR)	Milling machine[1] or ripper/ crusher equipment[2]	Recycled asphalt mixture	Central plant	Conventional HMA paver, motor grader, or Jersey spreader, conventional rollers	Base course

Type	Treatment Equipment	Product	Central Plant or In-Place	Placement and Compaction Equipment	Use
Full-Depth Reclamation (FDR)	Reclaiming machine	Recycled mix of asphalt, base and subgrade soil	In-place	Motor grader, vibratory pad-foot roller, steel drum roller, pneumatic rollers	Base course

N/A: Not applicable.
[1] Cold planing/milling machine cut/pulverize W/grinding heads, e.g. conventional or micro milling machine.
[2] Ripping/crushing machine, earthmovers (dozer, excavator, backhoe) W/ripper teeth, scarifiers, grid rollers

Table 1-2 Summary of Concrete Pavement Recycling Applications

Recycle Method	Demolition and/or Removal Equipment	Recycle Material	Use
Slab Fracturing, Crack and Seat	Cracking equipment[1], pneumatic roller	PCC slabs resized through cracking operation	Converts JPCP into base layer to support new HMA overlay
Slab Fracturing, Break and Seat	Cracking equipment[1], pneumatic roller	PCC slabs resized through cracking operation	Converts JRCP and CRCP into base layer to support new HMA overlay
Slab Fracturing, Rubblization	Rubblizing equipment[2], vibratory roller	PCC material resized by rubblizing operation	Converts JPCP, JRCP and CRCP into high quality granular base layer to support new HMA overlay
Recycled Concrete Aggregate (RCA)	Demolition equipment[3], backhoe or front-end loaders (with Rhino horn), crushing plant	RCA	In PCC, lean concrete base, asphalt treated base mixes. As unbound base or subbase. Small sizes of RCA used as aggregates for HMA and PCC mixtures

[1]Cracking equipment includes pile drivers, guillotine hammers, whip hammers, and impact hammers.
[2]Rubblizing equipment includes resonant pavement breakers and multi-head breakers.
[3]Demolition equipment includes drop balls, gravity-drop hammers, hydraulic or pneumatic hammers, trailer-mounted diesel hammers, spring-arm whiphammers, and vibrating-beam breakers.

CHAPTER 2 EVALUATION AND SELECTION OF REHABILITATION STRATEGY

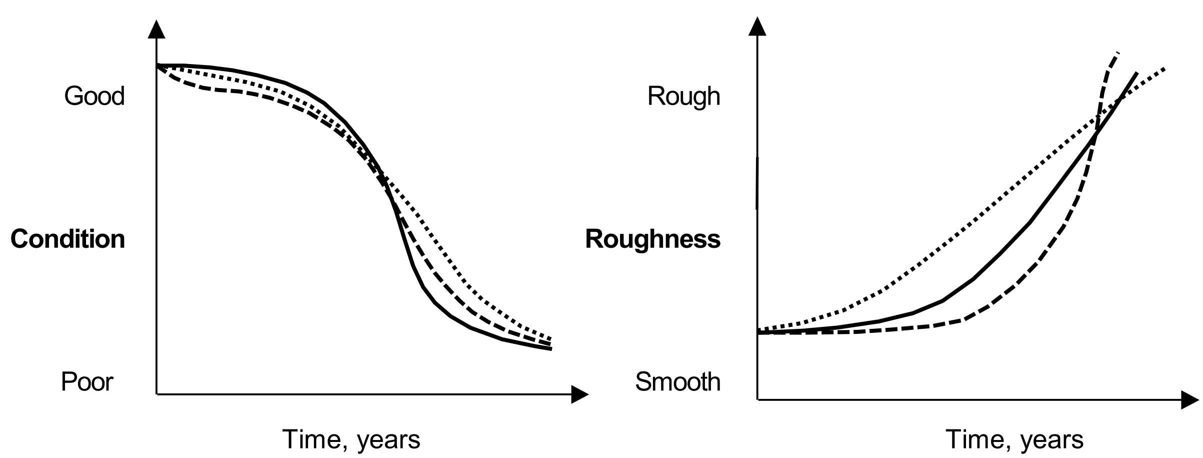
2-1 INTRODUCTION.

The detrimental effects of traffic loading and environmental factors degrade all pavements. The deterioration manifests in a variety of ways (such as cracking, rutting, raveling, spalling), that reduce the structural integrity and functional quality of the pavement. Loss of structural integrity translates into a loss of load-carrying capacity. Loss of functional quality (increased roughness, decreased friction and surface drainage, foreign object damage (FOD) potential) compromises safety and reduces comfort of operation.

Although the manner and speed with which pavements deteriorate differs, the overall trend is one in which the pavement condition changes from good to poor and the pavement surface condition progresses from smooth to rough, as illustrated in Figure 2-1. Factors governing changes in pavement condition include (ARRA, 2015):

- Pavement type
- Quality of project design
- Quality of original construction, including mixes and materials
- Type, thickness, and properties (strength, stiffness, durability, etc.) of individual pavement layers
- Subgrade soil type, bearing properties, and moisture content
- Traffic composition and loading characteristics
- Environmental conditions
- Types, levels, and effectiveness of maintenance activities

Figure 2-1 Pavement Deterioration Trends



(a) Condition deterioration (b) Roughness progression

2-1.1 Pavement maintenance and rehabilitation (M&R) slows deterioration, extends pavement life and addresses the following (Zimmerman):

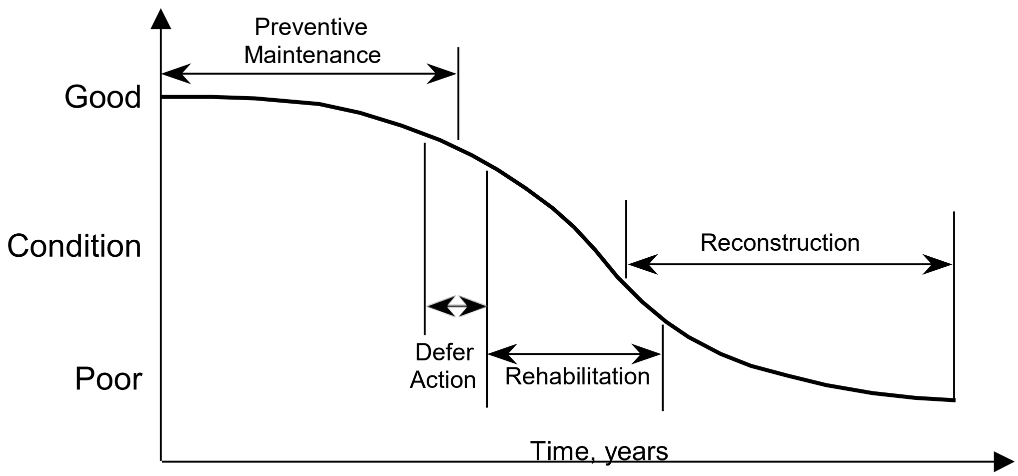
- Inadequate smoothness.
- Excessive pavement distress.
- FOD potential (generally airfields only).
- Reduced surface friction.
- Excessive maintenance requirement.
- Unacceptable user costs.
- Inadequate structural capacity for planned use or projected traffic.

2-1.1.1 Many types of M&R treatments are available for these purposes. They range from localized corrective maintenance (e.g., surface patching, full-depth repairs, rut patching and filling) to preventive maintenance (e.g., crack and joint sealing, surface treatments, thin overlays) to minor rehabilitation (e.g., grooving, functional overlays, limited restoration) to major rehabilitation (e.g., structural overlays, extensive restoration, rubblize-and-overlay).

2-1.1.2 The selection of M&R treatment and timing is a critical component in the economical operation of a pavement network. In the pavement life cycle shown in Figure 2-2, localized corrective maintenance is required at any point on the deterioration curve except at the highest condition levels. However, as the condition level significantly decreases, the costs of corrective maintenance become excessive in the absence of rehabilitation or reconstruction.

2-1.2 Preventive maintenance is a cost-effective treatment that preserves the pavement, retards future deterioration, and maintains or improves functional condition. It is most appropriate when the pavement is in relatively good condition (Zimmerman). As seen in Figure 2-2, the window of opportunity for cost-effectiveness is during the early stages of pavement life.

Figure 2-2 Timing of Pavement Activities*



*Source: Zimmerman.

Rehabilitation, defined as the structural or functional enhancement of a pavement that produces substantial extension in service life (Hall et al., 2001), is most appropriate when preventive maintenance is no longer cost-effective, yet the structure has not deteriorated so badly to warrant reconstruction. During this period, structural capacity remains such that one or several rehabilitation techniques are economically justified over reconstruction.

2-1.3 Although recycling techniques generally fall under the category of rehabilitation, certain forms of recycling, such as CM and HIR-I, constitute corrective maintenance. While HIR-I with an overlay is preventive maintenance. FDR is characterized as reconstruction.

2-2 SELECTION OF PREFERRED REHABILITATION ALTERNATIVE.

2-2.1 Introduction.

2-2.1.1 This chapter provides an overview of the rehabilitation selection process, as it pertains to asphalt and concrete pavement recycling methods. It is a general familiarization tool and a lead-in for the detailed, project-level applications presented in Chapter 3.

2-2.1.2 The selection process favors those recycling techniques that fall under the rehabilitation and reconstruction categories. Such treatments transform an existing deteriorated pavement into a new pavement with significant future performance expectations that necessitate an economic analysis. UFC 3-270-08 provides useful background guidance in the determination of feasible M&R alternatives, including many of the recycling techniques discussed in this manual.

2-2.1.3 Determining the most appropriate rehabilitation strategy for a given pavement at a given time is not a simple process, especially if cost-effectiveness is a consideration. The process requires information about the existing pavement as well as the needs and constraints of the rehabilitation proposed. In addition, there are usually several solutions to consider, each with unique advantages and disadvantages.

2-2.1.4 When identifying a pavement for possible rehabilitation, perform a sequential approach to evaluate strategies and identify possible solutions. First survey the existing pavement to identify and quantify the various types of distress and the rate(s) at which they are developing. Prepare a list of feasible rehabilitation techniques based on the distresses identified. Next, collect historical information, and perform a detailed evaluation to identify the mechanisms causing the distress and to determine the structural and functional capacities of the pavement. Formulate rehabilitation strategies (i.e., a specific treatment or a combination of treatments) that adequately address the cause of the distress. These strategies may or may not include recycling materials and techniques.

2-2.1.5 Then further develop the strategies to satisfy the needs and constraints of the project. After identifying a final set of feasible rehabilitation strategies, perform a cost analysis and evaluate the results in conjunction with non-monetary factors to select the preferred alternative.

2-2.2 Identification of Feasible Recycling Techniques.

2-2.1.1 As discussed in Chapter 1, there are several basic recycling methods for rehabilitating existing asphalt-surfaced pavements and rehabilitating existing concrete-surfaced pavements. Perform the basic asphalt recycling methods individually or in combination with other methods and supplement with HMA overlays or surface treatments to satisfy design life requirements. A summary of asphalt recycling methods covered in this document follows below. (*Asphalt Pavement Recycling* (ARRA and FHWA, 2001; Kandhal and Mallick, 1997) and *Basic Asphalt Recycling Manual*, Second Edition (FHWA/ARRA, 2015)).

- Cold Milling/Planing (CM)
- Hot Recycling (HR)
- HIR Type I—Surface Recycling (HIR-I)
- HIR Type II—Remixing (HIR-II)
- HIR Type III—Repaving (HIR-III)
- Cold In-Place Recycling (CIR)
- Cold Central Plant Recycling (CCPR)
- Full Depth Reclamation (FDR)

2-2.1.2 Concrete recycling methods:

- Slab Fracturing—Crack and Seat
- Slab Fracturing—Break and Seat
- Slab Fracturing—Rubblization
- Recycled concrete aggregate (RCA)

2-2.1.3 Consider many factors to determine the feasibility of each application. Obtain a preliminary indication by examining the current condition of the pavement, as reflected by pavement condition index (PCI) survey data and identify the types of pavement distress. Complete descriptions of the PCI procedure, including the distresses evaluated and distress deduct values, are provided in UFC 3-260-16, American Society for Testing and Materials (ASTM) D5340, *Standard Test Method for Airport Pavement Condition Index Surveys*, and ASTM D6433 *Standard Practice for Roads and Parking Lots Pavement Condition Index Surveys*.

2-2.1.4 Currently, airfield pavement PCI surveys are required on a regular basis for DoD pavements. Conducting PCI surveys on DoD roadway pavements helps determine the appropriate pavement maintenance, repair, or rehabilitation technique.

2-2.1.5 DoD agencies use the MicroPAVER™ pavement management system (PMS) to enter and store PCI survey data and track pavement conditions over time. The MicroPAVER™ system computes the structural condition index (SCI) of a pavement from the distress data collected in PCI surveys. The SCI represents the structural component of the PCI and considers only load-related distresses. Hence, deduct values are applied for distresses, such as, fatigue cracking, potholes, rutting, and shoving in asphalt pavements and corner breaks, longitudinal, transverse, and diagonal cracking, corner spalling, and divided/shattered slabs in concrete pavements.

2-2.1.6 A PCI trigger is more difficult to establish because of the inclusion of non-load-related distresses, but values of 65 to 70 are typical. Trigger levels for reconstruction on major facilities generally span the PCI range of 45 to 50.

2-2.1.7 The PCI is a good measure for determining the timing of an M&R activity; however, selection of an appropriate recycling method is best determined by considering the distresses exhibited. Table 2-1 illustrates typical pavement distresses along with recommended recycling techniques for repair. Repair techniques other than those presented in Table 2-1 may be appropriate, but Table 2-1 presents only recycling techniques. From functional treatments like CM with an HMA overlay to reconstruction using FDR with an HMA overlay, asphalt recycling provides a host of options.

2-2.1.8 Concrete pavements include two approaches for recycling: fractured slab technologies (crack and seat, break and seat, and rubblization) and recycled concrete aggregate.

2-2.1.9 Each recycling technique features advantages and disadvantages in terms of the specific pavement distresses treated and the ability to meet project objectives (e.g., design, construction, and environmental). Table 2-3 provides guidance in identifying feasible recycling techniques for deteriorated asphalt and concrete pavements. The table lists the appropriateness of each recycling technique in terms of how well it mitigates a particular distress.

Table 2-1 Suitability of Asphalt Recycling Techniques Based on Distresses

Pavement Distress	Suitable Asphalt Recycling Techniques					
	CM[2]	HIR[1]	HR[3]	CIR[4]	CCPR[4]	FDR[4]
Alligator Cracking	Green	Red	Green	Green	Green	Green
Jet Blast Erosion	Green	Yellow	Green	Red	Red	Red
Reflection Cracking	Red	Red	Yellow	Yellow	Yellow	Yellow
L&T Cracking	Red	Yellow	Red	Red	Red	Yellow
POL Spillage	Green	Yellow	Green	Red	Red	Red
Raveling	Yellow	Green	Green	Red	Red	Red
Rutting	Green	Yellow	Yellow	Yellow	Yellow	Yellow
Loss of Friction	Green	Green	Green	Red	Red	Red
Slippage Cracking	Green	Red	Green	Red	Red	Red

Key: Green—Likely applicable
Yellow—Maybe applicable
Red—Highly unlikely to be applicable

Notes:
[1] Do not use HIR on airfields without HMA overlay.
[2] CM generates FOD. Do not open milled surface to aircraft traffic under normal operations. Apply HMA overlay prior to opening to traffic. Milled roadway surfaces may be temporarily open to traffic with appropriate traffic control and warning measures. Due to safety concerns, noise and the rough surface associated with milled surfaces, do not allow traffic for extended periods.
[3] HR is suitable in all HMA mixes, except for airfield surface courses. Most HMA contains some RAP, so use HR where HMA is used. See specification requirements for limits on the amount of RAP allowed.
[4] Adhere to the minimum surface thickness requirements for flexible pavements above these recycled mixtures.

Table 2-2 Ideal Candidates for Asphalt and Concrete Recycling Techniques

Recycling Technique	Ideal Candidate Pavement Based on Existing Distresses
CM Only	Expedient repair technique to correct a friction-related and other surface problems, such as roughness, POL spillage, jet blast, etc. This technique is not allowed on airfields since it significantly increases FOD.
CM with HMA Overlay	Milling followed by HMA overlay is the most common approach for repairing existing asphalt pavements. This process works well for raveling, bleeding, cross-slope adjustment, rutting, and roughness.

Recycling Technique	Ideal Candidate Pavement Based on Existing Distresses
Hot Recycling (HR)	RAP is not allowed in HMA mixtures used as surface courses on DoD airfields. RAP is allowed in HMA mixtures used as base course or shoulder pavements on airfields. For DoD airfield pavements, the amount of RAP is limited such that the asphalt binder contributed by the RAP does not exceed 20 percent of the total asphalt content of the mixture, by weight. For DoD roadway and parking lot pavements, the amount of RAP is limited such that the asphalt binder contributed by the RAP does not exceed 30 percent of the total asphalt content of the mixture, by weight.
Hot In-Place Recycling (HIR)	HIR can solve surface problems such as raveling, surface cracking, minor rutting, and friction. Along with HMA overlays, HIR can solve more severe cases of rutting and cracking and add additional structure to the pavement. Do not use HIR on airfields without an HMA overlay.
HIR-I, Surface Recycling	HIR-I typically treats the uppermost pavement surface by heating, scarifying, adding virgin asphalt binder, and placing and compacting for minor HMA mix improvement and modification. Use HIR-I to rejuvenate surfaces that have experienced oxidation and to solve minor surface deficiencies. HIR-I is not allowed on airfields or on high volume roadway pavements.
HIR-II, Remixing	HIR-II is a remixing process that heats and loosens the existing asphalt pavement, combines with virgin aggregate and asphalt binder (or new HMA mix), and places and compacts for significant mix improvement, mix modification, or minor pavement strengthening. This process addresses pavement distresses such as rutting, raveling, loss of friction when confined to the pavement surface. HIR-II is not allowed on airfields or high volume roadway pavements.
HIR-III, Repaving	HIR-III is a more complex process in which the uppermost pavement surface is heated, loosened, combined with virgin asphalt binder, and placed integrally with an HMA overlay for the purpose of pavement strengthening or surface restoration.
Cold In-Place Recycling (CIR)	CIR is used for pavements with significant surface problems such as smoothness, rutting, and cracking. Works well to provide additional structural capacity when coupled with an HMA overlay. When used on an airfield or on high volume roadways, an HMA overlay is required.
Cold Central Plant Recycling (CCPR)	Same as for CIR.

Recycling Technique	Ideal Candidate Pavement Based on Existing Distresses
Full Depth Reclamation (FDR)	Use FDR to correct significant performance problems in an existing pavement, including fatigue cracking, rutting and other distresses that reduce the ability of the pavement to support traffic. Use FDR to significantly strengthen pavements. Rarely used on airfields or high volume roadways. Best used for low volume roads.
Crack and Seat	Crack and seat is a fractured slab technology appropriate for JPCP to reduce to delay, minimize or prevent the onset of reflective cracking in an HMA overlay. Crack and seat technology reduces the length of the existing PCC slabs to approximately 2 to 6 ft (0.6 to 1.8 m) to reduce the inducement of tensile strains at the interface with the new HMA overlay.
Break and Seat	Break and seat is similar to crack and seat, except that it is applied to JRCP and CRCP. In addition to reducing the base PCC slab size to approximately 1.5 to 4 ft (0.45 to 1.2 m), this method breaks the bond of reinforcing steel in the base slab prior to the application of the new HMA overlay.
Rubblization	As the name implies, rubblization is a fractured slab technology that breaks the base PCC slab apart into individual concrete particles ranging from dust to 15 inches (375 mm) diameter, depending on the thickness of the base slab, drainage and subgrade support. Rubblization is appropriate for JPCP, JRCP and CRCP and is effective in minimizing or preventing the onset of reflective cracking in an HMA overlay.
Recycled Concrete Aggregate (RCA)	RCA is appropriate for deteriorated concrete pavements where removal and replacement is the best rehabilitation alternative. Crush old concrete to acceptable particle sizes to produce unbound structural layers for use as base or subbase, and for blending into HMA or PCC mixtures. If used to produce concrete, RCA cannot contain particles that result in alkali silica reaction (ASR). For airfield pavements, only use RCA for aggregate base or lean concrete base.

2-2.3 Formulation of Feasible Rehabilitation Strategies.

Each pavement project comprises a unique set of conditions and circumstances beyond the types, severities, and extents of distresses present. These conditions and circumstances pose constraints on or limits to the effectiveness of individual recycling techniques, as well as the other forms of rehabilitation. A detailed project evaluation is crucial in determining the root cause(s) of pavement distress(es)—design inadequacies, applied loads, water, temperature, materials/construction shortcomings—and formulating a set of feasible rehabilitation strategies that adequately address the cause(s). Such an evaluation requires collecting key information about the existing pavement, establishing rehabilitation performance requirements/expectations, and identifying all factors affecting the suitability of alternative rehabilitation strategies.

Listed below are several specific informational items needed or desirable to formulating feasible recycling strategies. For some of these items, the airfield pavement structural evaluations and runway friction tests are valuable, especially if conducted recently. Pavement Information to collect includes the following:

- Pavement Cross Section—Define the existing pavement structure in terms of material layer types and thicknesses based on design information, as-built construction records, and maintenance data.
- Construction and Materials Quality—QC/QA data provides important information regarding the types of aggregates, binders, and additives used in HMA and PCC mixtures, as well as the mix properties (gradation, binder content, laboratory air voids, in-place density).
- Maintenance—Maintenance records may indicate the presence of chip seals, surface treatments, crack or joint sealant, machine patches, and other material applications that may factor into decisions about recycling and other rehabilitation strategies.

2-2.3.1 Detailed Evaluation of Existing Pavement Properties.

- Layer thicknesses—If historical data cannot characterize the pavement cross section or to obtain additional insight regarding the thickness and uniformity of material layers, then perform coring or ground penetrating radar (GPR) testing.
- Roughness and Friction—A detailed assessment of the pavement profile will quantify the overall roughness of the existing pavement and identify any significant differences in roughness throughout the limits of the project. Similarly, a detailed assessment of pavement friction using the Grip Tester or Mu-Meter will quantify the level of friction on the existing pavement and could identify differences in friction throughout the limits of the project. Texture depth testing via the sand patch method or laser systems (e.g., circular texture meter) can help assess the micro-texture and macro-texture components of pavement friction.
- Drainage—If needed, conduct a drainage survey to further assess the drainage characteristics of the existing pavement structure and determine the appropriateness of individual recycling alternatives. Moisture-related distresses identified in the PCI survey are a key part of this evaluation, as are cross-sectional design information and information about the design and condition of ditches, daylighted bases, and edge drains.
- Strength/Deflection—Nondestructive deflection testing (NDT) using impulse loading devices like the falling-weight deflectometer (FWD) and the heavy-weight deflectometer (HWD) can provide important information about the strength and structural capacity of the existing pavement.

- Strength/Bearing Capacity—The dynamic cone penetrometer (DCP) can evaluate the strength of unbound materials contained in the existing pavement structure. DCP readings can be directly correlated to the California Bearing Ratio (CBR). Like NDT data, CBR data may indicate a deficient unbound layer.
- Material properties—Examine and test pavement cores and other samples taken from throughout the project to gain additional information about the composition and condition of the pavement structure and the physical properties of the material layers.

2-2.3.2 Project Physical Characteristics.

- Project Size and Location—Although available funding may dictate project size, projects are typically defined as those pavement sections of an airfield or roadway pavement facility experiencing similar distresses. Develop a general idea of the project size and the proximity of the project to local aggregate sources and determine material production plants to understand mobilization and hauling considerations.
- Project Geometrics—Project geometrics include the need to maintain vertical alignment (adjacent pavements, in-pavement lighting, manholes, shoulders, curb-and-gutter, etc.), observe overhead clearances (bridges, power lines) or subsurface clearances (electrical circuitry, drainage structures), and address the impacts of lateral structures (e.g., buildings, hangars, lighting, barrier walls) on construction operations.

2-2.3.3 Design Characteristics/Performance Requirements.

- Design Life—Establish the required or desired design life of the rehabilitated or reconstructed pavement. Consider short and long term solutions and balance with budget considerations. Consider staged construction when appropriate.
- Traffic Projections—Determine the current composition of aircraft or vehicles using the pavement facility and their current levels of operation or volume, along with the projected growth rates of individual aircraft or vehicle types over the expected performance period.
- Climate—Climatic variables, such as temperature, precipitation, and freeze-thaw cycles can significantly impact the performance of recycled materials and must considered in the formulation of pavement rehabilitation strategies.

2-2.3.4 Construction Considerations.

- Construction Time Requirements—The available time for construction is often limited due to the scope of the project, the availability of alternate routes or facilities, regular traffic volume and the need to minimize disruptions due to mission requirements or safety concerns.

- Availability of Local Experience and Resources—Determine the knowledge and experience base of local contractors to perform rehabilitation or reconstruction activities, along with the availability of necessary equipment and local aggregates to fulfill the work requirements.
- Support of Construction Equipment—Consider how the removal or alteration of portions of a pavement structure may affect the ability to provide an adequate platform to support construction equipment and compaction of the constructed layers. Special consideration must be given to support of construction equipment when subgrade soils are saturated.

2-2.4 Selection of the Preferred Rehabilitation Strategy.

Selecting the preferred rehabilitation strategy requires evaluating economic and non-economic factors. The sections below briefly describe these factors.

2-2.4.1 Evaluation of Economic Factors.

Chapter 5 of UFC 3-270-08 outlines a procedure for conducting life cycle cost analysis (LCCA) for DoD pavement facilities. This procedure uses the net present worth (NPW) economic formula, an analysis period long enough to capture at least one major rehabilitation activity for each alternative, and a discount rate based on Army policies. An analyst estimates performance lives of the initial rehabilitation treatment and the sequence of M&R treatments expected over the analysis period, along with treatment costs. For each alternative, compute the NPW by summing the initial rehabilitation cost and each of the discounted future M&R costs. Compare the NPW of all feasible alternatives to identify the lowest life cycle cost alternative.

Use other economic factors in addition to life cycle costs for evaluation to include the following:

- Initial costs—Ensure that a project level alternative does not compromise the needs of the entire network (i.e., overall pavement management).
- Indirect/user costs—Costs incurred due to closures for construction and/or M&R work. These are a concern if the expected initial construction and/or future M&R operations generate a high degree of user dissatisfaction.
- Future maintenance costs—Alternatives requiring a disproportionate amount of future maintenance to sustain an adequate level of service, may exceed the personnel and/or equipment available.

2-2.4.2 Evaluation of Non-Economic Factors.

Evaluate numerous non-economic factors when selecting the preferred rehabilitation technique to include: Airfield class/type and traffic area type, roadway traffic level/composition, geometrics (lane widths affecting shoulder dimensions, drainage features, and horizontal and vertical alignment influence on traffic speed, drainage features), continuity of adjacent pavements and/or lanes, peripheral features, and future rehabilitation options and needs. Construction/materials considerations include availability of local materials and contractor capabilities, traffic control during construction (safety and congestion), duration of facility closure, recycling, conservation of materials and energy, roughness, and environmental implications. Consider the following maintenance issues: future maintenance operations, performance of treatment elsewhere under similar conditions, and maintenance capability. Design issues include noise issues (pavement-tire noise), subgrade soils, climate, DoD component or Base preference, safety considerations (friction/texture characteristics, pavement/shoulder contrast, and reflectivity).

CHAPTER 3 PROJECT PROCESS SELECTION AND STRUCTURAL DESIGN

3-1 INTRODUCTION.

This chapter describes a process of analyzing a pavement project to identify acceptable rehabilitation strategies and techniques. It also provides information on the structural design of recycled pavements and life cycle costs.

Airfield pavement conditions at individual military Bases are monitored through PCI surveys and structural evaluations utilizing an FWD. The collected condition data are entered and stored in the MicroPAVER™ pavement management system database. Some installations perform PCI surveys of roadway pavements. Airfield pavement PCI data and other available information determine maintenance and rehabilitation needs and identify those pavements that need detailed pavement structural evaluation or runway pavement friction testing. Base roadway pavements do not typically receive detailed structural evaluations.

Data used to determine the best treatment method includes PCI, FWD, construction and maintenance history, pavement coring and analysis, dynamic cone penetrometer (DCP), and other information. Since PCI and FWD data may have been collected over a considerable length of time, it may not be representative of current conditions. For that reason, a visual inspection may be needed to verify the overall condition and assess the need for additional testing.

3-2 PAVEMENT INFORMATION TO COLLECT.

3-2.1 Layer Thicknesses.

Coring, GPR, FWD, other tests and layered elastic analysis provide the layer information to validate recycling alternatives. The data also indicates the depth of pavement issues. The layer thicknesses and existing pavement issues influence the pavement design and help identify acceptable recycling alternatives.

3-2.2 Friction.

Friction test results and texture depth data provide information about the friction characteristics of the pavement surface. Steps to improve friction will require modifications to the pavement surface. Since friction is a surface problem, treatment for low friction are typically limited to surface repairs. Treatments include HIR, HR, or an HMA overlay. Surface milling can temporarily solve friction problems by improving the surface texture. Utilizing a milled surface is not ideal since the surface tends to have loose aggregate, is noisy under traffic, and can more quickly wear and damage tires of the vehicles and aircraft. FOD is a significant problem for milled pavement surfaces, so it is generally not acceptable to operate aircraft on this type of surface.

3-2.3 Roughness.

If available, roughness measurements, along with distress data from PCI surveys, can help determine specific performance problems causing increased roughness. Some roughness is attributable to design and construction, but most pavement roughness is the result of traffic operations and environmental effects. Performance problems causing roughness in the surface layer including segregation, raveling, and rutting favor recycling strategies such as HIR, HR, and HMA overlays. Conversely, roughness caused by problems in subsurface layers suggests the need for deeper, more extensive forms of recycling such as CM with HMA overlay, CIR, CCPR, FDR.

3-2.4 Drainage.

A drainage survey can identify excessive moisture, the sources of moisture, and the affected pavement layers and materials (Grogg et al., 2001). Surface drainage issues causing performance issues in the upper pavement structure are suitable for treatment using recycling strategies that address the upper layers.. However, if damage extends more deeply into the structure, consider more extensive recycling and/or drainage retrofitting. Subsurface drainage improvement may involve the installation or replacement of longitudinal edge drains and lateral outlets, or daylighting a base layer by replacing base material under shoulders with better-draining material (Hall et al., 2001).

3-2.5 Material Properties.

Pavement cores and other samples provide additional information concerning the cause of pavement distress. Evidence of asphalt binder stripping, bare and uncoated aggregate, friable or disintegrating mix, retention of excessive moisture, bleeding, and a tendency for layer debonding are examples of material deficiencies (ARRA, 2001) that aid in selecting feasible asphalt recycling alternatives. HMA mix properties (binder content and binder properties, aggregate gradation and quality, and voids in the mixture, etc.) and unbound material and subgrade properties influence the effectiveness of techniques that improve the existing materials. PCC pavement with ASR issues precludes the use of RCA materials on most airfield pavements as well as break/crack-and-seat and rubblization techniques.

3-3 RECYCLING METHODS TO ADDRESS PAVEMENT DISTRESSES.

3-3.1 Pavement Performance Problems.

Figures 3-1 through 3-12 illustrate pavement conditions suitable for recycling techniques. Other forms of rehabilitation, such as conventional overlays, with or without RAP, or pavement preservation activities, are also viable options. Use a combination of these techniques to compare their life cycle costs to select the final approach.

3-3.1.1 Alligator Cracking (Figure 3-1).

Alligator cracking often occurs in asphalt pavements and is an indicator of structural weakness. It can occur locally due to localized moisture problems or contamination in the underlying materials. Localized alligator cracking may be repaired by cutting out and patching the affected areas, but more widespread cracking throughout an entire section of pavement indicates pavement failure and likely requires rehabilitation. Alligator cracking is a structural problem that may be related to weakness in the underlying base or subgrade layer or may be related to a drainage problem. For these reasons, treatment of alligator cracking may require significant effort to address.

Figure 3-1 Alligator Cracking

3-3.1.1.1 Alligator cracking requires a detailed inspection and evaluation to determine potential causes. Identify whether drainage is a factor. Cutting a trench across the traffic lane allows inspection, sampling and testing of all layers including subsurface materials. Review available design and construction data. Nondestructive pavement evaluation provides insight into the pavement structure. If cracking is substantial, it may be difficult to conduct FWD testing since the cracking affects the pavement response making it difficult to obtain a good nondestructive evaluation.

3-3.1.1.2 Repair alligator cracking by cutting out and patching or by applying an HMA overlay to the surface. It is often difficult to obtain funding for a pavement just beginning to show distresses, hence, some justification for early repair is needed.

3-3.1.1.3 Rehabilitating alligator cracking often requires removing extra material to eliminate all unsatisfactory material. This is an ideal situation for cold recycling processes (CIR, CCPR, and FDR). For example, remove unsatisfactory material including the base course and pull it to the side for reuse. Stabilize the underlying material before reapplying the base course and a new HMA layer. Perform adjustments to the base materials prior to placement. Adjustments to the base course may include additional aggregate or water.

3-3.1.1.4 Remove the HMA mixture by milling. Treat the milled material with a small percentage of asphalt emulsion before replacing. Place one or more lifts of HMA as an overlay to the milled material. This process is acceptable for low volume roads and airfields. For high volume roads and airfields, HMA over the CIR are required to meet the minimum thickness requirements for HMA over crushed aggregate base course.

3-3.1.1.5 Some low volume roads are suitable for mixing the top several inches of existing structurally deficient pavement with a pulvimixer to produce homogenous underlying materials (FDR). Use this process to mix up to 15 to 20 inches of materials. Move the material to the side of the pavement under repair to rebuild the structure in layers having adequate density and smoothness. Add water or asphalt emulsion to aid in handling and compaction and provide some cohesion. Once the materials are thoroughly mixed, placed, and compacted, cover with an asphalt surface treatment or the minimum required thickness of HMA pavement.

3-3.1.2 Jet Blast Erosion (Figure 3-2).

Jet blast erosion occurs on asphalt pavements in areas where jets operate in slow moving or stopped conditions. The jet blast heats the pavement surface turning the area of direct heat impact black and in some cases actually blasting aggregate particles from the surface and burning the asphalt binder. In extreme cases, the blast removes the entire top layer. This generally only happens when there is delamination between the asphalt surface course and the underlying layer or when the total thickness of asphalt mixture is thin allowing removal of the entire thickness of asphalt.

Figure 3-2 Jet Blast Damage

3-3.1.2.1 Jet blast erosion is a surface problem that does not typically cause significant damage to underlying pavement layers. The normal procedure mills down approximately 2 inches or deeper as needed followed by a patch. On larger projects, recycle the milled material into the project. This is especially beneficial in remote areas. Clearly define in the statement of work whether the millings are contractor property or are retained in a government stockpile.

3-3.1.2.2 Do not use the HIR processes to repair the areas damaged by jet blast erosion. HIR on airfields require the placement of an HMA overlay, hence, HIR is not a good option for correcting areas of blast effect. It is also very difficult to modify the in-place asphalt binder due to the jet blast damage.

3-3.1.2.3 While surface recycling methods can potentially treat jet blast areas, these methods are not normally the best approach. A more straightforward approach is CM with an HMA overlay, which generally provides more satisfactory performance compared to HIR.

3-3.1.3 Reflective Cracking (Figure 3-3).

Applying an HMA overlay directly on an old concrete pavement frequently results in reflective cracking in the new HMA overlay. Applying an HMA overlay to a cracked HMA pavement can result in reflective cracking, but it seldom occurs and is typically not as distinctive the reflective cracking that develops in HMA over PCC. Reflective cracking is caused by the opening and closing of joints and cracks in the underlying layer due to temperature fluctuations. Seal reflective cracks as soon as they occur. If reflective cracks continue to propagate and deteriorate, additional work may be required, such as CM with an HMA overlay. Placement of a fabric or stress absorbing membrane interlayer (SAMI) prior to the HMA overlay may delay the onset or minimize reflective cracking in the HMA overlay, especially over cracked HMA pavements. If the pavement is in poor condition, consider using CIR or CCPR procedures to recycle an HMA pavement exhibiting reflective cracking. CIR or CCPR must incorporate an HMA overlay on DoD airfields and high volume roads.

Figure 3-3 Reflective Cracking

HIR may be effective to address reflective cracking on roadways. For moderate to high volume roadway pavements, apply an HMA overlay or asphalt surface treatment to the HIR surface. HIR may serve as the wearing course on low volume roadways.

3-3.1.4 Longitudinal and Transverse Cracking (Figures 3-4 and 3-5).

Longitudinal and transverse cracking is a common distress on HMA roadway and airfield pavements. Much of the longitudinal cracking is deterioration of the longitudinal paving joints (Figure 3-4). Low density at the longitudinal joint results in cracks forming over time. Longitudinal cracks can develop in the middle of the paving lane at the paver gear box. This phenomenon occurs when the auger flights fail to adequately maintain a uniform head of material in front of the screed. Identify and correct this problem during construction to promote long term performance. Longitudinal cracking can develop into fatigue cracking. In this case, the initial crack occurs longitudinally followed over time by additional cracking parallel and transverse to the intial crack, forming a system of interconnected cracks.

Low ambient temperatures and frequent and significant temperature changes cause cracking in the transverse direction (Figure 3-5) at some spacing along the roadway/airfield. As the pavement ages and becomes embrittled, transverse cracks develop between the earlier cracks, resulting in more closely spaced transverse cracking.

The first maintenance procedure for longitudinal and transverse cracks to seal the cracks to prevent water from entering into the joint and weakening the underlying layers. When cracks widen and become more closely spaced, more aggressive repairs are required. Consider CM with an HMA overlay or HIR with an HMA overlay.

Figure 3-4 Longitudinal Cracking

Figure 3-5 Transverse Cracking

3-3.1.5 Petroleum, Oil or Lubricants (POL) Spillage (Figure 3-6).

Petroleum, oil or lubricant spillage generally occurs under aircraft or vehicles during maintenance or refueling operations. This spillage can soften HMA pavements and can result in the loss of asphalt binder and fine aggregate particles. On roads, this type of damage usually arises from accidents or equipment malfunction. On airfields, POL spillage typically occurs in areas where refueling or minor maintenance is performed. Fuel-resistant HMA mixes should be specified for the surface of airfield pavements where there is risk of POL spillage.

Repair POL spills (Figure 3-6) to prevent raveling and subsequent loss of aggregate particles. Treat by milling the damaged areas and overlaying with HMA.

In many cases, blotting the POL spill on a roadway with sand or sawdust minimizes the damage and quickly allows the road to be opened to traffic. Large spills that are not promptly cleaned up will penetrate the pavement and lead to rapid failure. Remove the damaged material and patch with HMA. Collect the damaged material for treatment and off-site recycling. Further recycling is not cost effective for small areas.

Figure 3-6 Fuel or Oil Spillage

3-3.1.6 Raveling (Figure 3-7).

Raveling (Figure 3-7) typically occurs in areas having segregation or low density, such as longitudinal joints. Areas of segregation or low density observed on the surface may exist through the full depth of the layer. Localized problem areas may ravel enough to require some type of repair. The most common repair is to mill the problem area and patch with HMA. Bituminous surface treatment or an HMA overlay may also be suitable treatments.

When raveling is more widespread, rehabilitate the entire surface by mill and overlay with HMA. For large projects, remove the material from the project site for use as RAP.

Use the HIR process to treat raveled areas followed by application of an HMA overlay on airfields and high volume roads. The HIR process may eliminate the need for milling and may be more cost effective than traditional CM and HMA overlay. On low volume roads, the HIR process without an HMA overlay can be used to treat raveled pavement. HIR may reduce the initial cost and overall life cycle cost.

Figure 3-7 Raveling.

3-3.1.7 Rutting (Figures 3-8 and 3-9).

Rutting can occur in HMA pavements when subjected to slow moving traffic. Rutting can be related to structural weakness (Figure 3-8) in the underlying base, subbase, or subgrade layers or relatively high tire contact pressure that affects the surface layer (Figure 3-9). Rutting, when caused by underlying structural problems, is typically wider and deeper than rutting in the HMA layer caused by high tire pressures. The recycling techniques shown in Table 2-1, except HIR, may be considered for repair of rutted pavement. Rutting due to structural weakness requires excavating and replacing deficient material with satisfactory material. Repair rutting of the HMA layer by removing the top 2-4 inches (25 to 50 mm) of surface and replacing with acceptable HMA.

Prior to repairing a pavement experiencing rutting, investigate the extent of the rutting by cutting trenches across a rutted pavement. If the rutting extends into the base and underlying layers this is an indication that the underlying materials may require improvement or removal and replacement.

Consider recycling processes such as CIR and CCPR to rehabilitate rutted pavement caused by weakness of the underlying layers. For example, the investigation may indicate that there is a problem in the subgrade. In this case, excavate to the subgrade and repair by stabilization. Place the recovered materials back in their appropriate layer in the pavement. It may be necessary to modify or stabilize some of the materials prior to putting back in place.

Repair rutting confined to the existing HMA surface by CM followed by HMA overlay. Use the milled material as RAP in the recycled mixture.

Figure 3-8 Rutting of the Pavement Structure

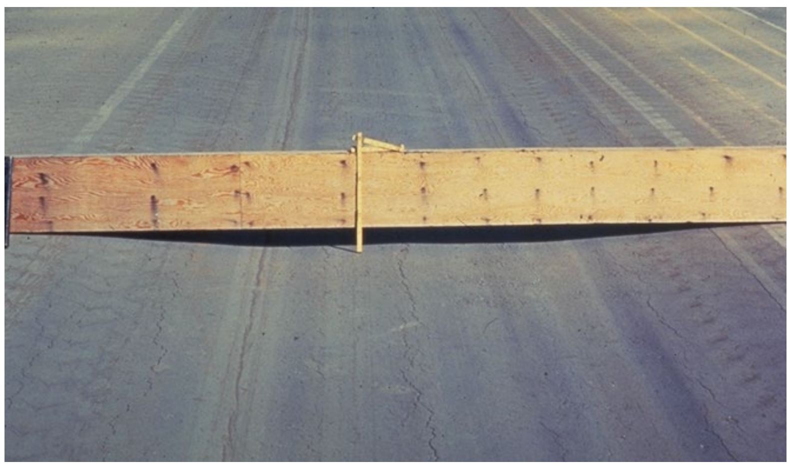


Figure 3-9 Rutting in the HMA Layers

3-3.1.8 Loss of Friction.

Loss of friction often occurs due to polishing of aggregate or asphalt binder bleeding to the pavement surface. Loss of friction can generate significant safety issues and requires prompt repair. Pavement surface issues cause friction problems and are corrected by modifying the surface.

As an expedient repair, mill the surface to improve friction. A milled surface has a rough surface texture that significantly improves friction. The milled surface may deteriorate with time when exposed to environmental conditions and traffic. Therefore, the milled surface is a temporary method. Be aware, using a milled surface to improve surface friction is a significant problem on airfields due to the potential for FOD as aggregates may ravel from the milled surface. Permanently correct the surface with an HMA overlay as soon as practical.

Friction test results and, if available, texture depth data, provide information about the friction characteristics of the pavement surface. Steps to improve friction require modifications to the pavement surface. Friction is a surface issue and the repair for low friction does not require significant modifications below the pavement surface. Repairs for friction problems include HIR, HR, or an HMA overlay.

3-3.1.9 Slippage (Figure 3-10).

Slippage occurs when delamination occurs between two layers of asphalt mixture (typically the top two layers). This is due to a number of factors including the type of tack coat used, application procedures for tack coat, and the cleanliness of underlying surface. Moisture problems can also cause delamination and loss of bond. If slippage occurs, remove the top layer by milling below the depth of delamination and applying an HMA overlay. The overlay can consist of HR.

Figure 3-10 Slippage due to Loss of Bond

3-3.1.10 Alkali Silica Reaction (ASR) (Figure 3-11).

ASR results in scaling or map cracking around joints or other areas subject to moisture. The ASR generates swelling in the concrete resulting in internal stresses. In time this leads to deterioration of the concrete surface. Typically, concrete pavements with ASR continue deteriorating, eventually requiring repairs. There is a risk of expansion and breakdown of this material if left in place, even if cracked and seated or rubblized, This risk increases in the presence of soils or ground water that contain Alkalis and/or Sulfates. ASR or sulfate reactions may generate additional swelling of the mixture, cause breakdown of the material or generate additional performance problems. Remove and crush this material to aggregate size and use as base course or similar use for roadways. Do not design, place or use this material under airfield pavement without prior approval of the DoD's Pavements Discipline Working Group (DWG). Requests to the Pavements DWG for use of ASR infected recycled concrete under airfield pavements must include a detailed risk assessment, the type of cement in the concrete or the type of cement used in concrete supplied by local ready mix plants for building foundations, field measurements of sulfate concentrations in the soil and ground water, the pH of the soil and ground water, a list and drawing showing the location of any utility, drain, gutter, foundation, or arresting system component within 20 feet (6 meters) of the material placement and a detailed list of design and operational means and methods that will be employed to monitor and mitigate any expansion of the material that may develop. Only submit such requests as value engineering proposal requests in Design-build or construction contracts of designs not including the reuse of the ASR recycled material on airfields. Do not bid a design-build contract assuming or accepting or calculating the use of ASR infected recycled concrete is or will be allowed in any airfield pavement.

Figure 3-11 ASR Distress (Scaling/Map Cracking) on Concrete Pavement

3-3.1.11 Shattered Slabs (Figure 3-12).

Shattered slabs occur when the pavement has exceeded its design life or the pavement is overloaded. Fractured slab technologies, such as crack and seat, break and seat, or rubblization, coupled with HMA overlay, work well to address concrete with shattered slab distress. Account for the loss of strength in the fractured concrete in the structural design of the HMA overlay. Alternately, remove and crush the concrete for use in HMA or PCC mixes or as base course.

Figure 3-12 Shattered Slabs on Concrete Pavement

3-4 PAVEMENT CONDITION AND PERFORMANCE TRENDS.

Finally, assess the feasibility of recycling based on pavement condition/performance trends. Historical PCI or SCI trends, or even trends of key distresses, indicate the rate of deterioration. Knowing the PCI or SCI deterioration rate allows a more accurate selection of techniques to address future conditions. As a general note, UFC 3-270-08 provides illustrations of low, normal, and high long-term rates of deterioration for four pavement types: asphalt concrete (AC) pavements, AC overlays of AC pavements, PCC pavements, and AC overlays of PCC pavements. Measure the long-term rate from the time of construction or last overall M&R activity. It also categorizes short-term deterioration rates, i.e. a drop in the pavement condition index (PCI) during the last year, as low (≤3 PCI points), normal (4 to 6 points), and high (≥7 points).

3-4.1 Evaluating Existing Pavement.

If available, detailed pavement structural and/or functional information may shed light on the causes of pavement distress, leading to a more viable set of candidate recycling strategies. PCI results are useful. Inspecting the project is essential. The following paragraphs discuss the indicators that pavement properties provide to identify appropriate repair strategies.

3-4.2 Design Considerations.

Following are aspects of CIR design.

3-4.2.1 Existing Pavement Structure and Conditions Analysis (ARRA, 2001).

Carry out a detailed review of written and/or verbal historical information. While much of this information may not exist, collect as much data as possible. If sufficient data is lacking, collect it through the site inspection and additional testing.

Past project design documents and construction records such as QC data and inspection reports are helpful. Other useful information includes data collected since the construction of the road/airfield such as the types of maintenance performed and documentation of observed performance problems. Surface treatments are particularly important as they have a high asphalt binder content to account for in the new mix design.

The following is information and techniques useful in evaluating the composition and condition of a pavement structure.

a. General information.
  - Thickness of HMA layers
  - Moisture problems such as delamination, poor bond, and stripped aggregates
  - Asphalt binder properties in HMA layers
  - Maximum aggregate size
  - Presence of paving fabric
  - Presence of special mixes such as porous friction course (PFC), open graded, or stone matrix asphalt (SMA).
  - Patch location and age
  - Patch materials (e.g., HMA, cold mix asphalt, injection spray patching)
  - Crack seal material type and ages
  - QC/QA information, including:
    - Asphalt binder content
    - Aggregate gradation, angularity, flat/elongated particles and/or petrographic analysis
    - Voids total mix (VTM), voids in mineral aggregates (VMA), voids filled with asphalt (VFA)
    - Field compaction
    - Recovered asphalt binder properties

b. Pavement performance curves or data that indicates the rate of pavement deterioration

c. Visual inspection of the pavement conducted by an experienced person. Verify the following information:

- Type and severity of the surface and structural distresses (localized or generalized problems)
- Segments with similar problems
- Identification of localized problems that may need special treatment
- Segments that need correction of the surface profiles
- Presence of manholes or similar structures
- Characteristics of the shoulders
- Adequate area to stage construction equipment

d. Non-destructive deflection testing (NDT) evaluation to identify limits of sections with relatively uniform support. It is important to know if the pavement has structural capacity to support the CIR construction equipment and to verify the design for repair. Conduct destructive evaluation on pavement having special problems or to obtain samples for laboratory testing.

e. Obtain representative RAP samples using random sampling techniques for adequate CIR mixture design. Take sufficient cores to provide material for the testing described in the mix design section.

f. Core samples are typically 6 inches (150 mm) in diameter. The number of samples depends upon the size of the project. Large projects, greater than 4 miles (6.4 km) long, require at least two samples per lane-mile (1.6 lane-km) with a minimum of six samples per project. Additional cores may be required to provide enough material for mix design. Small projects require at least eight samples per mile (1.6 km) or one per block if the pavement is not homogeneous (ARRA, 2001; FHWA, 1997).

3-4.2.2 Identifying Distress Causes.

Identifying distresses and their likely causes during the visual inspection is mandatory to identify all root causes to consider in the decision-making process. For example, rutting on the pavement surface may be caused by a number of factors including but not limited to weak subgrade or an unstable mixture. The repair for rutting in asphalt layers is much different from repairing rutting in the underlying layers.

3-4.2.3 Analysis of Road/Airfield Profile/Geometric Assessment.

Analysis of the road or airfield pavement profile and a geometric assessment is of paramount importance to determine project requirements, including the following:

- Major realignment, widening or drainage corrections
- Special consideration for underground utilities and drainage structures

- Attention to bridges and overpasses. Evaluate structural capacity to determine if they provide adequate support of construction equipment
- Longitudinal grade corrections
- Corrections for cross slope and fall

These analyses assist in evaluating whether the project is a good candidate for recycling or other alternatives.

In urban areas, check whether construction equipment can maneuver onto or exit the construction site.

In general, correct small problems with longitudinal/transverse profiles during the paving process. If these defects are serious, consider the following alternatives:

- Use CM to correct profile deficiencies if the road or airfield HMA pavement has adequate thickness
- Use additional granular material or RAP to correct profile
- Correct during CIR and add a leveling course or HMA overlay

3-4.2.4 Selection of Best Materials and Methods.

It is essential to know the properties of the existing in-place materials before selecting the best new materials to add. The mix design topic discusses how to evaluate material properties.

3-4.2.5 Traffic Assessment.

For an existing pavement, historical traffic data can be used to assess remaining structural life as well as the effect of construction quality on the adequacy of the original design. For new pavements, the designer develops a forecast of future traffic to support the selection of layer materials and compute individual layer thicknesses within the optimized design solution.

3-4.2.6 Layer thicknesses.

Results of coring and other tests such as GPR and NDT can provide the layer information needed to verify the appropriateness of recycling alternatives and indicate the depth of any pavement problems that must be addressed. This information, in turn, may determine acceptable recycling alternatives.

3-4.2.7 Friction.

Friction test results and texture depth data provide information about the friction characteristics of the pavement surface. Steps to improve friction require modifications to the pavement surface. Friction is a surface issue and the repair for low friction does not require significant modification below the pavement surface. Techniques used to address friction problems include HIR, HR, or an HMA overlay. Temporarily solve friction problems using CM to improve the surface texture. Do not allow aircraft to operate on milled pavement surface due to potential FOD damage to aircraft engines and tires. If it cannot be avoided, vehicular traffic may be allowed on milled roadway pavements for a short duration, with adequate traffic control to reduce safety concerns due to loose aggregate, vehicle damage, and noise.

3-4.2.8 Roughness.

Evaluate roughness from test results and from PCI survey distress data. Correct roughness in the surface layer caused by segregation, raveling and rutting using recycling strategies such as HIR, HR, and CM with an HMA overlay. Roughness from subsurface layers will require more extensive forms of recycling including CM with HMA overlay, HR, CIR, cold central plant recycling (CCPR), and FDR.

3-4.2.9 Drainage.

A drainage survey and evaluation can identify excessive moisture, the sources of moisture, and the affected pavement layers and materials (Grogg et al., 2001). Surface drainage issues are suitable for treatment by recycling strategies that target the surface layer. However, if the effects are deeper in the structure, more extensive recycling or drainage retrofitting may be necessary. Subdrainage improvement may involve installing or replacing longitudinal edge drains and lateral outlets or daylighting a base layer by replacing base material under shoulders with better draining material (Hall et al., 2001).

3-5 STRUCTURAL DESIGN.

Structural design of airfield and roadway pavements is accomplished by engineering analysis of test results and material properties to develop pavement rehabilitation alternatives to support intended traffic over an established design period. Design of flexible and rigid pavements can be accomplished using layered elastic or mechanistic design methods. NDT is conducted to estimate pavement layer and subgrade elastic properties. DCP testing can be used to estimate mechanistic properties such as CBR or k-value. Load transfer efficiency across joints and cracks and the presence of voids under slab corners and edges may assist the designer in developing rigid pavement design alternatives.

Structural pavement design for pavement rehabilitation alternatives using recycling technologies is the same as those for ordinary pavements.

3-5.1 Structural Design for Roads.

The primary structural design tool for DoD roadway pavements is the Pavement-Transportation Computer Assisted Structural Engineering (PCASE) computer program. PCASE performs flexible and rigid pavement design for roads using mechanistic or layered elastic methods. The equivalency factors for use in designing pavements using recycling technologies are provided below.

3-5.2 Structural Design for Airfields.

PCASE is also the primary structural design tool used for DoD airfield pavements. PCASE performs flexible and rigid pavement design for airfields using mechanistic or layered elastic methods. The equivalency factors for use in designing pavements using recycling technologies are provided below.

PCASE Web Site - http://www.pcase.com

PCASE Computer Based Training – http://www.pcase.com/cbt/

Tri-Service Transportation Web Site – http://www.triservicetransportation.com

3-5.3 CBR Design Method.

The CBR design method is detailed in UFC 3-260-02 and UFC 3-250-01. The CBR design method is automated within PCASE. In the CBR method, the thickness and strength of each layer must protect the layers below. PCASE estimates layer thicknesses for conventional flexible pavements. In the case of stabilized layers, modify the layer thickness by using equivalency factors, such as those shown in Table 3-1, which have been developed based on research and field experience.

Design the pavement structure using the equivalency factors shown in Table 3-1 for recycled layers. If the aggregates to be recycled are angular, according to appropriate specifications, then the recycled material can be used for base course. Otherwise, the material can only be used for subbase. Typically, the recycling techniques shown in Table 3-1 are for base material and require a minimum thickness of HMA as a surface course. Low volume roads may use bituminous surface treatment as the wearing surface.

3-5.4 Layered Elastic Design of Airfield Pavements.

The layered elastic design method can be used for the structural design of DoD airfield pavements and is detailed in UFC 3-260-02. The layered elastic design method is automated within PCASE. In this method, failure is defined as excessive tensile strain at the bottom of the HMA layer or excessive compressive strain at the top of the subgrade. Stresses, strains and deflections are computed assuming elastic properties in each pavement layer. The following assumptions apply:

- The pavement is a multilayered structure.
- Each layer is described by its thickness, modulus of elasticity and Poison’s ratio.
- The interface between layers is continuous. In other words, the friction resistance between layers is greater than the developed shear force.
- The subgrade is modeled as a homogeneous, isotropic, elastic half-space.
- All loads are static, circular and uniform over the contact area.

Table 3-1 Granular Base Equivalent Factors

Recycling Technique	Equivalency Factor	
	Base	Subbase
HMA (including HR and HIR)	1.15	2.30
Crushed aggregate base	1.00	2.00
Uncrushed aggregate subbase	---	1.00
Pulverized/crushed RAP blended granular base	1.00	2.00
CIR, CCPR, and FDR (asphalt/cement stabilized)	1.00	2.00
Rubblized portland cement concrete	1.00	2.00

3-5.5 Recommendations for Pavement Design.

The following recommendations are for the CBR method of design when using PCASE:

- Use the appropriate equivalency factors shown in Table 3-1.
- Only use uncrushed aggregate as subbase.

3-6 DETAILED DESIGN OF RECYCLING STRATEGIES.

Evaluate feasible recycling strategies by establishing the specific details for each strategy in terms of the pavement cross-section and the engineering properties of the recycled and new surface layers. These details dictate the quantity of material required, the scheduling of work tasks, and the future M&R requirements.

Formulating a detailed design requires considering the needs and constraints of the project. The needs define the service life of the recycled pavement, including the potential levels of future M&R. The constraints pertain to the available funds for the recycling work and to a variety of construction considerations. A discussion of how these items affect the recycling design strategies follows.

3-6.1 Performance Requirements.

Available funding often controls the selected technique and the expected life of a recycling project. The condition of the existing pavement also affects the expected life.

Selecting and designing the recycling strategies to achieve the desired design life follows one of two approaches. In the first, if sufficient performance data exists for a particular recycling strategy and the data are representative of projects with similar conditions (traffic, climatic, etc.), use the data to formulate a design that achieves the design life requirement. In the second approach, make certain assumptions about the strength and durability of the recycled layer and any surface layer. Then, coupled with an understanding of the strength of the underlying subgrade, subbase, and base layers, determine the thickness of the recycled layer and surface layer in relation to climatic properties and the projected design traffic. Utilize as much confirmed engineering data regarding the subgrade and underlying layers as possible.

Although substantial performance data exist for recycled materials on specific projects, predominantly for highway pavements, nationwide performance data is not available.

Recognizing that actual performance largely depends on project conditions, facility type, projected traffic, climate, recycling design details, and the quality of materials and workmanship, the ranges of expected mean service life are as follows (Sullivan, 1996; ARRA, 2001; Grogg et al., 2001; FHWA, 2005):

- HR: 9 to 16 years (HR mix generally accepted as having the same performance as new HMA)
- HIR-I only: 3 to 5 years
- HIR-I with surface layer: 6 to 10 years
- HIR-II only: 7 to 14 years
- HIR-II with surface layer: 7 to 15 years
- HIR-III: 6 to 15 years
- CIR with surface layer: 5 to 15 years
- CCPR with surface layer: 7 to 15 years
- Break/crack-and-seat with HMA overlay: 8 to 12 years
- Rubblization and HMA overlay: 15 to 20+ years
- Recycled concrete aggregate (RCA) PCC: 15 to 20+ years

Mean service life differs from design life. Mean service life represents the timeframe over which a pavement has a 50-percent probability of providing acceptable service under the conditions (traffic, environment) in which it must function. Acceptable service is generally defined as PCI>70 for Primary pavements and PCI>65 for Secondary pavements. Design life represents the timeframe over which a pavement is structurally designed to serve based on a specified degree of reliability (typically, between 80 and 95 percent probability of providing acceptable service). Hence, a 10-year design life using 90-percent reliability will likely yield a mean service life of 12 or more years.

3-6.2 Future M&R Requirements.

Pavement facilities requiring minimal disruption to traffic and thus minimal numbers and durations of M&R require enhanced designs for some recycling strategies. For instance, the addition of chemical additives such as cement, lime, or fly ash and increasing proportions of virgin HMA or aggregate will achieve stronger and more durable recycled asphalt material. Increasing the thickness of surface layers will generally extend the life of the recycling technology.

3-6.3 Pavement Cross-Section.

For HMA pavements, the presence of a concrete layer, stress absorbing membrane interlayer (SAMI), paving fabric, rubber modifier, and other distinct paving layers can dictate the maximum depth of recycling. Likewise, the total thickness of asphalt bound layers and the depth to which distortions such as rutting, depressions, or swells exist in the pavement profile also influences recycling depth. A limited recycling depth may require thick recycled base and surface layers or greater proportions of virgin materials to achieve the intended design life.

For concrete pavements, rubblization requires a thicker HMA overlay compared to crack/break-and-seat. This is due to the fact that rubblization destroys any capability of the PCC to function as a slab and effectively converts the PCC layer into a high-quality aggregate base. Crack/break-and-seat, on the other hand, reduces the length of the slab, but still allows the remaining pieces of PCC to provide structural support to the pavement system.

3-6.4 Construction and Materials Quality.

Variability in the mix properties of recycled HMA may preclude the use of certain recycling techniques such as in-place recycling on high-quality pavements. Variability of recycled HMA may also require thicker base and surface layers or greater proportions of virgin materials to create a durable pavement that will meet the intended design life. For concrete pavements, the extent and severity of D-cracking or ASR may preclude the use of any recycling technique or may require a thick HMA overlay over fractured PCC. Any ASR will preclude the use of RCA techniques on most airfield pavements.

3-6.5 Maintenance.

The presence of previous M&R treatments including chip seal, surface seal, crack/joint sealant, machine patches, or other materials may influence the detailed design of a recycling strategy. Some technologies may require additional work to remove a previously applied surface treatment prior to recycling. In other cases, special design measures may be used to accommodate the mix properties of these treatments.

3-6.6 Project Size and Location.

Occasionally, the size and location of a project provides a cost advantage to one recycling techniques over others. For example, on a significantly large project, the mobilization of in-place recycling equipment or on-site recycling plants may be more cost-effective than a central-plant setup. Do not discard more expensive recycling strategies too quickly; rather, develop detailed designs and perform LCCA to evaluate and compare alternatives.

3-6.7 Project Geometrics.

If vertical alignment is constrained to the existing surface grade, some recycling strategies are not practical. The same is true if overhead clearances severely restrict building up the cross-section and/or if subsurface clearances limit recycling depths. Recycling strategies must account for these types of constraints and satisfy the performance goals.

Slab fracturing techniques, including cracking or breaking and seating, are a cause for concern in situations where buried utilities, like sewer and water lines, are near the surface. The concentrated impact force induced by the drop hammer poses a much greater threat of damage to utilities compared to the distributed impact forces associated with rubblization.

Another consideration for overhead clearances is the ability of recycling equipment and haul trucks to pass under such features and the ability of recycling equipment to effectively operate next to lateral constraints (e.g., buildings, hangars, barrier walls, straight-faced curbs) and around sharp curves or in tight settings (e.g., short perpendicular taxiways, roadway intersections).

3-6.8 Construction Time Requirements.

Pavement facilities with high-type functional uses and/or high levels of traffic often limit the duration of construction activities. Such limitations may preclude certain recycling strategies and influence the adoption of other strategies and their associated operations (e.g., in-place recycling, on-site plants, multiple recycling trains, night work). For instance, because the depth of the recycled layer and the type of asphalt emulsion influences the length of time required for the asphalt emulsion to break, CIR may not be feasible or may require thin recycled layers to meet a compressed schedule. Proprietary “engineered emulsions” offer reduced break/cure time and can be compacted immediately following mixing.

3-6.9 Availability of Local Resources.

The equipment and technology base for most recycling techniques is common throughout the U.S. However, in less populated areas, locally experienced and properly equipped contractors may be limited. Further, the availability of local good-quality aggregates for use in recycled mixes and/or surfacing mixes may also be limited. For projects facing these limitations, eliminate the affected recycling strategies from consideration or properly account for them in the detailed design process.

3-6.10 Structural Capacity.

Recycling often involves removing or reprocessing an existing HMA layer, which may reduce the structural capacity of the pavement system to a low enough level where the remaining layers are no longer able to support construction equipment. Similarly, the remaining layers must provide sufficient platform stiffness during construction to allow the recycled layer to be compacted. The most critical elements in determining the maximum recycling depth and formulating a detailed design are:

(a) Thickness and condition of the non-recycled portion of asphalt bound layers.

(b) Thickness and strength of underlying unbound base and subbase layers.

(c) Subgrade strength.

(d) Anticipated loading characteristics of the construction equipment.

3-6.11 Traffic Accommodation.

In some cases, the project layout is more conducive to certain recycling techniques in terms of accommodating traffic during construction and providing better overall safety.

3-7 SELECTING THE PREFERRED REHABILITATION STRATEGY.

The LCCA procedure described in UFC 3-270-08 represents a traditional approach to life cycle costing. The procedure makes use of the NPW economic formula, an analysis period of between 10 and 30 years, a set discount rate, and a deterministic computational approach. To ensure that alternative pavements are of equal value at the end of the analysis period, compute the cost to rehabilitate the pavement for each alternative. A more commonly used approach to account for value differences in the competing pavement alternatives at the end of the analysis period computes salvage value in terms of the remaining service life of the final pavement structure.

CHAPTER 4 COLD RECYCLING FOR ASPHALT SURFACED PAVEMENTS

4-1 INTRODUCTION.

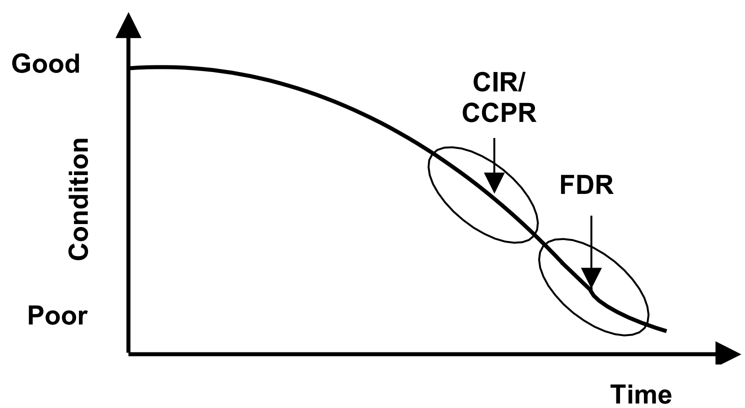
Cold mix recycling involves reusing existing pavement by reprocessing and adding asphalt binder at ambient temperatures. This chapter discusses the application of the three types of recycled cold mix: CIR, CCPR and FDR.

Cold mix recycling takes advantage of chemical additives such as cement, lime or fly ash to increase the early strength and resistance to moisture of the new mixture. Alternative additives include cutback asphalt, foamed asphalt, asphalt emulsion, and a combination of emulsion with cement, fly ash, or lime.

CIR and CCPR are generally used to correct pavements with functional distresses and provide minor strengthening. FDR is appropriate when major structural rehabilitation is required.

Figure 4-1 shows when it is advisable to use CIR/CCPR or FDR in the typical pavement life cycle.

Figure 4-1 Indication of CIR/CCPR or FDR as a Function of Pavement Life



4-2 COLD IN-PLACE RECYCLING.

4-2.1 Introduction.

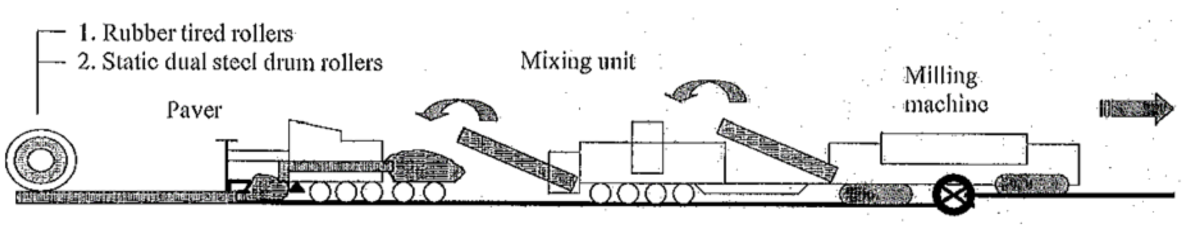
CIR is a partial-depth pavement recycling process. Remove some HMA pavement by milling 2 to 4 inches (50 to 100 mm). CIR creates a layer of material to serve as base course, but it sometimes serves as the surface course on highways with low to medium traffic volume. For example, CIR can be used as the surface for secondary roads if a surface treatment is applied.

CIR is a good technique to rehabilitate thick HMA pavements exhibiting cracks, rutting, shoving, raveling, potholes, bleeding, poor skid resistance, corrugations, fatigue, block cracking, slippage, longitudinal and transverse cracking, reflection cracking, and poor ride quality. However, it requires underlying layers and the drainage system to be in good condition.

CIR can increase pavement strength when placed with an HMA overlay on the recycled material for additional pavement thickness and to provide a higher quality surface.

CIR transforms a distressed pavement into one similar to a new pavement. The CIR process uses special equipment similar to that depicted in Figure 4-2. Ensure the equipment can mill deteriorated pavement and convey the RAP into a unit that crushes the RAP, sizes the RAP, and blends the material into a homogenous mixture. The mixing unit adds asphalt binder and water to the RAP and blends before feeding the mix into the paver hopper. The paver places the recycled mixture at the desired thickness and grade. Vibratory and rubber-tired rollers compact the mix. Cover the CIR with an HMA overlay or surface treatment to provide a smooth riding surface and protect the mixture from water and traffic. When used on airfields, ensure the thickness of the HMA over the CIR meets the minimum HMA thickness required over a crushed granular base course.

Figure 4-2 CIR Recycling Train*



*Source: Hajek et al, 2005.

4-2.2 Past and Current Use.

Mixtures similar to CIR have been used for over 50 years (Bardesi, 2000). Cold recycling has become more common since the 1990s due to technological advances in pavement and material engineering.

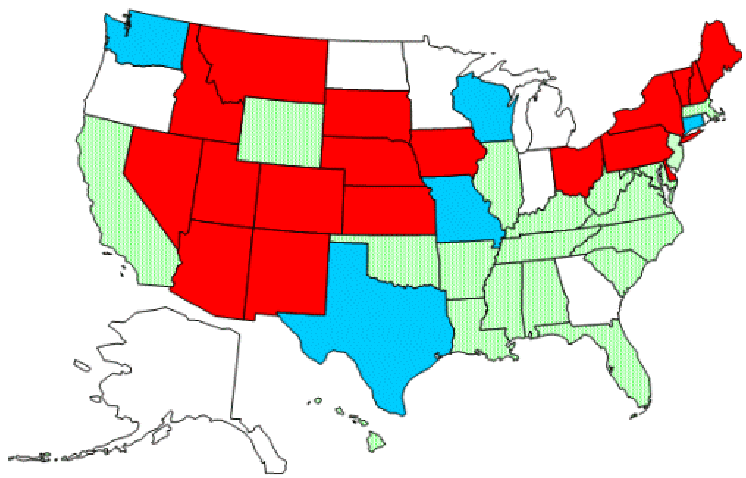
In the past, CIR was used on roads with low to medium traffic volume. Currently, there is no limit to using CIR on high traffic volume roads or as base course material for airfields when properly designed and constructed.

State DOTs have placed millions of square yards of CIR since the 1970s. The main reasons to use of CIR are to correct premature full depth thermal cracking that causes poor ride quality or to address fatigue cracking, rutting, and asphalt stripping problems. A surface treatment or an HMA overlay is used as a surface on most CIR projects.

Asphalt recycling grew rapidly after the early 2000s as highway agencies looked for significant cost savings in highway rehabilitation as well as methods that reduce emissions during construction.

Figure 4-3 shows Federal Highway Administration research on CIR use in the United States (FHWA, 2007). Eighteen states (red) extensively used CIR, five states (blue) reported low use, nineteen states (green) had no use and six states (white) did not respond.

Figure 4-3 Use of CIR in the United States*



*Source: FHWA, 2007.

4-2.3 Guidelines for Use of CIR.

4-2.3.1 Primary Purpose.

CIR is a technology that transforms HMA surfaces into asphalt base material, restores a profile or cross-slope and mitigates surface distresses prior to receiving an HMA overlay or surface treatment. In general, potential projects for CIR are pavements with fatigue cracking, permanent deformation, and surface roughness.

Corrective actions may be necessary for rough or distorted pavement or for flushed pavement. When the pavement is rough, the CIR process may require cold milling (CM) before the CIR operation. When the pavement surface is flushed or is bleeding, adding virgin aggregates may reduce the propensity of the flushing to exist in the CIR mixture.

4-2.3.2 Advantages and Disadvantages.

The main advantages of CIR are as follows:

- Reduced environmental impact due to reduced demand for virgin asphalt binder and aggregates.

- Energy savings compared to other construction techniques.
- Fewer vehicles transporting material at the site. Reduced traffic damage to the pavement when compared to conventional rehabilitation techniques.
- Significant savings compared with conventional rehabilitation techniques.
- Capability to correct surface roughness and reducing cracking.
- Capability to correct surface characteristics such as rutting, potholes, shoving, bleeding and raveling.
- No interference or disturbance of base, subbase and subgrade materials.
- Capability to adjust the mixture by adding virgin aggregates or recycling agent.
- Improved surface ride quality.

The main disadvantages of CIR are as follows:

- Not all materials are economically recycled.
- CIR cannot solve problems associated with layers other than the surface.
- CIR requires a curing period to gain strength and it cannot open immediately to traffic after construction.
- This technology does not apply to projects that require nighttime work in some regions due to temperature limitations and moisture conditions.
- The presence of paving fabric in the existing pavement presents some limitations on the use of CIR.
- CIR is not applicable to pavements with poor drainage or weak base support.

4-2.3.3 Mix Design.

Before starting a mix design, ensure all samples are broken into small particle sizes to simulate RAP during milling operations. Use a small laboratory crusher to crush the RAP in the laboratory to produce a gradation similar to that during actual construction.

There is no nationally accepted cold mix recycling design method. An adaptation of the Marshall Design method (Modified Marshall, Method A) is the method used by most agencies (ARRA, 2001; FHWA, 1997; Asphalt Institute, 2002). Determine the amount of virgin asphalt binder needed in the recycled cold mix by conducting a conventional HMA mix design on the RAP obtained during sampling prior to start of construction.

4-2.3.3.1 Trial Mixes, Curing Time and Job Mix Formula (JMF).

Prior to starting the mix design process, crush the recovered asphalt mix to produce a gradation similar to that expected with the milling machine. Compact the sample at 50 blows per face for low-pressure tires or 75 blows per face for high-pressure tires such as airfields and heavy-duty roads. Equivalent gyratory compaction is permissible.

The main parameters sought are density, stability, flow, voids in the total mixture, and voids filled with asphalt. Plotting these parameters versus asphalt content assists the designer in identifying the optimum asphalt content for the mixture. The optimum additional asphalt is often between 0 and 3%. Do not add additional asphalt if the optimum value is 0% or lower. In this case, only add water to lubricate the mixture so that the expected maximum dry density is achievable in the field. In fact, if the laboratory air voids are too low (below approximately 3 percent), add virgin aggregate to increase the air voids in the mixture to an acceptable level.

In summary, the mix design method consists of:

- Obtain samples of the HMA pavement. Remove samples equal to the depth of milling expected during construction. Crush RAP in the lab to approach the expected gradation of RAP during the milling operation.
- If new aggregate is added, determine the percentage of virgin aggregate to add.
- To determine the percentage of asphalt that provides 3.5 to 4% air voids, design as a hot mix, adding the RAP, virgin aggregate and varying the asphalt emulsion content. The heating process removes the moisture in the mix since this is designed using HMA procedures.
- Once the optimum emulsion content is determined, add the emulsion to the RAP then vary the moisture content in 0.5 percent increments from 0 percent to 2.5 percent. Determine the optimum moisture content by adding moisture in 0.5 percent increments to the cold mix and compacting using 50 blows with the Marshall hammer to determine the optimum additional moisture content to provide maximum dry density. Determine optimum moisture content at room temperature.
- Cure the compacted mixture for 96 hours at 140 ºF (60 ºC).
- Remove the samples from the oven and cool to room temperature. Test the specimens for bulk specific gravity. Then reheat to 140 ºF (60 ºC) and determine Marshall stability and flow.

Table 4-1 shows the mix design parameters recommended by UFGS 32 01 16.70.

Table 4-1 Recommended CIR Mix Parameters[1]

Parameter	Requirement 50 Blows
Voids in total mix (%)	3-5
Voids filled with asphalt (%)	75-85

[1]UFGS 32 01 16.70.

4-2.3.3.2 Evaluation of Existing Salvage Material through Lab Analysis of Field Samples.

- RAP Properties: Determine RAP gradation using ASTM C136 *Standard Test Method for Sieve Analysis of Fine and Coarse Aggregate.*
- Extracted Aggregate: Obtain the extracted aggregate after removing the asphalt binder from the mixture using one of the asphalt extraction tests (ASTM D6307 or ASTM D2172).

4-2.3.3.3 Determining Amount of Virgin Aggregate.

Evaluation studies of existing material are very important for determining the adequate amount of virgin aggregate. The gradation of the aggregate recovered from the RAP may be unsatisfactory or the recovered aggregate quality may not be acceptable. This may require adding virgin coarse or fine aggregate. The majority of CIR projects do not add virgin aggregate.

There are two primary cases that require the addition of virgin aggregates: 1) excess asphalt binder content in the RAP or 2) poor aggregate quality of the RAP. In both cases, the addition of virgin aggregate allows minor adjustments to the RAP mixture to address these deficiencies.

4-2.3.3.4 Asphalt Emulsion.

Most projects use asphalt emulsion to introduce additional asphalt binder to a CIR mixture. In this case, the small amount of additional asphalt binder does not significantly modify the properties of the existing asphalt binder, but serves as additional asphalt to fill voids and improve cohesion. On the other hand, a recycling agent tends to mix and soften the oxidized binder to improve the overall binder properties. A potential problem with adding a recycling agent is incomplete mixing with the other components, which results in uneven distribution of the recycling agent in the mix. The result is that one portion of the mix may become too soft and another portion too brittle. Thoroughly blend all mixture components.

Important specifications for asphalt emulsions for cold-mix recycling are ASTM D5297 for anionic asphalt and ASTM D2396 for cationic asphalt emulsions. Most cold mixes use anionic emulsions. Use cationic asphalt emulsions if past experience with cationic emulsions has been successful.

The grades of asphalt emulsion most commonly used are MS, HFMS, and SS.

- Medium-Setting (MS): designed for mixing with open or coarse-graded aggregate. Because they do not break immediately, mixes with medium-setting emulsions keep their workability for a significant amount of time.
- High Float Medium-Setting (HFMS): designed for mixes that work at high temperatures, which allows better aggregate coating and asphalt retention.

- Slow-Setting (SS): these emulsions are generally more stable. Asphalt droplets in a slow-setting asphalt emulsion stay in suspension in the water for a longer period of time and over a wider range of temperatures, which results in fewer construction problems.

4-2.3.3.5 Recycling Agent.

Recycling agents are used in CIR mixes to improve the properties of the asphalt binder. The oxidized asphalt binder in old HMA mixtures benefits from the use of recycling agents. The recycling agent tends to soften the asphalt binder, resulting in improved properties. If experience shows success with the recycling agents, use it in place of asphalt emulsion. Specify asphalt recycling agents using ASTM D5505.

4-2.3.3.6 Moisture in Mix.

Moisture is necessary to facilitate mixing, handling, and the compaction process. RAP may contain enough free moisture so that adding water is unnecessary. Add water before adding recycling additives to lubricate and promote cooling of the cutting head. If using a pugmill, add water simultaneously with the recycling additive. Slow-setting asphalt emulsions and the anionic grades of medium-setting asphalt emulsions require moisture to promote adequate coating during mixing process. High float emulsions and cationic medium-setting asphalt emulsions may contain petroleum distillates and require less moisture to provide good workability and compaction.

Conduct coating tests for any type of asphalt binder additive used to verify if the mixing water is adequate to disperse the additive. It is a very simple test that requires 2.2 pounds (1000 g) of RAP with the estimated initial amount of recycling additive. Test different samples with 0.5% increments of water. Add water and mix briefly (maximum of 30 seconds) to humidify the RAP. Incorporate the recycling additive and blend the mixture for 2 additional minutes. Perform this test manually, because it is easier to observe mix workability and coating. Visually evaluate and select the dispersion and the lowest moisture content that results in no additional increase in coating. The total liquid content (sum of the mix water content + recycling additive + moisture of the RAP) is different for each project and is determined during the mix design.

4-2.3.4 Structural Design.

Chapter 3 provides a general overview of structural design and its application to pavement recycling. One concern in the structural design of a pavement using CIR mixtures is the difficulty in characterizing the mixture sufficiently for use in the CBR method or layered elastic design method. Information required for design includes the equivalency factor for CIR and the modulus and thickness of the CIR layers. Chapter 3 provides this information.

4-2.3.5 Construction.

4-2.3.5.1 Types of Equipment.

The CIR train consists of a cold milling machine capable of reclaiming old asphalt pavement to depths of 2 to 6 inches (50 to 150 mm). The equipment for CIR is available in different configurations: single machine (single-unit train), two-unit train and multi-unit train. Use the same compaction equipment as used for HMA.

4-2.3.5.2 Single Machine (Single-Unit Train).

The milling machine of the single-unit train cuts the old pavement to a specified depth, providing the desired profile grade and transverse slope. The equipment separates the RAP into sizes and mixes the RAP with asphalt emulsion or recycling agent. Figure 4-4 shows one example of these machines.

Figure 4-4 Single Machine*

*Source: Roadtec, https://www.roadtec.com/

- Simple operation.
- High production capacity.
- Good for operation in urban areas and roads with small turning radius.

One disadvantage of the single machine is its lack of control of oversize RAP aggregate. The operator is unable to control the exact amount of material and is unable to control minimal mix times. Since the single-unit train lacks screening and crushing units, the operator likely will have difficulty controlling the maximum particle size. Old pavement with serious fatigue cracking exacerbates this limitation. Do not use the single unit train for pavements that present edge drop-off and severe distortion caused by rut depth because the application rate of recycling additive cannot be controlled. Base the amount of additive on the volume of material considered and it depends on the cutting depths and widths as well as the previously estimated speed for the machine operation.

If the mix design recommends incorporating aggregates or dry additives, such as lime or cement, spread the additives on the pavement prior to milling.

4-2.3.5.3 Two-Unit Train.

The two-unit train has an advantage when compared to the single machine, namely, it allows precise control of liquid additives in the RAP. Control of liquid additives is based on weight rather than the volume of material or speed.

The two-unit train incorporates pugmill mix pavers in the system and is able to mill a full lane wide. An example of this machine is in Figure 4-5.

Like the single-unit train, the two-unit train is able to work in urban areas and on roads with short turning radii. The primary disadvantage is its lack of crushing and screening units which means this type of equipment is not able to control aggregate oversize. Simple operation and high production capacity are the main advantages when compared with the multi-unit train.

The two-unit train removes the RAP with the milling machine and deposits the mix into the pugmill of the mix paver. The pugmill has a feeder belt with a scale and a computer system estimates the weight of the liquid recycling additive to incorporate into the mix.

CIR is a process of milling a portion of existing pavement to a specified depth, screening and crushing the reclaimed material to comply with specifications, incorporating aggregates, mixing additives and water, spreading and compacting the mixture. Typically, the maximum particle size ranges from 1 to 1.5 inches (25 to 37.5 mm) (Hajek et al, 2005).

Do not operate during rainfall. In addition, ensure the ambient temperature is at least 50 ºF (10 ºC) and freezing temperatures are not expected for at least 5 days. In general, the warmer the weather, the better the final properties of the CIR mixture.

Figure 4-5 Two-Unit Train*

*Source: Lee and Kim, 2007.

4-2.3.5.4 Multiple-Unit Train.

The multiple-unit train, as indicated in Figure 4-6, has the highest degree of quality control and productivity of CIR. The multi-unit train produces as much as 2 lane miles/day (3.2 lane km/day). The sequence of the multi-unit train operation is as follows (ARRA, 2015):

- Mill the pavement to the design depth and slope with a milling machine.
- The milling machine can work with the “down cutting mode”, which produces finer RAP aggregates or with the “up cutting mode”, which allows higher working capacity. The down cutting mode should reduce the chance for scabbing during the milling operation.
- The RAP is screened and oversized material is sent to a crushing unit.
- The crushed material is sent back to the screening unit.
- An aperture below the screens controls the maximum RAP size.
- After passing through the screening and crushing unit the RAP goes to the pugmill mixer.
- The belt that transports the RAP has a scale that controls the weight of the RAP that goes into the pugmill.
- A computerized system controls the amount of liquid recycling additive, based on the weight of the material estimated by the belt scale.
- A pump equipped with a meter device indicates the flow rate and the amount of liquid recycling additive incorporated in the pugmill
- The pugmill thoroughly mixes the RAP with liquid recycling additive or asphalt emulsion.
- The mixture is conveyed to a windrow or paver hopper.
- A windrow elevator takes the mix from the windrow and feeds it to a conventional HMA paving machine.

Figure 4-6 Multiple-Unit Train*

*Source: Ken, 2008.

The main advantages of the multi-unit train are:

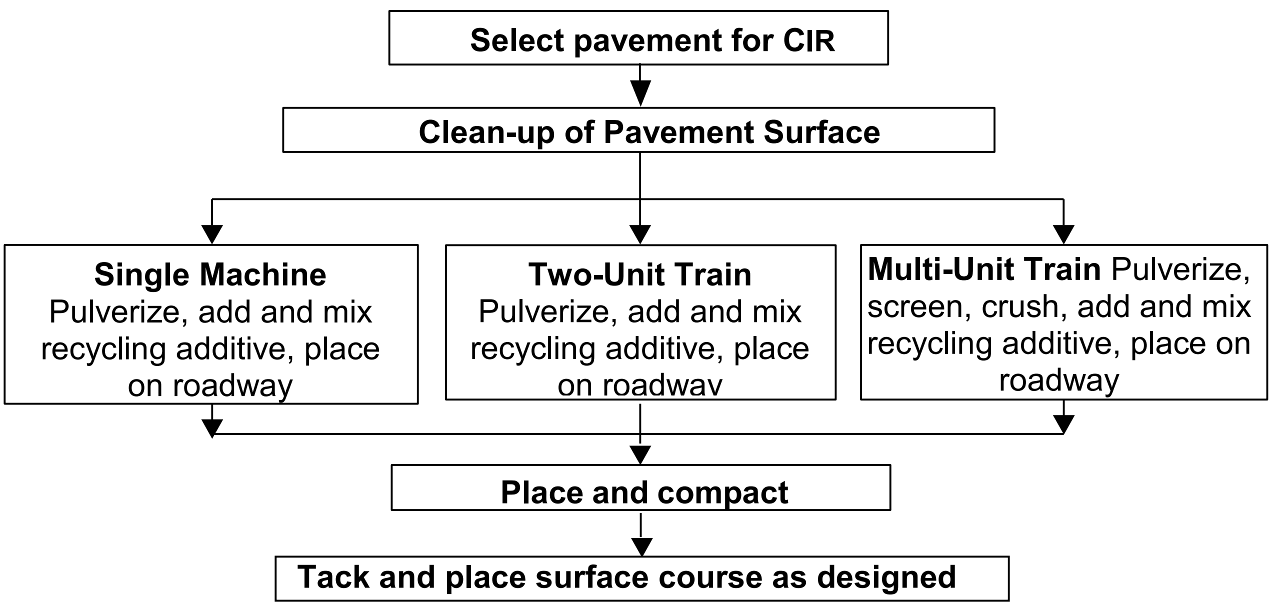
- high productivity.
- high quality control process.

The main disadvantages are:

- length of the train.
- It is not suited for urban areas or roads that have no room for maneuvering.

Figure 4-7 presents an abbreviated summary of the CIR construction process for the three types of equipment configurations.

Figure 4-7 CIR Construction Process*



*Source: ARRA, 2001.

4-2.3.5.5 Technical Aspects on CIR Construction.

Some additional technical aspects are necessary during CIR construction.

a. Clean-Up of Pavement Surface. Inspect the pavement surface before recycling operations begin to clear vegetation and debris across the pavement and shoulders.

b. Cold Milling Process. Mill existing pavement to a pre-defined depth and width in one pass. The cold-milling machine removes a portion of the existing HMA layer, typically between 2 and 6 inches (50 and 150 mm) deep, always leaving at least 1 inch (25 mm) of HMA in place.

Generally, the particle size of the removed material is satisfactory for recycling and no further crushing is necessary.

c. Placement of the Recycled Material. Place and finish recycled material in one continuous pass, without segregation. Compact material in minimum 2 inches (50 mm) thick and no more than 4 inches (100 mm) thick. Increase the upper limit to 6 inches (150 mm) when required to place more than 4 inches in one pass, but only if the contractor has suitable equipment to place and compact this thicker layer.

Begin by spreading the material along the centerline of areas paved on a crowned section or on the high side of areas with one-way slope, always in the primary direction of traffic flow. Pavements surrounding curbs, manholes and other structures may need special attention.

d. Field Adjustments of the Mix. Adjust the job mix formula (JMF)in the field to take into consideration the gradation of the RAP. Modification of the percentage of additives and water may improve the aggregate coating and mix workability. Determine the optimum amount of water. Excessive water content may flush the asphalt to the surface during the placement and compaction process. Lack of adequate water may cause mix segregation, loss of workability, raveling and poor density.

Excess asphalt emulsion or rejuvenating agent may lead to an unstable mix. On the other hand, an insufficient asphalt emulsion may cause mix raveling due to low asphalt content. A practical rule is to adjust the asphalt content by 0.2% increments. However, only an experienced technician should make adjustments to the mixture.

e. Curing. Cold mix recycled mixtures gain strength and stability with time as they cure. Factors that affect the cure time are:

- Type of emulsified asphalt
- Mix water content
- Gradation
- Layer thickness
- Ambient and mixture temperatures
- Wind velocity
- Humidity

When multiple lifts are required, allow 2 to 5 days cure time between them depending on the amount of moisture and porosity of the mixture. Ensure the water content of the recycled mixture is less than 1.5% prior to placing additional layers.

The final curing time is typically between 7 and 14 days. In general, depending on the climatic conditions, the cure period is about 2 days for each 1 inch (25 mm) of lift thickness.

f. Compaction. The objective of compaction is to achieve the desired mat density. Start compaction as soon as the emulsified asphalt breaks or when the mixture is adequately aerated. Usually the mixture starts to break between 30 minutes to 2 hours depending on ambient conditions such as temperature, wind speed, and humidity. However, if portland cement, lime or fly ash are used as recycling additives, begin rolling immediately after placement. Ensure the minimum layer thickness is no less than twice the size of the maximum aggregate particle of the RAP or aggregate. The compaction process encompasses three phases:

- Carry out breakdown rolling with vibratory roller(s). If the mix is tender and moves excessively underneath the vibratory roller, use a pneumatic tire roller. This phase of rolling continues until obtaining a tight, smooth, stable surface.
- Conduct intermediate rolling with at least 12-ton double drum vibratory steel-wheeled or pneumatic rollers preferably weighing approximately 20 tons. Achieve adequate density before completing intermediate rolling.
- Carry out finish rolling with steel-wheeled static or double-drum vibrating rollers operating in static mode to eliminate roller marks.

Use the theoretical maximum density in accordance with ASTM D2041 to establish field density and control compaction. Theoretical maximum density is the density which corresponds to zero air voids in the mixture.

Construct a test section to evaluate various combinations of rollers and monitor the process step-by-step with a density gauge to determine the relative increase in density with roller passes. Set the number of passes required to provide a density equal to or exceeding the minimum density requirements.

g. Field Density Measurements. It is very difficult to cut and remove undamaged cores from completed CIR mixtures. The longer the mixture has cured, the easier it will be to obtain good cores without damage. Alternatives to obtain samples of in-place pavement within 24 hours include:

- Ice placed on the sample locations for 1 to 2 hours before coring samples will cool the material during the coring operation, reducing the damage caused by the heat developed during this process.
- Use a concrete saw to cut small cubes from the pavement.
- Use density gages as an indication of the densities. This device does not eliminate the need to take actual pavement cores for testing later, but it will provide a reasonably good first estimate of the in-place density.

Modify rolling procedures to improve the compaction and meet the specified density requirements.

4-2.3.5.6 Surface Course.

Since CIR contains high voids in the total mix, do not use it as a wearing course. For low volume roads, use single or double bituminous surface treatment to cover the CIR. For roads with high volume traffic and for airfields, cover the CIR with an HMA overlay having thickness equal to or exceeding the minimum thickness required for HMA placed over granular base course.

4-2.4 Specifications, Quality Control, Inspection and Acceptance.

4-2.4.1 Specifications.

The specification for cold mix recycling is UFGS 32 01 16.70. This specification includes the in-place mixture and compaction requirements as well as the plant mixed cold recycling processes. It includes requirements for using asphalt emulsions as well as requirements for using asphalt recycling agents.

4-2.4.2 Quality Control/Quality Assurance.

A good QC/QA plan is a key factor for the success of a cold in-place recycling project.

Old pavement sections present great variability in aggregate gradation, asphalt content, and areas subjected to different maintenance types, etc. As a result, during the CIR process, small changes may be necessary in the rolling patterns, aggregate gradations, moisture and recycling agent content to improve performance of the resurfaced pavement. QC personnel should prepare a QC plan that accommodates changes without needing to redesign the mixture.

Follow testing requirements identified in UFGS 32 01 16.70 for the contractor QC plan. Inspect work continuously and identify any deviations from the specifications or from good standard construction practices.

4-2.4.3 Inspection and Acceptance.

4-2.4.3.1 Inspection is one of the most important steps for CIR construction. Inspection must identify problems early so that the construction process can change to correct the problem before too much CIR is constructed. Identifying problems early allows prompt resolution of construction deficiencies with less effort. However, missed problems are a bigger problem to correct later in the paving process.

4-2.4.3.2 Conduct both inspection and acceptance in accordance with specification requirements. While the specifications identify many items related to inspection, many other important items that may not be in the specifications are presented and discussed in the following paragraphs.

4-2.4.3.3 Regular meetings during construction ensure compliance with all aspects of the specifications and ensure timely implementation of necessary adjustments. Identify problems early and take steps to correct these problems before performing a large quantity of unacceptable work. Meetings are a good place to identify problems and the necessary steps to correct them.

4-2.4.3.4 On some projects, traffic flow is a concern. Develop plans to control traffic flow and inspections to minimize traffic problems. At times the completed layer may temporarily serve as a riding surface for traffic. Temporary pavement markings are a part of the project.

4-2.4.3.5 Control the materials used for the project to ensure acceptable quality and that the quantity of material is sufficient. Control aggregate quality at delivery and perform aggregate handling in a manner that avoids segregation. Supply the specified asphalt emulsion or recycling agent and provide test certificates.

4-2.4.3.6 Specific equipment requirements are minimal. Ensure that the contractor has the flexibility to select equipment necessary to produce the mixture according to the specifications and to ensure compaction requirements are met. However, maintain all equipment in good working condition.

4-2.4.3.7 Remove isolated locations of unsuitable material as part of the project. Identify and discard this material and ensure that no discarded material is used in the project.

4-2.4.3.8 The mix design identifies the materials and proportions used in the project. Only an authorized government official can approve changes to the mix design. Supply issues or changes in quality may require a change in the mix design.

4-3 COLD CENTRAL-PLANT RECYCLING.

4-3.1 Introduction.

CCPR recycles RAP in a central plant to produce recycled mixes. Two conditions make CCPR a feasible technique: (a) availability of stockpiles of high quality and uniform RAP and (b) inability to use CIR process.

The general process is that the RAP is hauled to a plant site or stockpiled. The plant crushes, screens, and mixes in additives prior to the mix being transported to a job site. The mix is then placed and compacted in accordance with specifications. In some circumstances, it is also possible to use a portable unit to process the RAP at the stockpile area.

Use CCPR as stabilized base course with an HMA overlay for roads with higher traffic volume as well as for airfields. For low traffic roads, it can be used along with a single or double bituminous seal coat to seal and protect the surface.

4-3.2 Past and Current Use.

The U.S. does not use a large amount of CCPR; however, its use is significant in several other countries. The use of CCPR has decreased in the U.S. due to improvements in CIR and FDR and the cost effectiveness of these processes. CIR methods are less expensive and less likely to cause traffic problems when transporting materials from the plant to the project site.

4-3.3 Guidelines for Use of CCPR.

The guidelines established to use CIR and FDR are applicable to CCPR. When better control is required, use CCPR over a CIR approach.

4-3.3.1 Primary Purpose.

CCPR is an adequate technique when a pavement cannot be in-place recycled and the HMA layer must be removed to allow for treatment of underlying layers. In other words, CCPR is a good solution for pavements that present problems in underlying layers such as lower HMA lifts or aggregate base layers. Successful CCPR projects should only be used in areas having no major problems with realignment, drainage, or frost heave.

The ability to control aggregate gradation, percentage of water, recycling additives and stabilizers makes CCPR an attractive alternative for some special cases. Use the CCPR process when additional aggregate is required to correct pavement cross slope and when there are restrictions for CIR equipment in the work area.

4-3.3.2 Advantages and Disadvantages.

The main advantages of using CCPR are similar to those advantages for CIR and FDR. Other complementary advantages are: 1) stockpiled RAP is cleaner than in-place recycled material, 2) crushing RAP allows gradation requirements to be met, 3) RAP is mixed with asphalt emulsion in a central plant allowing better control, and 4) multiple feed bins provide an opportunity for better control of aggregate gradations.

The primary disadvantages of using CCPR are higher cost and increased material handling required to move materials from the job site to the plant, feed materials into the plant, and haul the completed mixture back to the job site.

4-3.3.3 Performance and Costs.

Similar to CIR and FDR, the performance of CCPR depends on several aspects such as local conditions, climate, traffic, types of material, quality of construction, specifications, and QC/QA. The estimated life of a CCPR mix with surface treatment is between 6 and 8 years and with HMA overlay is between 12 and 15 years (ARRA, 2015).

4-3.3.4 Mix Design.

The discussion carried out for mix design of CIR applies to CCPR. Removing materials from the project site prior to producing CCPR mixture provides time to take samples of materials and conduct mix design. Take core samples prior to starting work. However, the mix design based on these samples is not as reliable as samples taken from the milled material.

4-3.3.5 Structural Design.

All the considerations for structural design for CIR apply to CCPR.

4-3.4 Construction.

As pointed out before, transport the RAP to a special location for crushing, screening and blending with recycling aggregates. Process in a central mixing plant. Another option is to process the RAP at the project location using a mobile mixing plant located at or near the job site. In both situations, use a pugmill mixer.

Store RAP as any other aggregate. Be aware of the variability inherent in different sources of RAP. Contractors typically have sources of RAP to produce the CCPR or the specifications may require that only RAP from the existing project be used. If using RAP from other sources, evaluate this RAP to ensure it is satisfactory for the existing project. The most common problem that may occur is the RAP source may contain aggregates with unsatisfactory aggregate properties. In any case, manage the stockpiles to minimize segregation of materials.

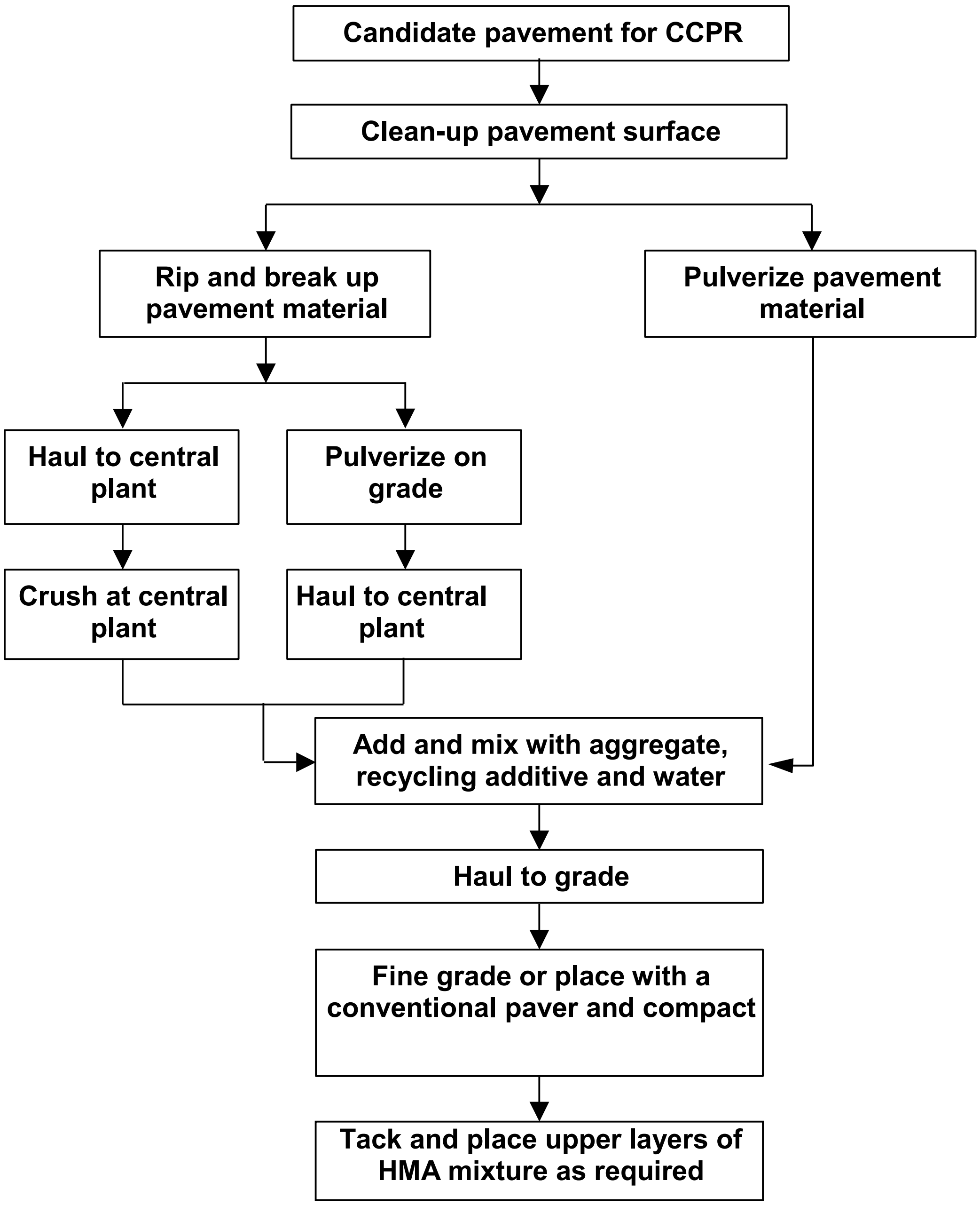
4-3.4.1 Types of Equipment.

Process equipment produces RAP by milling, ripping, breaking, crushing or pulverizing old HMA layers. Other equipment transports the RAP to the plant and handles the RAP at the plant. The central plant is similar to an HMA plant and should have the following parts:

- Screening and crushing units to keep the maximum size of the RAP under control. Alternatively, it can use a scalping screen to remove oversize particles in the RAP.
- RAP feed hopper.
- Conveyor belts with a belt scale.
- A computerized system, connected to the belt scale, controls the amount of liquid recycling additive and water added to the pugmill, based on the weight of the RAP estimated by the belt scale.

Figure 4-8 shows the steps in the CCPR process.

Figure 4-8 CCPR Construction Process*



*Source: ARRA, 2015.

4-3.4.2 Technical Aspects on CCPR Construction.

Additional technical aspects to consider during work at the central plant:

- Complete coarse aggregate coating is not required during the mixing process. Additional coating will occur during the hauling, spreading, and rolling of the mix.
- Ensure the mixing time is sufficient to obtain good mixing of all materials. Excessive mixing causes excessive breakdown of the material and may adversely affect the coating. Under-mixing results in lack of good coating of materials.

4-3.4.2.2 Clean Up Pavement Surface.

It is a good practice to inspect the pavement surface before the recycling operation to clear vegetation and debris across the pavement and shoulders.

4-3.4.2.3 Cold Milling Process.

Conduct cold milling and pulverization of asphalt pavement layers according to the required depth and maximum RAP size specified for the project.

4-3.4.2.4 Placement of the Recycled Material.

Haul the mixed material to the project site and laydown the recycled material with an asphalt paver. A paver works better than other equipment to place the recycled mixture in a uniform manner to the desired grade. The paver provides some initial compaction.

Aeration may be necessary to decrease water and/or volatile content before the compaction process. Perform placement in several lifts as required by the project. Maximum lift thickness is limited to 4 inches (100 mm) when compacted.

Inspect the placement of the CCPR to minimize segregation. When segregation occurs, stop the project until the causes of segregation are identified and corrected.

4-3.4.2.5 Field Adjustments of the Mix.

Perform field adjustments of the mix during construction of the test section as discussed in UFGS 32 01 16.70. Consider using a variety of roller combinations during construction of the test section. Monitor changes step-by-step with a density meter to understand the relative increase in density with roller passes. Ensure the test section has a minimum length of 150 ft (15 m) and is the width of two pavers. Place the test section and compact to the thickness required for the project. All CCPR projects require compliance with performance specifications.

4-3.4.2.6 Curing, Compaction, and Field Density.

See the discussion for CIR.

4-3.4.3 Surface Course.

Since CCPR contains high voids in the total mix, do not use as a wearing course. For low volume roads, use single or double bituminous surface treatment to cover the CCPR. For roads with high volume traffic and for airfields, keep the thickness of HMA equal to or greater than the minimum requirements for thickness of HMA placed over a granular base course.

4-3.5 Specifications, Quality Control, Inspection and Acceptance.

4-3.5.1 Specifications.

The specification used for CCPR are UFGS 32 01 16.70. In addition to the specifications for CIR, define the spreading depth because it only applies to CCPR. Monitor this feature to avoid inadequate thickness and to assure compliance with the design requirements.

4-3.5.2 Quality Control/Quality Assurance and Inspection and Acceptance.

See comments for CIR.

4-4 FULL-DEPTH RECLAMATION.

4-4.1 Introduction.

Full-depth reclamation rehabilitates flexible pavements with significant deterioration. For example, a pavement with base failure is an excellent candidate for FDR. The process can involve modification to the HMA layers and possibly underlying granular layers. The technique consists of uniformly breaking up the material to a specified depth between 4 and 12 inches (100 and 300 mm), pulverization, incorporation of a stabilizing agent, blending, shaping and compaction of the reclaimed mixture as a base layer. Mechanically stabilize the material if the pavement is for low and medium traffic. For pavements with higher traffic or higher load capacity, including high volume roads and airfields, chemically stabilize the FDR material by introducing and blending additives such as cement, fly ash, lime, foamed asphalt, and asphalt emulsions.

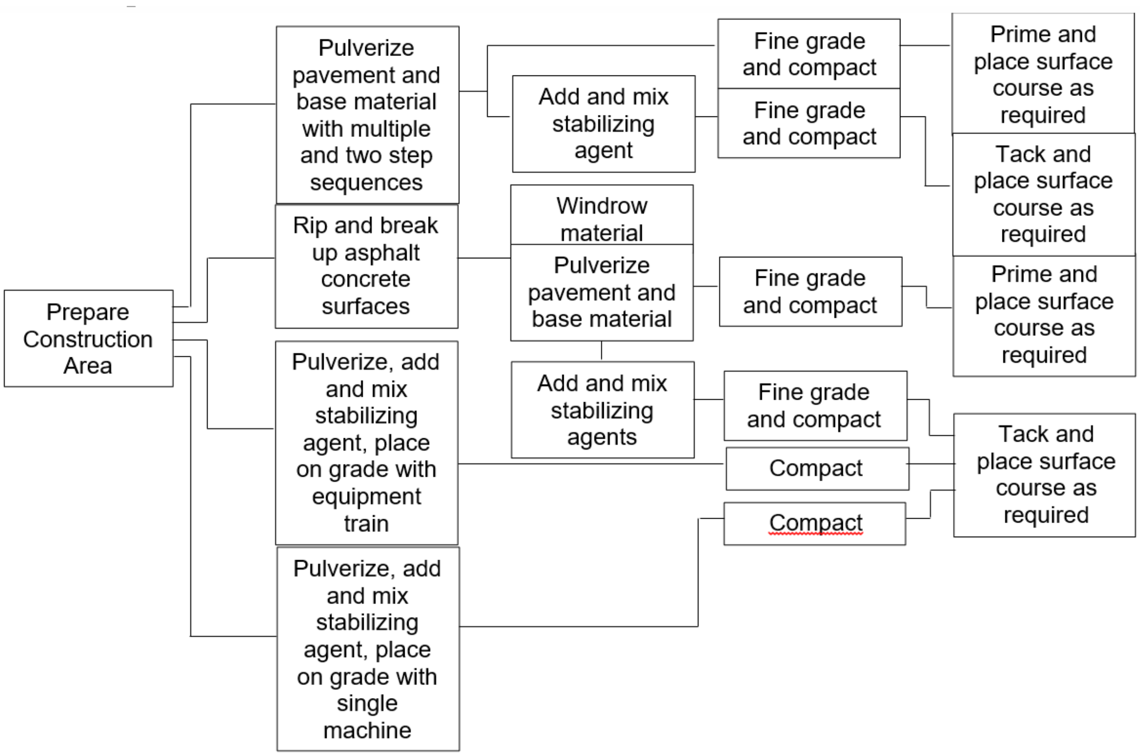
Pavements that do not have structural capacity to support CIR equipment are also good candidates for treatment with FDR. This is usually a pavement with less than 3.5 inches (90 mm) of HMA and a weak subgrade with a resilient modulus less than 5000 psi (34.5 MPa) (PIARC, 2003).

Figures 4-9 and 4-10 show examples of recycled material and a schematic of the FDR process, respectively.

Figure 4-9 Recycled Material*

*Source: https://cdn.ymaws.com/arra.site-ym.com/resource/resmgr/files/ARRA_Full_Depth_Reclamation_.pdf

Figure 4-10 Full Depth Reclamation*



*Source: Kandhal and Mallick, 1997; https://cdn.ymaws.com/arra.site-ym.com/resource/resmgr/files/ARRA_Full_Depth_Reclamation_.pdf

4-4.2 Past and Current Use.

Full-depth recycling is not new and was first competed in the early 1900s (Kandhal and Mallick, 1997; Sullivan, 1996). Several state DOTs have experience with FDR.

FDR technology applies to airfields. One example is an airport that used FDR with cement stabilization to rebuild a runway pavement. The construction period was only 30 days and they estimated that they saved approximately $1 million by using FDR compared with other paving options (Arroyo, 2007).

Since the 2000s one state DOT implemented a large FDR program with stabilized base. One project saved $200,000 on a $3 million project to reconstruct a 6-mile section of roadway. This state DOT stabilized projects with cement and fly ash (Terra, 2008).

One city in Canada began to use FDR with foamed asphalt in 2000. Since then, they have successfully constructed more than 30 million sq yd (25 million sq m) of FDR, much of which was stabilized with foamed asphalt.

4-4.3 Guidelines for Use of FDR.

Most of the guidelines suggested for CIR are applicable to FDR. There is no UFGS specification for FDR. Hence, DoD projects must use local state DOT specifications for FDR. The following sections discuss some aspects unique to FDR.

4-4.3.1 Primary Purpose.

FDR is suitable for pavements with structural problems such as deteriorated HMA and base layers. Figure 4-11 shows good candidates for FDR where there are significant problems with the HMA mixture and likely with underlying granular layers and subgrade.

Under the correct conditions, FDR allows:

- Adjustment of the profile and cross slope of the pavement
- Accommodation of pavement widening, if necessary
- Ability to improve quality of underlying pavement layers

4-4.3.2 Advantages and Disadvantages.

4-4.3.2.1 Advantages.

FDR has advantages similar to CIR to include:

- Crown and cross-slope are easily restored.
- Reflective cracks are eliminated or reduced.
- FDR is cost effective in the long-term since FDR can eliminate problems with an inadequate base course.

- FDR offers a low environmental impact, because materials are not transported back and forth.
- Reduction in future maintenance costs due to the long-term correction of structural and other problems.
- The typical FDR depth is between 6 and 9 inches (150 and 225 mm). However, the literature indicates the possibility of depths over 12 inches (300 mm).
- With good quality control during construction, pulverizing base and HMA layers and mixing with stabilizing additives increases the structural capacity of the pavement.

Figure 4-11 Good Pavement Candidates for FDR*

*Source: ARRA, "Full Depth Reclamation."

4-4.3.2.2 Disadvantages.

The main disadvantages of using FDR are:

- The mixing and uniformity of mixture are not as well controlled for FDR compared to CCPR or CIR.
- Any construction problem at the longitudinal joints in between adjacent strips may cause longitudinal cracks.
- Usually FDR requires more time than required to construct an HMA overlay.

4-4.3.3 Performance and Cost.

The performance of FDR depends on several aspects such as local conditions, climate, traffic, type of material, quality of construction, specifications, and QC/QA. Several states in the US have good experience with FDR and excellent results.

Shuler and Schmidt (2008) evaluated the performance of a number of recycling methods. The research concluded that it generally took 6 to 8 years for the recycled pavement to reach the condition of the original pavement prior to application of the recycling technologies. This was true for every distress except roughness. It took an average of 14 years to reach the same level of roughness.

4-4.3.4 Mix Design.

The CIR mix design concepts apply to the mix design of FDR. The following sections discuss other details concerning FDR mix design.

4-4.3.4.1 Trial Mixes, Curing Time, and Job Mix Formula.

Most of the information concerning CIR mix design applies to FDR. Additional aspects to consider due to the variability of stabilization methods available for FDR are:

- Mechanical Stabilization - use one or more of the following options:
  - crushed virgin aggregate.
  - reclaimed asphalt pavement.
  - crushed concrete, etc.
- Chemical Stabilization – use one or more of the following options:
  - Portland cement (dry or slurry).
  - lime applied dry or in a slurry.
  - fly ash.
  - calcium chloride.
- Asphalt Stabilization – use the following options:
  - emulsified asphalt.
  - foamed asphalt.

Apply cementitious and pozzolanic materials as dry powder in front of the reclaimer, in slurry form together with the pre-pulverized material, or in suspension by using a spray bar. Pavements with severe deterioration and high deflections are excellent candidates for FDR with cement.

Apply liquid stabilizing/additives like calcium chloride ahead of the reclaimer, together with the pre-pulverized material, or by injection with the reclaimer additive system.

Asphalt stabilization reduces the effects of moisture and improves the strength of the reclaimed material. When compared with other chemical stabilizers it creates a more flexible base which is more resistant to fatigue. Asphalt can stabilize 100% RAP or a mix of RAP and granular base and subbase. Require that the fine materials have a plasticity index of no more than 6%.

The same considerations carried out for CIR apply to FDR. Table 4-2 provides general guidelines to select stabilizers for FDR (lab testing).

Table 4-2 General Guidelines for Selecting Stabilizers for FDR

	Characteristics of Reclaimed Pavement Materials
Hydrated lime or quicklime (2 to 6% by weight)	RAP having some amount of silty clay soil from subgrade with a plasticity index greater than 10.
Class C fly ash (8 to 14% by weight)	Materials consisting of 100% RAP or blends of RAP and underlying granular base or soil. The soil fraction can have plasticity or be similar to soils acceptable for lime treatment.
Portland cement (3 to 6% by weight). The maximum limit of Portland cement for airfields is 4%.	Materials consisting of 100% RAP, or blends of RAP and underlying granular base, or nonplastic or low plasticity soils. Sufficient fines are necessary to create an acceptable aggregate matrix for the cement treated base (CTB) (not less than 45% passing the 4.75 mm or No. 4 sieve preferred).
Emulsified or foamed asphalt (1 to 3% by weight)	Materials consisting of 100% RAP, or blends of RAP and underlying granular base, or nonplastic or low plasticity soils. Limit the maximum percent passing the 75 µm (No. 200) sieve to 25%. Limit the plasticity index to 6%. Limit the sand equivalent 30 or greater or the product of multiplying the P4 and the percent passing the 75 µm (No. 200) less than 72.
Calcium chloride (1% by weight)	Materials consisting of a blend of RAP and nonplastic base soil with 8 to 12% minus 75 µm (No. 200) material. Small amounts of clay (3 to 5%) are also beneficial.

4-4.3.4.2 Mechanical Stabilization.

Mechanical stabilization is simple and sometimes requires imported material such as virgin granular materials to improve the gradation of the reclaimed material. This increases the structural stability of the mixture and the excess bituminous material has more surface area to coat. In other cases, additional granular material is necessary to reach the specified thickness of the material.

4-4.3.4.3 Chemical Stabilization.

Portland cement is the most common additive used for chemical stabilization. The following sections discuss the main steps to stabilize FDR with cement.

a. Gradation. To achieve a suitable gradation, determine whether to add new material to the mixture. It is desirable to achieve a gradation similar to the Talbot's curve shown below:

$$y = 100 \times (d/D)^{0.4}$$

Where:
y = percentage passing sieve "d"
d = sieve size in mm (inch)
D = maximum aggregate size in mm (inch)

b. Water Content. Obtain the optimum water content of the reclaimed pavement material mixed with cement as the peak of the moisture-density tests. Use modified Proctor procedures for compaction (ASTM D1557).

c. Mix Density. Ensure that the mix density is at least 97% of the Modified Proctor laboratory density.

d. Optimum Cement Content. Ensure that the cement content provides the specified strength, is economically feasible, and keeps shrinkage cracks as fine as possible. On airfields limit the cement content to 4%.

Obtain the optimum cement content by running moisture-density tests. Prepare at least three sets of specimens with material obtained from the pavement incorporating imported material, as necessary, and compact to the minimum density expected. Test specimens to obtain the axial compression strength at 7 days.

Subsequently, prepare specimens by varying the initial amount of cement ± 2%. This approach guarantees that the amount of cement will include the target value. For larger projects, test the compressive and indirect tensile strengths at 28 and 90.

e. Types of Cement. Cements with a high percentage of pozzolans are best suited for FDR and for roller compacted cement treated materials.

The density and cement content are more important than limiting the type of cement. Review the available types of cement in the market. Test to ensure that the cement produces the required characteristics in terms of strength, workability, and mix homogeneity. Using high-strength cements can produce a very low cement content of 2 to 2.5% by weight of dry material.

Note: It is possible to meet strength requirements and lack adequate homogeneity. Other classes of cement may produce a mix with a cement content as high as 3 to 6%. In this case, recycled material incorporated into the mix design has fewer homogeneity and workability problems.

f. Workability Time. Evaluate the impact of a limited workability period, or setting time, for cement treated material carefully. Air temperature and humidity interfere with the period of workability. When cement starts hydrating, it binds the aggregates and the compaction may break these links. Complete compaction before the cement begins to set and bind the aggregate.

Check the workability time by verifying the decrease in sample density when compacted at increasing times. For practical purposes, the workability period ends when the density drops to 98% of the density obtained for specimens compacted immediately after mixing.

4-4.3.4.4 Determining the Proper Amounts of Virgin Aggregate to Add.

Apply the same steps described for CIR for FDR. As discussed above, obtain additional information when stabilizing with cement.

4-4.3.4.5 Requirements for Aggregates.

The requirements for aggregates are similar to those for granular base, soil-cement, and cement treated base.

4-4.3.4.6 Recycling Additives.

Recycling additives are the same as for CIR and as discussed in this section for FDR.

4-4.3.5 Structural Design.

Follow the discussion in Chapter 3 for structural design.

4-4.4 Construction.

The construction considerations for CIR apply to FDR principally regarding the use of asphalt materials as a stabilizer. Some additional considerations are necessary when cement is the additive. The following sections discuss important considerations when cement is the additive.

4-4.4.1 Types of Equipment.

In general, use the same equipment described for CIR for FDR. However, each project has unique equipment requirements. Tables 4-3 and 4-4 present the necessary equipment and operational steps for FDR stabilization with cement for low and medium/high volume roads.

Table 4-3 Steps for Recycling Low Volume Roads[2]

		Typical Equipment
Pavement scarification[1]	Loosen the existing pavement	• Front loader with ripper • Bulldozer with ripper • Recycler
Eliminating large particles	Eliminating large particles over 80 mm (3.2 inches): • By crushing • By removal	• Stationary or mobile crushing unit • Manual work • Agricultural equipment
Leveling	Distribution of milled material	• Motor grader
Adding imported aggregate (if needed)	• Improvement of aggregate gradation • Cross slope correction • Increasing treated surface thickness	• Aggregate spreader • Bituminous mix paver • Motor grader
Moistening[2]	Achieve optimum moisture content according to moisture- density test (Modified Proctor)	• Water tanker with spraying bar • Water tanker connected to recycler • Slurry mixer
Binder distribution	Introduction of binder in proportion to site requirements and working depth	• Manual spreading (grid of cement bags) • Binder spreader (cement as powder is spread ahead of mixing plant) • Slurry mixer (cement and water are mixed and introduced as slurry into the recycler)
Mixing	Homogeneous mix of loosened pavement material with binder, water and any additives	• Rotary plough • Pulvimixer with horizontal mixing rotor • Recycler
Trimming	Eliminating surplus material to achieve final level	• Grader
Transverse joint cutting	Prevention of reflective cracking	• Mechanically driven machines • Hand driven device (vibrating plate or roller with welded knife)
Compacting	Achieving required density	• Vibratory roller
Curing and protection seal	• Curing of recycled surface • Protection of applied seal	• Water tanker[3] • Emulsion spreader • Chip or sand spreader + pneumatic tire roller

(1) When using a recycler, if it is not necessary to eliminate large particles, perform this step after distributing the binder (or at the same time).
(2) Allow excessively moist milled material to dry before incorporating the binder and any imported material.
(3) During warm and dry weather conditions, have a water tanker readily available to moisten the surface before spraying the curing seal.

[2]PIARC, 2003.

Table 4-4 Steps for Recycling of Medium and High-Volume Roads[3]

		Typical Equipment
Adding imported aggregate (if needed)	• Improvement of aggregate gradation • Cross slope correction • Increasing treated surface thickness	• Aggregate spreader • Bituminous mix paver • Motor grader
Moistening[1]	Achieve optimum moisture content according to moisture-density test (Modified Proctor, AASHTO 1557)	• Water tanker with spraying bar • Water tanker vehicle connected to recycler • Emulsion spreader
Binder distribution	Introduction of binder in proportion to site requirements and working depth	• Binder spreader (cement as powder spread ahead of mixing plant) • Slurry mixer (cement and water are mixed and introduced as slurry into the recycler)
Pavement scarification[2]	Loosen the existing pavement	• Recycler
Mixing	Homogeneous mix of loosened pavement material with binder, water and any additives	• Recycler
Transverse joint cutting	Prevention of reflective cracking	• Mechanically driven machines • Hand driven device (vibrating plate or roller with welded knife)
Initial compaction	Achieving 90-92% of reference density	• Vibratory roller
Trimming	• Eliminating surplus material to achieve final elevation • Improvement of surface evenness	• Grader
Final compaction	Achieving required density	• Vibratory roller + pneumatic-tire roller[3]
Curing and protection seal[4]	• Curing of recycled surface • Protection of applied seal	• Emulsion spreader • Chip or sand spreader + pneumatic tire roller

[1] Allow excessively moist milled material to dry before adding the binder and any imported material.
[2] In recycled pavement layers, crush or remove particles larger than 3.2 inches (80 mm),
[3] Or two vibratory rollers.
[4] During warm and dry weather conditions, have a water tanker readily available to moisten the surface before spraying the curing seal.

[3]PIARC, 2003.

4-4.4.2 Technical Aspects on FDR Construction.

In general, the process of laydown, compaction and overlaying the in-place cold recycling is the same as that for conventional stabilization operations. However, consider the uniqueness of each problem, type of additives, proposed technique and the variability found in FDR techniques.

Focus special attention on the variability of the strength of reclaimed pavement stabilized with cement. Research indicates that the tensile strength obtained from cores of cement-recycled pavements after 1 to 2 years was between 60 and 290 psi (0.4 and 2 MPa). The respective moduli of elasticity were between 508,000 and 5,438,000 psi (3,500 to 37,500 MPa) (PIARC, 2003). These are very highly variable results and the selected specifications, testing procedures and performance requirements must account for the possibility of highly variable results while using similar materials under the same environmental conditions.

4-4.4.2.1 Pavement Surface Cleanup.

See CIR section.

4-4.4.2.2 Cold Milling Process.

See CIR section.

4-4.4.2.3 Placing Recycled Material.

See CIR section.

4-4.4.2.4 Field Adjusting the Mix.

See CIR section.

4-4.4.2.5 Curing.

See CIR section.

4-4.4.2.6 Compaction.

Compact each strip within the workability timeframe prior to starting on a subsequent strip. When the time for compaction is within the workability time, the rollers will not damage the previous strip and form cold joints. Complete any trimming prior to starting the compaction process.

Ensure that cement recycled layers are no less than 8 inches (200 mm) and no more than 14 inches (350 mm) thick. The minimum thickness requirement avoids areas with insufficient thickness that leads to premature fatigue. The capacity of recyclers and compaction equipment limits the maximum layer thickness. Figure 4-12 shows an example of incorporating and spreading granular material on the top of old pavement to achieve the necessary compacted thickness.

Figure 4-12 Granular Material Added to Achieve Compacted Thickness*

*Source: PIARC, 2003.

4-4.4.2.7 Field Density.

Refer to the CIR section. However, the minimum field density suggested for FDR stabilized with cement is 97% of the maximum laboratory density obtained when compacted in accordance with Modified Proctor (ASTM D1557).

4-4.4.2.8 Surface Course.

The same considerations carried out for CIR are valid for FDR.

4-4.5 Specifications, Quality Control, Inspection and Acceptance.

See CIR section.

4-4.5.1 Specifications.

See CIR section. The UFGS specifications related to FDR are:

- UFGS 32 11 26.19, *Bituminous Stabilized Base and Subbase Courses*
- UFGS 32 01 16.70
- UFGS 32 11 36.13

4-4.5.2 Quality Control/Quality Assurance.

The QC/QA procedures for CIR apply to FDR. Because other stabilizers were included for FDR, Table 4-5 summarizes the methods for evaluating stabilized materials.

Table 4-5 Testing Methods for Evaluation of Stabilized Materials

	Applicable Testing Procedures
Hydrated lime or quicklime	Liquid Limit, Plastic Limit and Plasticity Index of Soils (ASTM D4318) Moisture Density Relations of Soils and Soil-Aggregate Mixtures (ASTM D698 or D1557) Unconfined Compressive Strength of Compacted Lime Mixtures (ASTM D5101, Procedure B)
Class C fly ash or cement	Moisture-Density Relations of Soil-Cement Mixtures (ASTM D558, Method B) Compressive Strength of Molded Soil-Cement Cylinders (ASTM D3633) Wetting and Drying Compacted Soil-Cement Mixtures (ASTM D559, Test Method B)
Asphalt emulsion or foamed asphalt	Percent Air Voids in Compacted Dense and Open Bituminous Paving Mixtures (ASTM D3203) Effect of Moisture on Asphalt Concrete Paving Mixtures (ASTM D4867) Indirect Tension Test for Resilient Modulus Bituminous Mixtures (ASTM D4123)
Calcium chloride	Liquid Limit, Plastic Limit and Plasticity Index of Soils (ASTM D4318) Moisture-Density Relations of Soils and Soil-Aggregate Mixtures (ASTM D1557)

4-4.5.3 Inspection and Acceptance.

Apply the requirements for inspection and acceptance formulated for CIR to FDR and are supplement with the appropriate UFGS requirements.

CHAPTER 5 HOT RECYCLING FOR ASPHALT SURFACED PAVEMENTS

5-1 INTRODUCTION.

There are two basic methods of hot mix recycling: HR and HIR. HIR includes three sub-categories: The HIR Type I, Surface Recycling, HIR Type II, Remixing, and HIR Type III, Repaving. Table 5-1 presents the advantages and disadvantages of using HR and HIR Types I, II and III.

Hot mix recycling uses heated materials that combine RAP with virgin aggregates and, if necessary, new asphalt binder and recycling agents. HR and HIR mixes serve as base, intermediate and surface layer materials in all types of roadway pavements, but only as base or intermediate courses in airfield pavements. RCA may serve as a portion of the aggregate in HMA for some road and airfield specifications.

5-2 OVERVIEW OF HOT RECYCLING METHODS.

5-2.1 Hot Central Plant Recycling (HR).

HR combines RAP with new aggregates, new asphalt binder, and recycling agents, in a plant to produce recycled HMA. The process removes existing pavement, crushes the reclaimed mix, mixes the reclaimed mix with virgin aggregate, and virgin asphalt in a conventional asphalt plant, places and compacts the recycled mix using the same procedures and equipment as for a virgin mix. Figures 5-1 and 5-2 show schematics for two general types of asphalt plants used for HR.

HR is allowed for all pavement layers other than surface layers on airfields. HR is an excellent option for roadway pavements with high traffic volume. However, never use HR as the wearing surface for airfield pavements subjected to traffic. For airfields, HR mixes are allowed for shoulders and underlying layers in trafficked areas. HR is applicable to all levels of traffic and can use RAP from pavements with a range of asphalt mixture issues as long as the quality of the aggregate and asphalt binder is reasonable. Compared with other recycling processes, HR produces the highest quality pavement material because it provides uniform mix production and presents the lowest construction variability (Kandhal and Mallick, 1997).

5-2.1.1 Past and Current Use.

Currently, hot recycling of RAP in an asphalt plant is the most used asphalt recycling method. Prior to use of RAP many RAP stockpiles throughout the U.S. contained a large percentage of material that had to be wasted or utilized for other than HMA applications.

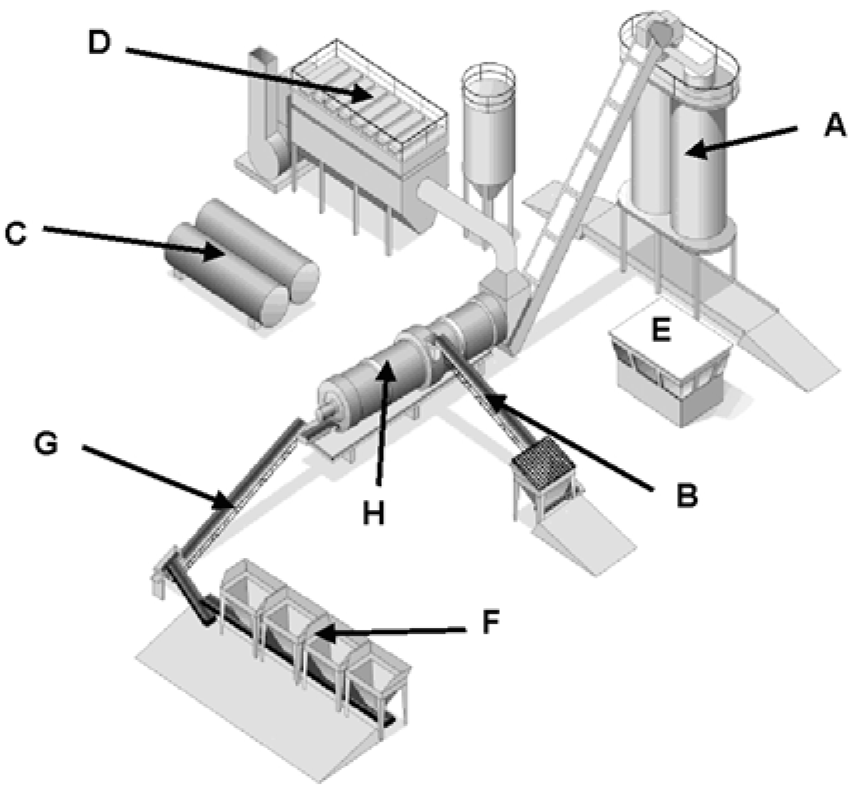
Table 5-1 Asphalt Recycling Technique Advantages and Disadvantages[4]

Technique	Advantages	Disadvantages
Applied to HIR in General	• Conservation of non-renewable resources. • Energy savings. • Less truck hauling at the work site. • No need for material removal. • Work the entire lane width at once. • Maintenance of curb height and overhead clearance. • Correction of aggregate and/or asphalt binder problems. • Remixing and recoating of aggregates with stripping problems. • Reduction of traffic disruptions and user nuisance. • Possibility of roadway opening to traffic at end of day. • Considerable economic savings.	• Does not improve load carrying capacity of pavement. • Not applicable to pavements with base failures and drainage problems. • Existing pavement surfaces should be at least 3 in (75 mm) thick. • Process does not correct large surface wavelengths or large changes in grades. • Difficult to use on narrow roads due to the width of the equipment. • Process not suited to streets with many utilities such as manholes, access covers, etc. • Cold weather can require more time for heating the pavement. • Surface treatments, like multiple chip seals affect pavement re-heating time. • Limitation for pavements with aggregate larger than 1 in (25 mm) diameter. • The heating process must be highly controlled to avoid creating air quality problems or overheating and damaging the asphalt binder.
Surface (HIR-I)	• Reduces frequency of reflection cracking. • Promotes bond between old pavement and thin overlay. • Provides a transition between new overlay and existing gutter, bridge, and/or pavement that is resistant to raveling (eliminates feathering). • Reduces localized roughness. • Treats a variety of low level pavement distresses (raveling, flushing, corrugations, rutting, oxidized pavement, faulting) at a reasonable initial cost. • Improves skid resistance.	• Provides limited structural improvement. • Heater-scarification and heater-planing have limited effectiveness on rough pavement without multiple passes of equipment. • Limited repair of flushed or unstable pavements. • Some air quality problems. • May damage vegetation close to the roadway. • Some equipment cannot treat mixtures with maximum aggregate sizes greater than 1 in (25 mm).

Technique	Advantages	Disadvantages
Remix and Repave (HIR-II and HIR-III)	• Provides structural improvement. • Treats all types of pavement distress. • Can reduce reflection cracking. • May reduce frost susceptibility. • Improves ride quality. • Improves skid resistance. • Minimizes hauling.	• Quality control not as good as central plant. • Traffic disruption. • PCC pavements cannot be recycled in-place. • Curing often required for strength gain.
Central (HR)	• Conservation of non-renewable resources. • Energy savings. • Provides significant structural improvements. • Treats all types and degrees of pavement distress. • Can eliminate reflection cracking if removing a sufficient depth of asphalt. • Improves skid resistance. • May reduce frost susceptibility. • More easily alters geometrics. • Improves ride quality.	• Traffic interruption. • Additional costs for transporting materials. • The recycled mix uses less than 100 percent RAP, so virgin aggregate and virgin binder are required. Typically up to approximately 20% RAP is used in recycled mixture.

[4]ARRA, 2001; Kandhal and Mallick, 1997.

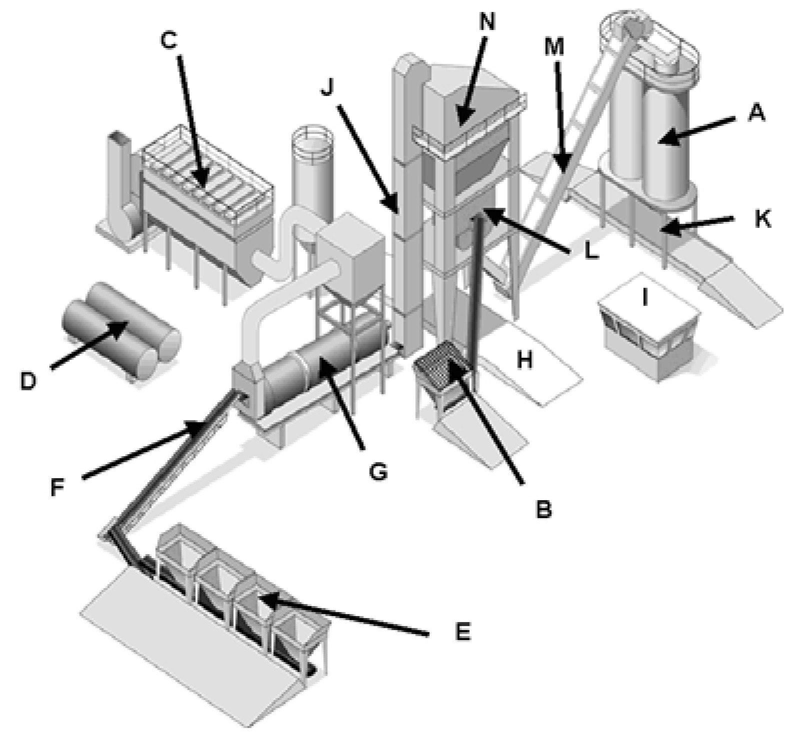
Figure 5-1 Drum Mix Asphalt Plant*



A- Storage Silo
B- RAP Feeder
C- Asphalt Cement Storage
D- Baghouse
E- Control House
F- Aggregate Feeders
G- Cold Elevator
H- Drum Mixer

*Source: NAPA.

Figure 5-2 Batch Asphalt Mix Plant*



A- Storage Silo
B- RAP Feeder
C- Baghouse
D- Asphalt Cement Storage
E- Aggregate Feeders
F- Cold Elevator
G- Drum Dryer
H- Truck Scales
I- Control House
J- Hot Elevator
K- Truck Scales
L- Pugmill
M- Slat Elevator
N- Screening Deck

*Source: NAPA.

The maximum amount of RAP allowed on DoD airfields projects is such that the asphalt binder from RAP cannot exceed 20 percent of the total asphalt content. RAP is not allowed in the surface course of airfield pavements. Other current requirements for use of RAP are in HMA on DoD airfield pavements is provided in UFGS 32 12 15.13.

The maximum amount of RAP allowed on DoD road and parking lot projects is such that the asphalt binder from RAP cannot exceed 30 percent of the total asphalt content. Other current requirements for use of RAP are in HMA on DoD roadway pavements is provided in UFGS 32 12 16.16.

Successfully using HR requires a good evaluation of the RAP, an adequate mix design, a rigorous QC/QA program and good construction practices (ARRA, 2001).

- When feeding RAP into the plant, ensure the maximum RAP chunk size does not exceed 2 inches (50 mm).
- Ensure the individual aggregates in a RAP chunk does not exceed the maximum size aggregate of the specified gradation.
- Use the procedures described in the Mix Design section of the UFGS cited in the paragraphs above to design recycled HMA

Many DOTs use Reclaimed Asphalt Shingles (RAS) to offset the cost of asphalt mixtures and utilize waste shingles that typically contain approximately 20 percent asphalt binder. RAS is not allowed on DoD airfield or roadway projects.

5-2.2 Hot In-place Recycling (HIR).

HIR can rehabilitate existing HMA pavements with distresses such as bleeding, shoving, raveling/segregation, corrugation, slippage, potholes, rutting, poor surface friction and cracking. HIR reprocesses existing HMA materials in-place at temperatures similar to conventional HMA by softening with heat, scarifying to depths of 3/4 to 2½ inches (20 to 60 mm), mixing new aggregate and binder, as required, placing and compacting (ARRA, 2001; Kandhal and Mallick, 1997; Hajek et al, 2005). The differences in the construction process and treatment of pavement distresses defines the three subcategories of HIR (Surface Recycling, Remixing, and Repaving).

HIR rejuvenates the surface of existing pavements having generally good structural capacity but that contain distresses in the surface layer. Conduct a comprehensive pavement evaluation prior to selection of HIR techniques to determine the asphalt concrete properties, the need for rejuvenators, and/or fine or coarse aggregates. Surface recycling is applicable for pavements that have no major distresses or deterioration and, hence, do not require additional material. Since repaving (HIR-III) is a combination of surface recycling or remixing with HMA overlay, it is applicable to high volume roads and airfield pavements.

Pavements without structural problems are ideal candidates for HIR. The type, extent, and severity of distress determines the applicable HIR type. Table 2-1 presents suggestions for selecting different HIR processes as a function of the pavement distress (ARRA, 2001).

5-2.2.1 Hot In-place Surface Recycling (HIR-I).

Surface recycling is the oldest HIR process. Formerly known by several names including heater-scarification, heater-planing, reforming, and resurfacing. It consists of heating, scarifying, adding asphalt binder or rejuvenator, leveling, reprofiling and compacting of the existing HMA mixture. The HIR-I process adds no new aggregates or new HMA. Treatment depth ranges between 3/4 to 1½ inches (20 to 40 mm).

Surface recycling prepares pavement for subsequent HMA overlay or chip seal. Steps in surface recycling are:

1. Dry and heat the upper HMA layers of the existing pavement such that surface temperatures range from 230 to 300 ºF (110 to 150 ºC) when at least two heaters are used in tandem.
2. Scarify the heated and softened HMA pavement.
3. Add a recycling agent if the mix design and JMF require.
4. Mix the loosened recycled mix.
5. Spread and place the recycled mix.
6. Compact the recycled mix using conventional HMA rollers and procedures.

5-2.2.2 Remixing (HIR-II).

Remixing consists of heating, softening and scarifying existing HMA pavement, adding virgin aggregate, new asphalt binder, recycling agent and new HMA, if necessary, followed by final mixing. HIR-II rehabilitates pavements that need an additional thickness of asphalt. The recycled mix acts as the wearing surface, but can be covered with a chip seal or overlaid with new HMA or HR to provide an improved surface that better resists traffic and environmental effects.

Perform remixing using a single or multi-stage approach. The single-stage approach successively heats and softens pavement to a specified full treatment depth followed by full material scarification. Multi-stage remixing heats thin layers of the pavement (normally between two to four layers), softens and scarifies them until achieving the desired full treatment depth. The scarified material is accumulated in a windrow to allow continued heating and scarification of underlying layers. The treatment depths for single-stage and multiple-stage are 1 to 2 inches (25 to 50 mm) and 1 ½ to 3 inches (40 to 75 mm), respectively (ARRA, 2001; Federation of Canadian Municipalities, 2005; Kandhal and Mallick, 1997).

5-2.2.3 Repaving (HIR-III)

Repaving combines surface recycling or remix with an HMA overlay and is frequently called the Cutler process. The surface recycled mix works like a leveling course and the new HMA as a wearing course. The thickness of the HMA overlay depends on the maximum aggregate size of the mix and varies between 3/4 inch (20 mm) and 3 inches (75 mm). The repaving process can significantly increase the pavement thickness (ARRA, 2001; Federation of Canadian Municipalities, 2005; Kandhal and Mallick, 1997).

Repaving is carried out by one unit equipped with several separate pieces of equipment including heaters, scarifiers, hot milling machines, pavers, and two screeds. The unit scarifies the heated and softened pavement at a temperature of approximately 375 ºF (190 ºC), adds the necessary quantity of recycling agent and mixes the recycled mix before the first screed. The screed levels and shapes the recycled material. Another screed on top of the recycled layer adds and spreads a new HMA layer. Rubber-tired and vibrating steel drum rollers compact the two layers as a single layer. The repaving process steps are:

1. Heat
2. Scarify using teeth or a rotary mill
3. Add recycling agent
4. Mix the recycling agent and loosened mixture
5. Spread and screed the recycled mixture
6. Place a new HMA overlay
7. Compact the two layers as a single layer

HIR-III recycling is only suitable for secondary or tertiary roads. Do not use this type of construction on airfields or parking areas subjected to heavy concentrated loads such as cargo yards, munitions haul roads, or similar critical roadways. For roads receiving HIR-III recycling, use the recycled layer as a base and determine the thickness of the new surface with the appropriate design analysis.

5-2.2.4 Past and Current Use.

Resistance to using HIR remains for the following reasons: (a) greater confidence in the conventional HMA overlay (b) lack of knowledge or appreciation of the new HIR technology, and (c) lack of appreciation of the quality of the pavement achieved with this technology. The quantity of the three types of HIR used in the United States is approximately the same (Emery, 2007; Kandhal and Mallick, 1997).

HR has been widely used in the US since the early 1980s. Most projects incorporate approximately 20 to 25 percent RAP or less.

5-2.3 Mix Design.

Follow the basic steps below for mix design for HIR/HR mixes.

1. Conduct analysis of existing pavement structure and surface condition.
2. Evaluate existing in-situ materials.
3. Sample the asphalt mixture selected for recycling by coring, sawing, or milling the pavement surface. Normally for HR, the contractor maintains RAP stockpiles as the RAP source.
4. Conduct either Marshall or Superpave mix design.

HIR is not normally recommended for airfield use, but has been used in conjunction with an HMA overlay. For roads, perform mix design with Marshall or Superpave mix design methods as specified in UFGS 32 12 16.16. For airfield pavements, perform mix design with Marshall or Superpave methods as specified in UFGS 32 12 15.13. Take samples of the surface pavement to be recycled, crush, and mix with asphalt binder or asphalt rejuvenator to determine the optimum asphalt content. Mix samples with various amounts of asphalt binder or rejuvenator and compact with a Marshall hammer or Superpave gyratory compactor. Select the asphalt content that provides approximately 4 percent air voids.

Design HR using the procedures addressed in Chapter 3. Use the two UFGS specifications (UFGS 32 12 15.13 and 32 12 16.16) to ensure production of a quality mix and successful placing and compaction.

5-2.3.1 Analysis of Existing Pavement Structure and Conditions.

Ideally, conduct a FWD evaluation and analysis prior to designing the pavement structure. If the structure is satisfactory or it needs only 1 or 2 inches (25 or 50 mm) of additional asphalt mixture, then HIR methods are suitable. If structural problems exist, or if the traffic volume or weight will increase, perform a structural analysis and design. See a description of design considerations above.

5-2.3.2 Samples.

See discussion on CIR and the following additional guidelines (NCHRP, 2001):

- For samples taken from a stockpile, take approximately 10 random samples from throughout the stockpile.
- For the samples taken from haul trucks, take samples from approximately three locations along the center of the truck bed. Take a sample approximately ¼ the way from front to back of the truck, approximately ½ the way from front to back, and about ¾ of the way from front to back. Samples should be taken underneath the surface by removing surface material with a shovel. All samples should be combined to obtain a representative sample of the truck.
- If the samples are for mix design, obtain at least 55 lbs. (25 kg) of RAP.
- If the samples are for gradation and asphalt content for QC testing, the sample size is approximately 22 lb (10 kg).

5-2.3.3 Identification of Distress Causes.

See Chapter 3 for common distresses and potential recycling methods that address distresses.

5-2.3.4 Analysis of Road Profile and Geometric Assessment.

Evaluating the existing pavement profile and cross slope can determine if a project is suitable for HR or HIR. A pavement that needs major realignments, drainage corrections or frost heave mitigation repairs, could use HR. In general, one of the three types of HIR can correct small problems with longitudinal or transverse profiles. In other circumstances, consider the following alternatives:

- Prior to overlay correct profile deficiencies by milling if the asphalt layer has sufficient thickness.
- Add granular material and new HMA or RAP to correct the profile. In this case, the options are Remix (HIR-II) or Repave (HIR-III).
- Correct what is possible during the HIR process and add HMA leveling or wearing course.
- If the HIR processes cannot correct the profile, then HR is a viable alternative.

5-2.3.5 Analysis of the Drainage Systems and Base Problems.

Thoroughly evaluate the drainage system to remove surface and subsurface water from the pavement structure. Solve drainage problems as part of any rehabilitation process. Otherwise, the problems will reoccur and significantly reduce the pavement life.

5-2.3.6 Selection of Materials and Methods.

Select satisfactory materials for use in HIR and HR. These include virgin aggregates to mix with existing materials to provide a satisfactory aggregate gradation. Select an appropriate asphalt binder so that when added to the RAP binder it produces satisfactory binder properties. With HIR, only limited additional materials can be used. Hence, improvement in the mix is limited.

5-2.3.7 Marshall and Superpave Mix Design Procedure.

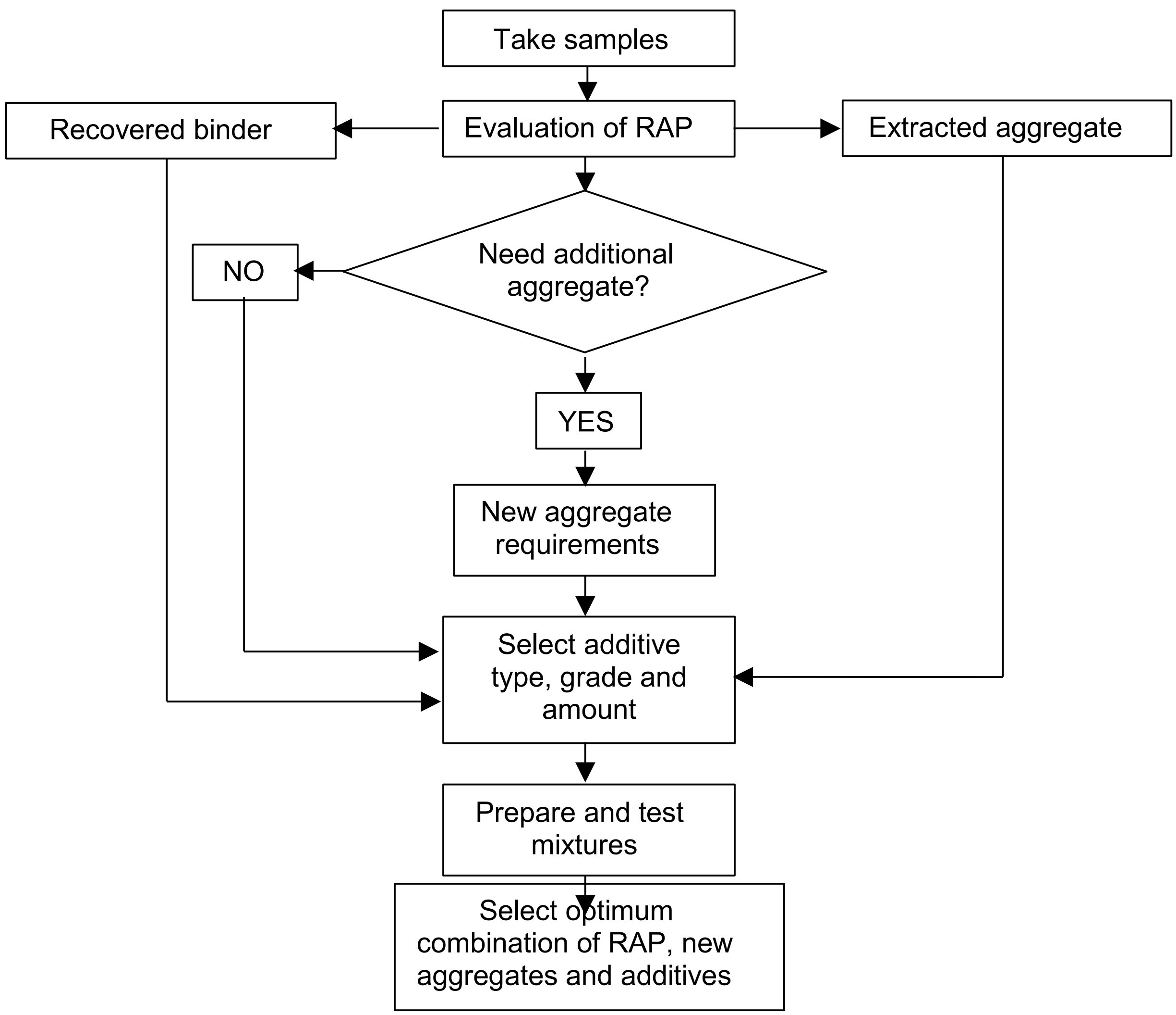
Perform a mix design to determine the percentages of RAP, new aggregate, recycling agent, and asphalt binder to use in the mixture. Base the amount of RAP used in a recycled mixture on the amount of the available reclaimed materials, the quality of the RAP, the desired properties of the recycled mix, aggregate gradation requirements, and economic considerations.

Figure 5-3 is a flowchart for the mix design procedure for the hot recycled mixtures. HIR adds very little or no additional virgin aggregates to the mixture, whereas, with HR there is at least 80% virgin aggregates in the mixture.

Compact samples of the recycled mixtures at various asphalt contents. Add the amount of new asphalt or recycling agent in 0.5 percent increments from 0 percent to 1.0 percent beyond the estimated optimum asphalt content. Compact the samples at the required effort, either 50 blows with a Marshall hammer (or 50 Superpave gyrations) for low-pressure tires (<100 psi or 6.9 kPa) or 75 blows with a Marshall hammer (or 75 Superpave gyrations) for high-pressure tires (>100 psi or 6.9 kPa), and determine the density, stability, flow, voids total mixture, and voids filled with asphalt. Only determine stability and flow with samples compacted with the Marshall hammer. Plot these determinations and draw curves to select the optimum asphalt content.

Determine the optimum asphalt content by selecting the virgin asphalt content equal to the amount that provides 3.5 percent air voids for HIR and 4.0 percent air voids for HR. The optimum additional asphalt binder is often between 0 and 1 percent for HIR mixtures. When the selected optimum additional asphalt is 0 percent or less, add no additional asphalt binder, since it may cause low voids in the asphalt mixture resulting in an asphalt mix that tends to bleed, rut, or shove under traffic. When the optimum asphalt content is very low use a recycling agent instead of asphalt binder.

Figure 5-3 Mix Design Procedure for Hot Recycled Mixtures



5-2.3.8 Evaluation of Existing Materials.

When evaluating existing materials, determine the properties of the RAP, extracted aggregate and recovered binder. Test samples of RAP, taken from stockpiles or directly from the existing pavement, in the laboratory. If performing a 5-point Marshall mix design, obtain a total of 18 to 20 cores, 2 inches (50 mm) thick and 6 inches (150 mm) in diameter or approximately 90 pounds (40 kilograms) of material.

5-2.3.8.1 RAP Properties.

Evaluate RAP properties to identify deficiencies to improve by adding rejuvenators, asphalt binder, fine and/or coarse aggregate or new hot mix for HIR. Determine the gradation of the RAP aggregate after solvent extraction (ASTM D2172) or ignition test (ASTM D6307) to remove asphalt binder. Determine the aggregate gradation using ASTM C136, the fractured faces by ASTM D5821, and flat and elongated particles by ASTM D4791. Properties of the combined aggregate from RAP and new aggregate sources must meet the same requirements as virgin aggregates in conventional HMA. It is difficult to recover enough aggregate from the RAP to conduct all of the required aggregate tests. Hence, the typical aggregate tests conducted are gradation, fractured faces, and fine aggregate angularity.

Determine the asphalt binder content of the asphalt mixture.

5-2.3.8.2 Virgin Aggregates.

a. Without adding significant amounts of new aggregate when producing HR, air pollution during mix production for most plants would exceed allowable levels. Adding new aggregate in a drum mix plant creates an aggregate shield preventing the flame from directly contacting the RAP and thereby burning the asphalt binder in the reclaimed asphalt pavement. Burning asphalt binder is the main source of air pollution during HR production.

b. Improve RAP aggregate gradation when using HR or HIR by adding virgin aggregates. Many times existing pavements do not contain the desired aggregate gradation. If they do contain a satisfactory gradation, this gradation may change during milling or crushing. Therefore, adding new aggregate modifies the recycled mix gradation to an acceptable level.

c. Often, the quality of the aggregates in an existing mix is not acceptable, even though the gradation is satisfactory. One cause of poor quality in an aggregate blend is an excessive amount of natural sand. Natural sand is a poor aggregate for asphalt mixtures, but because of its abundance and low cost, asphalt mix designs often use it in excess. The maximum amount of natural sand allowed by the airfield specifications is 15 percent, but many RAP stockpiles contain significantly more natural sand. Adding crushed stone decreases the relative percentage of natural sand in the mixture and improves the RAP aggregate quality.

d. Existing HMA pavements may contain filler (material passing the No.200 sieve) significantly higher than the 6 percent maximum allowed for HMA mixtures. Milling and crushing RAP generates up to 1 to 3 percent additional filler due aggregate breakdown. To control the filler use new aggregates with minimal filler content. In some cases, wash the virgin aggregates to minimize the filler material or screen the RAP into coarse and fine RAP stockpiles. The coarse RAP stockpile will have significantly less filler than the fine aggregate stockpile and thus less effect on the total amount of filler.

5-2.3.8.3 Recycling Additive.

a. The oxidized asphalt binder in existing HMA pavement requires some modification during recycling to produce an asphalt binder with acceptable binder properties. Ensure the mixture of old and new HMA material meet the specifications for the asphalt mixture using virgin materials. If not adding new aggregate to the mix, such as in HIR, adding asphalt or recycling agent to produce satisfactory asphalt binder properties may generate a rich mixture. The asphalt binder content of an existing pavement mixture is generally near the optimum asphalt content; thus, adding more asphalt binder or recycling agent for HIR mixtures generates excessive asphalt content. Not modifying the existing asphalt binder with low viscosity asphalt or recycling agent produces a brittle mixture. Using RAP in a mix such as for HR mixtures allows significant modification of the RAP aggregate quality and binder properties since there is significantly more virgin materials in the mixture. However, for HIR mixtures, most aggregate comes from the RAP, so this quality is much more important.

b. Restoring the existing asphalt binder is important for the success of a recycled mixture. Using a high amount of RAP in a mixture, such as for HIR, it is difficult to control the properties of combined binder as the amount of reclaimed asphalt binder likely exceeds the amount of virgin asphalt binder. For HIR, determine the amount and type of new asphalt binder required using the mix design process and to obtain the desired total binder properties. Recommendations for recycling additives for HIR are (ARRA, 2001):

- Use a recycling agent only to restore or rejuvenate the existing asphalt binder properties. Assume that the recycling agent thoroughly mixes with the aged asphalt binder during plant or in-place mixing.
- Use a performance grade (PG) binder with reduced high temperature grade as the new asphalt binder instead of a recycling agent. The assumption is that a new asphalt binder of lower PG grade will effectively combine with the aged binder resulting in an acceptable combined asphalt binder.
- Use a recycling agent and a soft new asphalt binder combined to rejuvenate the aged asphalt binder.

- Select asphalt binders according to the following standards (UFGS 32 12 15.13, UFGS 32 12 16.16):
  - ASTM D6373 for performance grade
  - ASTM D946 for penetration grade (penetration grading is used in some areas outside the U.S.)

c. When selecting PG asphalt binders in the U.S., consider adopting local DOT requirements for binder selection. Tweak the identified grades to meet mission needs. This makes it easier to obtain sources for asphalt binder and reduces the cost.

d. Typically, rutting is not a major problem on most airfield runways. However, for high traffic volumes on taxiways and at the end of runways, pavement rutting may occur under slow moving traffic with high tire pressures. High tire pressures exceeding 200 psi (1.4 MPa) may contribute to rutting. Some aircraft tire pressures exceed 300 psi and these high pressures can produce rutting in an asphalt mixture.

e. Use PG graded asphalts in HR mixture. Use recycling agents in HIR mixtures. Since a small amount of recycling agent will modify the RAP binder, ensure it contains an optimum residual asphalt content. Use the recycling additive to achieve the desired asphalt binder physical properties. Compare the physical properties of the combined asphalt binder (new recycling additive plus aged asphalt binder) with those of the original aged asphalt binder to establish the amount of recycling additive necessary.

f. In general, use softer recycling agents and lower new binder contents for HIR recycling methods (FHWA, 1997). Select the appropriate tests to ensure grade conformance of new asphalt specified, using the following guidance.

- If using a PG asphalt, use the dynamic shear rheometer and bending beam tests.
- If specifying a penetration grade asphalt, use a penetration test.

g. Ensure the new asphalt binder added to the HR mix has a grade that is no more than two PG grades different from that specified in paragraph ASPHALT CEMENT BINDER of the UFGS 32 12 15.13 or UFGS 32 12 16.16 specifications. Ensure the temperature of unmodified asphalts is no more than 325 ºF (160 ºC) when added to the aggregates and the temperature of modified asphalts is no more than 350 ºF (175 ºC) when added to aggregates.

5-2.3.8.4 Mix Properties.

Ensure the HR mix properties comply with the requirements indicated in Table 5-1 for airfields (UFGS 32 12 15.13) and Table 5-2 for roads (UFGS 32 12 16.16).

Table 5-2 Hot Mixed Recycled Properties for Airfields[5]

Parameter	Requirement	
	75 blows 75 gyrations	50 blows 50 gyrations
Minimum stability[4], pounds	2150	1350
Flow, 0.01 inch	8-16[1]	8-18[1]
Air voids, percent	4	4
Minimum percent voids in mineral aggregate	---[2]	---[2]
Dust proportion[3]	08-1.2	0.8-1.2
TSR, minimum percent	75	75

[1]The flow requirement is not applicable for polymer modified asphalts. Do not use flow with Superpave gyratory compactor.

[2]Aggregate gradation 1, minimum VMA = 13 percent; aggregate gradation 2, minimum VMA = 14 percent; aggregate gradation 3, minimum VMA = 15 % (see UFGS 32 12 15.13).

[3] Calculate dust proportion as the aggregate content, expressed as a percent of weight, passing the No. 200 sieve, divided by the effective asphalt content, in percent of total weight of the mixture.

[4]The stability requirement is not applicable when Superpave gyratory compactor is used.

Table 5-3 Recycled Asphalt Mix Properties for Roads[6]

Parameter	Requirement	
	75 blows 75 gyrations	50 blows 50 gyrations
Minimum stability[2], pounds	1800	1000
Flow[2], 0.01 inch	8-16	8-18
Air voids, percent	3-5	3-5
Minimum percent voids in mineral	---[1]	---[1]
TSR, minimum percent	75	75

[1] Aggregate gradation 1, minimum VMA = 13 percent; aggregate gradation 2, minimum VMA = 14 percent; aggregate gradation 3, minimum VMA = 15 % (See UFGS 32 12 16.16)

[2] Marshall stability and flow not used when compacted with Superpave gyratory compactor

UFC 3-250-03 presents additional information on mix properties and complete description on mix design.

[5]UFGS 32 12 15.13.

[6]UFGS 32 12 16.16.

5-2.3.9 Structural Design.

See guidance on structural design above.

The structural design of road and airfield pavements with hot recycled asphalt mixes (HR, HIR) follows the same criteria and procedure as for the conventional design for flexible pavements for roads and airfields. HIR and HR mixes perform the same as virgin asphalt mixtures. Use the same thickness design requirements for HIR and HR for conventional asphalt pavement design. For CBR design, the equivalency factors for HIR and HR are the same as for conventional asphalt mixture.

5-3 CONSTRUCTION.

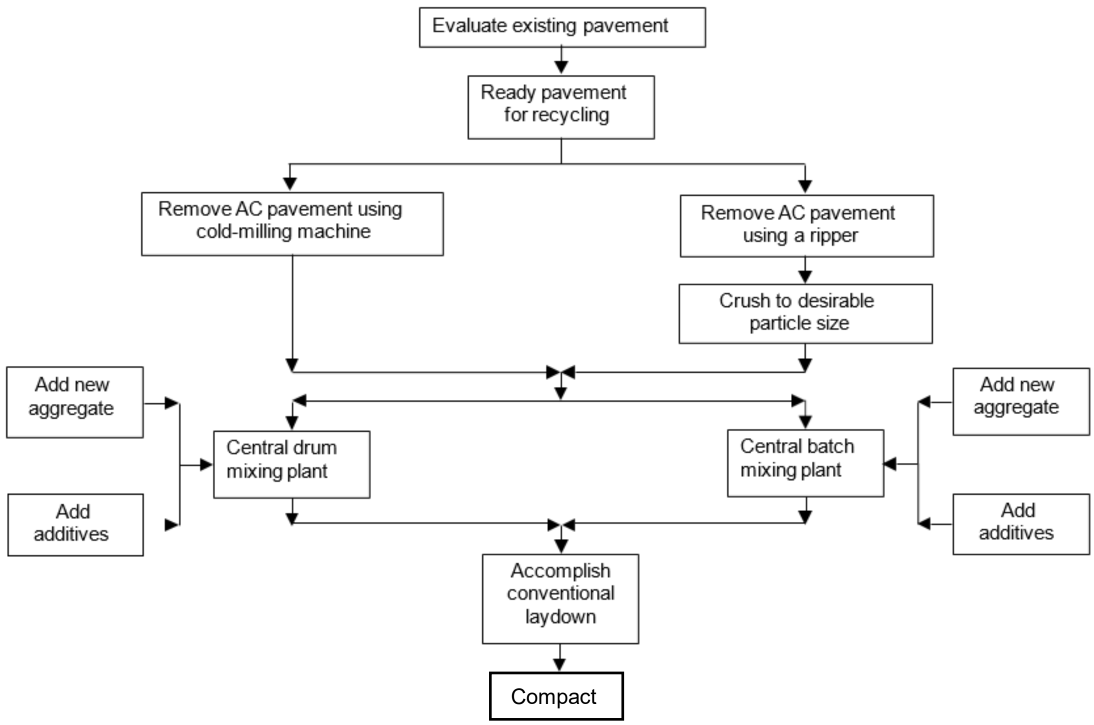
5-3.1 HR.

The HR process encompasses six basic construction steps (ARRA, 2001):

1. Remove the existing pavement materials to the desired depth.
2. Prepare the RAP for recycling (stockpiling and crushing).
3. Utilize RAP as available from other projects.
4. Blend old and new materials in a HMA production facility.
5. Mix the components in the proper proportions per the mix design.
6. Place the mixture and compact.

Figure 5-4 depicts these processes below.

Figure 5-4 Hot-Central Plant HR Recycling Process



HR mixture is a commonly used HMA mixture. In fact, most HMA mixtures now contain some amount of RAP in the mix. Asphalt mixtures on average among the various state DOTs contain approximately 20 percent RAP. The procedures used to produce and construct HR mixtures are essentially the same as used to construct HMA without RAP.

The construction equipment include: 1) equipment to remove existing material, 2) equipment for crushing RAP, 3) equipment for mixing and placing the HR, and 4) equipment for field compaction. The following sections discuss this equipment.

Transport HMA from the mixing plant to the site in clean, tight truck beds. Schedule deliveries for uniform placement and compaction of the mixture with minimum paver stopping and starting. Provide adequate artificial lighting for night placement. Do not permit hauling over freshly placed material until the material is compacted and allowed to cool to 140 ºF (60 ºC).

5-3.1.1 Removing and Processing Existing Material.

Remove asphalt mixtures with a milling machine to the desired depth. On some projects, a ripper tooth removes the asphalt mixture, but this requires crushing prior to re-use and is reserved for small jobs where full depth removal is required. A milling machine can remove up to 4 inches (100 mm) of HMA in one pass. It uses sensors that follow a grade reference and/or slope control to establish the finished grade. Since heat is not used, there is no smoke pollution. However, excess dust may occur, and this is solved by spraying a small amount of water onto the pavement in front of the milling machine. Milling machines are used during all weather conditions and produce finished milled surfaces that conform to the project specifications (UFGS 32 01 16.71). The milled HMA becomes RAP material to be used on the existing project or on future projects to produce HR. Ensure project specifications clearly state who owns the RAP since most state DOTs provide the RAP collected from a project to the contractor at the end of the project.

5-3.1.2 Mixing and Placing.

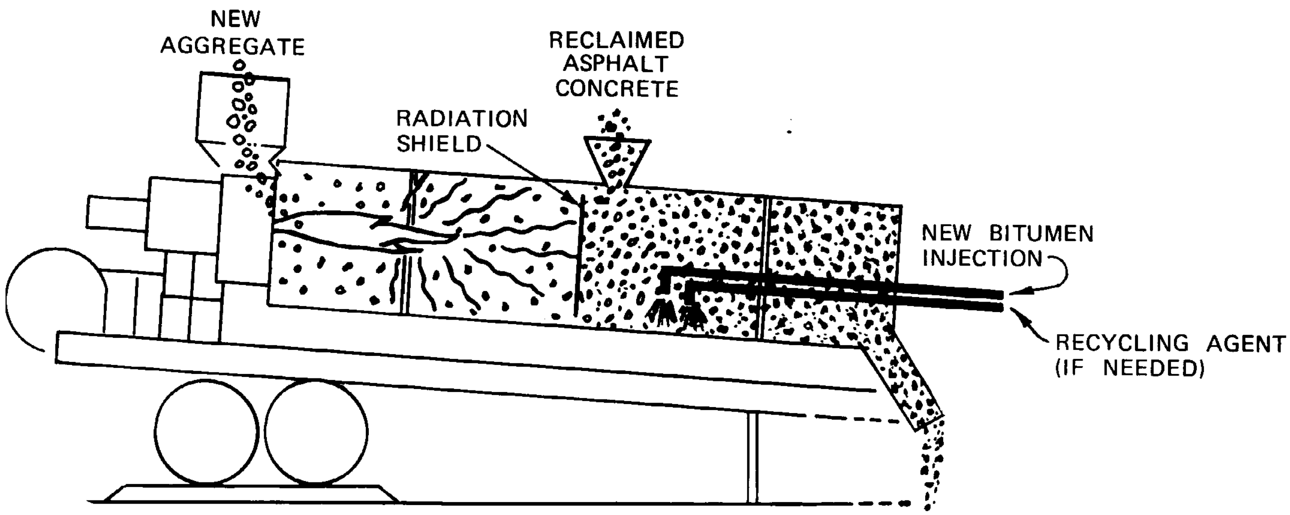
Use a batch or drum mix plant to blend recycled materials. Place recycled material with a conventional asphalt paver. When using a parallel flow drum mixer (aggregate flow and flame moving in same direction) for recycling, add the new aggregate at the high side of the drum near the flame, as indicated by Figure 5-5. The aggregate absorbs much of the heat from the burner and acts as a shield to protect the reclaimed asphalt concrete, new asphalt binder, and recycling agent from the adverse effects of the open flame. Add the RAP to the drum near the midpoint followed by the recycling agent and new asphalt. If air pollution is a problem, modify the mix design by lowering the percentage of RAP used in the mix to reduce emissions to an acceptable range.

When using a counter flow drum mix plant (aggregate flow and flame going in opposite directions), add the aggregate at the top of the drum and the flame is located at the bottom end of the drum. Add the RAP and asphalt binder in one of several processes, but in a way to keep the asphalt binder away from the open flame. This counter flow process has fewer emission issues when compared to the parallel flow drum plant.

Modify batch plants to produce recycled mixtures as shown in Figure 5-6. The modification consists of adding a feeder and conveyor to carry the reclaimed asphalt pavement directly to the weigh bucket. Superheat the new aggregate that passes through the dryer between 500 and 600 ºF (260 and 315 ºC) so that when blending, the resulting mix temperature is suitable for mixing and compaction. Increasing the amount of reclaimed asphalt in the mix requires an increase in the new aggregate temperature to achieve the desired mixture temperature. In addition, additional moisture in the new aggregate or reclaimed asphalt pavement stockpiles requires additional heat to dry and adequately mix the mixture components.

Place and compact the mix at a temperature suitable for obtaining density, surface smoothness, and other specified requirements (UFGS 32 12 15.13 and UFGS 32 12 16.16). Upon delivery, collect the mixture from the trucks and place across the full width of the pavement with an asphalt paver. Using a material transfer vehicle (MTV) allows the paver to move forward continuously and minimizes segregation. Airfield construction requires using an material transfer vehicle (MTV) (UFGS 32 12 15.13). Using an MTV, produces a smoother, more uniform pavement surface. Place the mixture uniformly at a depth that, when compacted, produces the required thickness and conforms to the specified grade and contour. Regulate paver speed to eliminate asphalt mat pulling and tearing. Unless otherwise permitted, begin placing the mixture along the centerline of a crowned section or on the high side of areas with a one-way slope.

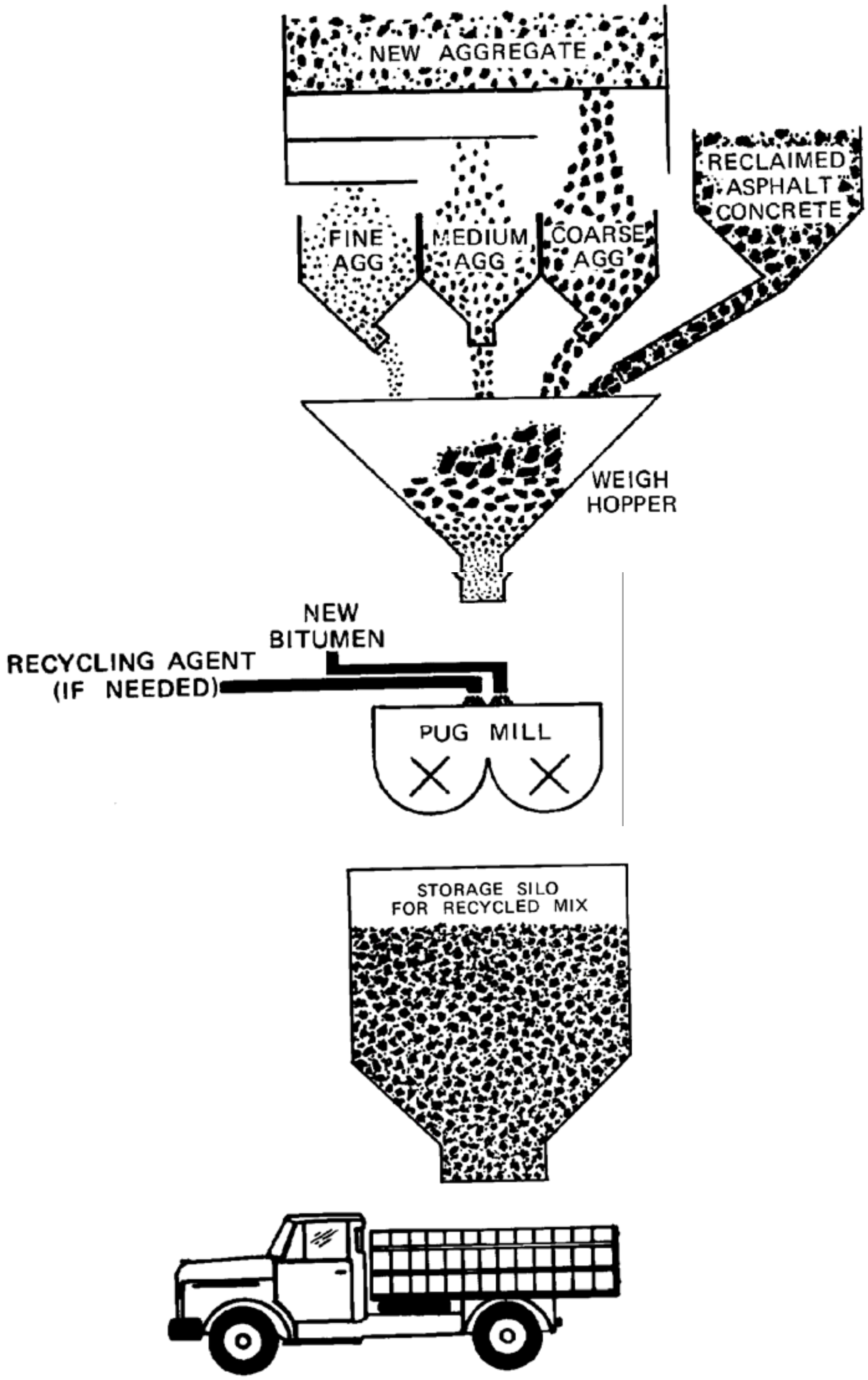
Figure 5-5 HR Production in a Parallel Flow Drum Mix Plant



5-3.1.3 Field Adjustments of the Mix.

The JMF obtained in the laboratory may require adjustments in the field to ensure that mixture and material properties meet the specifications. Make these adjustments based on the visual appearance of the recycled mix, test results obtained from samples of the HR, test results of the recovered aggregate, and test results from the recovered asphalt binder (ARRA, 2015).

Figure 5-6 Hot Recycled Asphalt Mix Production in a Batch Plant



5-3.1.4 Compaction.

Rollers used to compact asphalt mixtures include static steel-wheel, vibratory steel-wheel, and rubber-tired rollers. These rollers perform breakdown, intermediate, and finish rolling. Conduct breakdown rolling in vibratory mode, and occasionally, in static mode. Perform intermediate rolling in the vibratory mode while finish rolling in the static mode.

Rubber-tire rollers perform intermediate rolling of HMA mixtures. These rollers provide an increase in compaction after breakdown rolling and seal the surface. Ensure rubber-tired rollers are equipped with an operational watering system for the tires and that scrapers and pads affixed to prevent accumulation of materials on tires. Ensure rubber-tired rollers have skirts affixed to the roller that shield the tires from wind to prevent tire heat loss. Use a 10-ton or larger rubber-tired roller to compact all heavy-duty HMA pavements. Operate rollers at or below 3 to 5 mph (4.8 to 8 km/h) (fast walking speed). Make gradual starts and stops to avoid damaging the freshly laid mixture. Do not allow quick turns or any turns that cause cracking on freshly laid mixture. The contractor has discretion on sequence of rolling operations and the type of rollers used.

Compact the paving mixture while the mix is sufficiently hot, because rolling is relatively ineffective after the mixture cools below a minimum temperature and it is very difficult to obtain the required density. Following compaction and a cooling period, the pavement becomes very stable due to coarse and fine aggregate interlocking and adhesion of the asphalt binder as well as a high resistance to moisture penetration and frost damage.

Determine density results from 4 inch (100 mm) or 6 inch (150 mm) diameter cores randomly cut from the pavement. Use density gauges for QC testing, but not for final acceptance testing. Use cores for final acceptance of compaction.

5-3.2 HIR.

HIR treatment application is normally one lane wide (12 ft or 3.7 m). If pavement width is not a multiple of the treatment width, then overlap treatments. Limit overlaps to 2 to 6 inches (50 to 150 mm).

5-3.2.1 Construction Process.

5-3.2.1.1 Surface Recycling (HIR-I).

Major equipment includes brooms, trucks, front-end loaders, graders, asphalt distributors, self-contained heating units, heater-scarifiers, hot-milling machines, pavers, trucks, and/or cold-milling machines. Figures 5-7 through 5-9 show examples of a surface recycling heating unit, surface recycling scarification teeth, and surface recycling, respectively. There are single-pass (surface is recycled and left as final wearing course) and double-pass (surface is recycled and then an HMA overlay or a surface treatment is applied over it) procedures.

Figure 5-7 Surface Recycling Heating Unit

Figure 5-8 Surface Recycling Scarification Teeth*

*Source: ARRA, 2001.

Figure 5-9 Surface Recycle Mix Placement*

*Source: ARRA, 2001.

5-3.2.1.2 Remixing (HIR-II)

Hot in-place remixing operations encompass heating, scarifying, rejuvenating, mixing (and/or adding new HMA), leveling, re-profiling, and compacting. The remixing equipment heats, scarifies, or hot mills the existing pavement, mixes new materials, and lays the combined recycled and new mixtures. Figure 5-10 shows an example of a remixing train. Remove the existing pavement to depths of 0.4 to 2 inches (10 to 50 mm) (Kandhal and Mallick, 1997). Modern remixing equipment can work with up to 2 inches (50 mm) of the pavement and increase the pavement thickness by 1 inch (25 mm) (ARRA, 2001). There are two remixing methods:

a. Single Stage Remixing. Heat the existing asphalt pavement, soften with recycling agent or soft asphalt binder and scarify to the desired depth (1 to 2 inches [25 to 50 mm]), mix new HMA with the scarified material, and re-lay and compact the combined recycled mix. Figure 5-11 is an example of this method.

b. Multiple Stage Remixing. Heat the existing asphalt pavement, soften with recycling agent or soft asphalt cement, and scarify in a number of thin layers until achieving the pre-determined full treatment depth. Two to four layers are normally heated and scarified. Accumulate the scarified material is accumulated in a windrow to facilitate the continued heating and scarification of underlying layers. The range of treated depths is between 1-1/2 and 3 inches (40 to 75 mm). Figure 5-12 shows a windrow with scarified material.

Figure 5-10 Example of Remixing Train

Figure 5-11 Example of Single Stage Remixing Train

Figure 5-12 Multiple Stage Remixing with Windrow of Scarified Material

5-3.2.1.3 Repaving (HIR-III).

The equipment used in this process are the same as for HIR-I and HIR-II. In addition, ensure the repaving equipment can place an integral HMA overlay as thin as 1/2 inch (12.5 mm), using the appropriate HMA (use a fine graded mixture) (ARRA, 2001). As discussed earlier, repaving is a combination of surface recycling or remix with an overlay of HMA. The surface recycled or remixed layer and the HMA overlay are compacted simultaneously, which results in a thermal bond between the two layers. The surface recycled mix works as a leveling course and the HMA layer as a wearing course. The construction of HIR-III uses one of two approaches:

- Single Pass Repaving. Single Pass Repaving uses one unit equipped with two screeds. The unit scarifies the heated and softened pavement, adds the required amount of recycling agent, mixes the recycled mix prior to the first screed, receives the new HMA, and transports it over the recycled mix. The first screed places the recycled mix while the second screed places the new HMA overlay on top of the recycled mix. The two layers are then compacted.
- Multiple Pass Repaving. In this case, place the surface recycled mix and work with its own placing and screeding unit to meet the longitudinal profile and cross-slope requirements. Immediately place the new HMA overlay material on the hot uncompacted recycled mix with a conventional asphalt paver and then compact the two layers.

5-3.2.2 Placement of the HIR Material.

Place the recycled mixtures with a screed, often attached at the end of a recycling train or on a separate paver. After placement, compact the mix with rollers to achieve the desired density. Single-pass methods provide a relatively small opportunity for corrections from the existing grade.

Difficulty in placing the recycled material increases when the HMA overlay thickness and the underlying HIR treatment depth is greater than 3 to 4 inches (75 to 100 mm) (ARRA, 2001). Do not use layers greater than 3 inches (75 mm) compacted thickness.

5-3.2.3 Field Adjustments of the Mix.

See paragraph for HR.

5-3.2.4 Curing.

HIR mixes require no curing. Once these mixtures cool to 140 °F or lower, allow traffic.

5-3.2.5 Compaction.

See paragraph for HR.

5-3.2.6 Field Density.

See paragraph for HR.

5-3.2.7 Surface Course.

Add surface course over HIR mixtures to provide improved resistance to climatic conditions and traffic.

5-4 QUALITY CONTROL ISSUES.

5-4.1 Specifications.

Conduct all hot recycling projects (HR, HIR-I, HIR-II and HIR-III) in accordance with the respective UFGS specifications: UFGS 32 01 16.74, UFGS 32 01 16.75, UFGS 32 12 15.13 and UFGS 32 12 16.16.

5-4.2 Quality Control/Quality Assurance.

QC/QA practices for hot in-place recycling are the same as typically used for conventional HMA. QC/QA includes extracting, recovering, and testing of the blended asphalt binder. Consider variability of the RAP when preparing QC/QA limits and pay factors for individual projects, mainly for HIR (Kandhal and Mallick, 1997). Develop a Quality Control Testing Plan as part of the approved recycled mixture project. Ensure the plan addresses all elements that affect the quality of the pavement including, but not limited to, the following elements (UFGS 32 12 15.13 and UFGS 32 12 16.16):

- recovered asphalt binder properties
- mix design and unique JMF identification code
- aggregate grading, angularity, flat/elongated particles
- quality of materials
- stockpile management and procedures to prevent contamination
- proportioning
- mixing and transportation
- correlation of mechanical hammer to hand hammer
- moisture content of mixtures
- placing and finishing
- thickness
- joints
- field compaction, including joints
- surface smoothness
- truck bed release agent

When the contractor develops a Quality Control Plan, ensure performance of all required testing and inspection in accordance with the specification requirements. Ensure the plan clearly explains how the contractor will control the quality of work.

5-4.2.1 Field Sampling and QC Testing.

The field sampling and QC testing depend on the testing program requirements. The testing program, the main part of the QC/QA process, includes, but is not limited to,

- Tests for the control of asphalt content, aggregate gradation and specific gravity.
- Temperatures, aggregate moisture, and moisture in the asphalt mixture.
- Laboratory determined air voids (air voids in total mix (Va), voids in mineral aggregates (VMA), voids filled with asphalt (VFA)).
- Marshall stability and flow tests.
- In-place density (use a density gauge to monitor pavement density, when correlated to core samples but not for acceptance of density).
- Grade conformance and surface-smoothness.
- Perform additional testing at the discretion of the contractor as necessary to control the process. When field sampling follow UFGS requirements

(UFGS 32 01 16.74, UFGS 32 01 16.75, UFGS 32 12 15.13; UFGS 32 12 16.16).

Additional guidelines for preparing a field-sampling plan for roads are below (ARRA, 2001; FHWA, 1997):

- Divide the project into homogeneous sections (similar materials and/or performance.
- Design field sampling according to these homogeneous sections.
- Use random sampling methods for setting field sampling according to the homogeneous sections for adequate recycling mix.
- Use pavement coring to obtain field samples (typically, 6-inch (150-mm) diameter cores).
- If necessary, use sawing for block sampling.
- Determine number of samples according to the size of the project:
    - Large projects, with more than 4 miles (6.4 km), require at least two samples for every mile (1.6 km) with a minimum of 6 samples per project
    - Smaller projects, like in urban areas, would require at least 8 samples per mile (1.6 km) or one per block if the pavement is not homogeneous

To prepare a field sampling plan for airfields use the approach presented in Chapter 4.

CHAPTER 6 RECYCLING FOR CONCRETE SURFACED PAVEMENTS

6-1 INTRODUCTION.

Concrete pavement recycling is a rehabilitation technique that reuses PCC material in an existing concrete pavement structure. Accomplish the reuse through fractured slab technologies including break/crack-and-seat and rubblization. Alternatively, conduct slab demolition, removal, and reprocessing activities to produce RCA. Depending on the technique, the recycled material can serve as a base material or as aggregate in new PCC or lean concrete base. Recycle composite pavements, where HMA overlays PCC, by first milling off the existing HMA.

Concrete recycling offers significant savings in the cost of hauling and disposing of old concrete and it saves natural resources and reduces or eliminates the need for new virgin aggregates. In addition, compared to the conventional form of PCC rehabilitation, HMA overlay directly over existing PCC, recycling can provide substantial performance benefits in terms of alleviating or eliminating reflection cracking in the HMA surfacing.

As discussed in Chapter 2, concrete recycling techniques are mostly suitable for existing pavement with substantially reduced structural capacity. Other forms of rehabilitation better serve pavements with functional distresses or limited structural distress such as concrete pavement restoration (CPR) and HMA or bonded PCC overlays.

This chapter presents detailed information and guidance on the four basic forms of concrete recycling: (1) break-and-seat, (2) crack-and-seat, (3) rubblization, and (4) central plant recycling. Following an overview of the applications of each method, topic sections cover structural and mix design considerations, construction details, and QC/QA issues.

6-2 OVERVIEW OF RECYCLING METHODS.

6-2.1 Break/Crack and Seat.

The break-and-seat recycling process involves fracturing the slabs of JRCP into small segments (1.5 to 4 feet [0.5 to 1.2 m]) and adequately rupturing the bond between PCC and reinforcing steel to ensure discontinuity among the fractured pieces. Firmly seat the pieces in place in preparation for an overlay. Typically, the overlay is HMA, but PCC overlays are also successful. Similarly, the crack-and-seat recycling process involves fracturing the slabs of JPCP into small segments (2 to 6 feet [0.6 to 1.8 m]), which are then seated firmly into place in preparation for an overlay (again, typically HMA, but PCC can be an option). Typical HMA overlay thicknesses range between 4 to 8 inches (100 to 200 mm), depending on expected traffic loading and the strength characteristics of the fractured PCC and base layers.

Breaking/cracking and seating reduces joint and crack movement by shortening the effective slab length and seating the broken pieces into the supporting layer (Hoerner et al., 2001). Greater impact energy is required for the break-and-seat process in order to rupture the concrete bond to the steel in the slab. In both applications, consider incorporating edge drains to facilitate drainage, given that the fractured slab allows water to flow more freely into the underlying pavement layers (Hoerner et al., 2001).

Break/crack-and-seat techniques are most appropriate for concrete pavements experiencing significant load-related distresses (e.g., linear cracking, divided/shattered slabs, corner breaks), faulting, or environmental or materials related distresses (e.g., D-cracking, ASR, scaling). However, as noted below, existing PCC airfield pavements that exhibit ASR distress are subject to restrictions with this technique. Pavements with other distresses, such as patch deterioration and unstable or settled slabs, can also benefit from breaking/cracking and seating.

PCC pavements with many failed or shattered slabs are not suitable candidates for break/crack-and-seat techniques (Ahlrich, 1992). Moreover, in situations where the pavement foundation is weak or questionable, the fractured slabs will “float” on a soft layer, manifesting in vertical and/or rotational movement of the slabs. Since these movements seriously undermine the performance of the HMA overlay, use a great deal of caution in determining when the break/crack-and-seat procedure is effective under these circumstances.

DoD policy allows the use of break/crack-and-seat techniques on all auxiliary airfield pavements and on all roadway pavements. However, caution is warranted when considering break/crack-and-seat techniques for PCC airfield pavements suffering from ASR damage. Because of the uncertainty of the effects of this phenomenon on pavement performance, TSPWG M 3-250-04.06-2 recommends consulting with AFCEC on projects involving this situation. Additionally, TSPWG 3-250-07.07-6 provides a detailed procedure for assessing and controlling the risk of break/crack-and-seat applications involving PCC with ASR distress. Recycle ASR-infected PCC can be considered on roadway pavements that are not mission critical. Practitioners are encouraged to use the risk assessment procedure outlined in TSPWG 3-250-07.07-6.

6-2.1.1 Past and Current Use.

The practice of break/crack-and-seat on airfield and roadway pavements dates back to the 1980s and 1990s. Early successes in delaying the development of reflective cracking led to increased usage of this technique.

In recent years, the use of break/crack-and-seat has decreased due to variability in performance coupled with increased success with rubblization. While most studies have shown a considerable delay in the development of reflective cracking, some studies have shown that the severity of cracking in the long-term (5 to 7 years) is comparable to that of conventional HMA overlays over non-fractured concrete.

The use of a reinforcing fabric or SAMI following placement of the first lift of HMA (leveling layer) delays reflective cracking. Consider the use of an interlayer if representative data are available to show its cost-effectiveness.

6-2.2 Rubblization and Overlay.

Rubblization fractures existing PCC pavements (JRCP, JPCP, or CRCP) in-place into small, interlocked pieces that serve as a base course for a new HMA or PCC overlay (Buncher et al., 2008). The rubblized material, ranging from sand-sized particles to 6 inches (150 mm) at the surface and 6 to 15 inches (150 to 375 mm) at the slab bottom, resembles a dense aggregate base layer with a high degree of particle-to-particle interlock. Seat the rubblized layer using specific rolling protocols. Although the thickness of an HMA overlay depends largely on expected traffic loadings and the bearing capacity of the rubblized and foundational layers, thicknesses between 4 and 10 inches (100 to 250 mm) are most common. Installation of an edge drain system dramatically improves the constructability and performance of the rubblized layer.

Rubblization eliminates joint and crack movement. The resulting fractured particle sizes somewhat resemble crushed aggregate base material. Also, because of the type of equipment used—resonant and multi-head pavement breakers—the impact load is lighter, which minimizes disturbance to the support layers and any underground features (Hoerner et al., 2001).

Consider rubblization when the amount of deterioration of the existing pavement is so great that normal break/crack-and-seat methods would not be effective (Hoerner et al., 2001). Rubblization is generally a viable option for CRCP that is distressed beyond the point that restoration strategies, such as full-depth repairs and grinding, are no longer cost-effective. One advantage of rubblization over break-and-seat is that the steel reinforcement in the pavement does not require rupturing, as the concrete completely debonds from the steel. The main disadvantage of rubblization, compared to break/crack-and-seat, is that it requires a thicker HMA surface due to the lower structural capacity of the rubblized material.

Current DoD policy allows rubblization on all airfield pavements and on all roadway pavements. However, as with break/crack-and-seat, exercise caution in considering the use of rubblization on PCC airfield pavements suffering from ASR damage. Because of the uncertainty of the effects on pavement performance, TSPWG M 3-250-04.06-2 recommends consulting with AFCEC in projects involving this situation. Additionally, TSPWG 3-250-07.07-6 provides a detailed procedure for assessing and controlling the risk of rubblization applications involving pavements with ASR. Apply this risk assessment procedure to projects that rubblize ASR-infected PCC roadway pavements.

6-2.3 Past and Current Use.

Rubblization is currently the most widely used PCC slab fracturing technique.

6-2.4 RCA Applications.

a. RCA recycling involves demolishing existing concrete pavement on grade, loading and hauling the material to an off-site crushing plant, and processing (i.e., crushing, sizing, and steel removal) the material to produce recycled aggregate of specified sizes (Hoerner et al., 2001). Use RCA in unbound base/subbase layers, asphalt or cement-treated layers, lean concrete bases, or PCC surface courses (low-type facilities only).

b. RCA is best suited for existing PCC pavements that have reached the end of their useful life. Hence, pavements with extensive amounts of slab cracking, joint deterioration, slab settlement, faulting, or environmental or materials-related distresses are good candidates for this activity. Compared to conventional reconstruction using virgin materials, reconstruction using RCA conserves materials, reduces landfill requirements, and reduces project costs.

c. RCA recycling can be performed on any existing PCC pavement type—JPCP, JRCP, or CRCP (Hoerner et al., 2001). Reinforcing steel hampered the productivity and effectiveness of many early RCA recycling projects. Equipment innovations over the years have virtually eliminated problems in processing reinforced concrete material.

d. The coarse fraction of RCA retained on the 3/8-inch (9.5-mm) sieve is preferred for most applications. This is because of the high degree of angularity and high absorption capacity of the RCA fine fraction adversely affects the workability of a resulting mix (Hoerner et al., 2001). The addition of natural sand can restore workability.

e. Current DoD policy allows RCA as aggregate base and subbase material, and as aggregate for lean concrete base on all airfield and roadway pavements. The use of RCA in new PCC is limited to auxiliary airfields and minor roads. Do not use RCA from pavements with severe D-cracking in PCC surface courses. In addition, because of the uncertainty of the effects of ASR-infected RCA on pavement performance, TSPWG M 3-250-04.06-2 recommends that such material not be used in any application within an airfield pavement structure. Additionally, TSPWG 3-250-07.07-6 provides detailed procedures for assessing and controlling the risk of RCA applications involving ASR-infected pavements. Use this risk assessment procedure for roadway projects in which RCA from PCC pavement with ASR distress is used.

6-2.4.1 Past and Current Use.

RCA is used predominantly as a replacement for virgin aggregate in granular, cement-treated, or lean concrete base layers and, to a lesser extent, in PCC and HMA surface layers (Saeed et al., 2006). Roughly two-thirds of RCA usage in pavement applications is for unbound base or subbase layers.

RCA has been used at several DoD locations including Selfridge ANG, Shaw AFB and North Auxiliary Field in South Carolina, Grand Forks AFB in South Dakota, Mountain Home AFB in Idaho, Offutt AFB in Nebraska, and Holloman AFB in New Mexico (Saeed et al., 2006). Commercial airport applications include Atlanta Hartsfield-Jackson International Airport and the former Denver Stapleton International Airport.

Several State DOTs use RCA in pavement construction. A survey of state DOTs indicates the following usage (FHWA, 2005):

- RCA Used as Aggregate: 41 of 50 states.
- RCA Used as Base Aggregate: 38 of 50 states.
- RCA Used as PCC Aggregate: 11 of 50 states.
- RCA Used as HMA Aggregate: 8 of 50 states.

6-3 STRUCTURAL DESIGN CONSIDERATIONS.

6-3.1 Break/crack-and-seat and overlay.

a. The structural design of break/crack-and-seat and overlay projects centers on the structural characteristics of the fractured layer and underlying base and subgrade layers in response to anticipated traffic loading (Huang and White, 1995). The values selected for these parameters determine the thickness of the HMA overlay placed on the fractured PCC layer. Perform the HMA overlay thickness design using the flexible pavement design procedures provided in UFC 3-260-02.

b. Directly test fractured layer characteristics after completing the breaking/cracking process. Estimate initial values using the best available information. Key aspects include the condition/quality of the existing PCC, the presence of steel reinforcement, and the targeted size of PCC segments.

c. The size of the broken segments is critical to the performance of the HMA overlay (Hoerner et al., 2001). Small pieces generally reduce the likelihood of reflective cracking in the HMA overlay due to reduced horizontal thermal movements in the fractured layer. At the same time, a breaking or cracking concrete into smaller pieces produces an inherently weaker fractured layer (Ceylan et al., 2005). This places greater emphasis on the structural support from the underlying layers or may require a thicker, costlier overlay to meet the structural requirements of the rehabilitated pavement.

d. For crack-and-seat, broken pieces are limited to a maximum nominal diameter of 3 feet (0.9 m). For break-and-seat, 80 percent of fractured pieces must have a diameter smaller than 2 feet (0.6 m) with no pieces larger than 2.5 feet (0.8 m). These recommended values are variable based on the quality of the subgrade and base materials, and other factors. With regard to dimensions, several studies have recommended that broken/cracked pieces be nearly equal in length and width, or that the length be slightly greater than the width (Hoerner et al., 2001).

e. NDT testing of break/crack-and-seat airfield and highway pavements indicates that the range of back-calculated elastic moduli range from a few hundred thousand psi to a few million psi (National Asphalt Pavement

Association [NAPA], 1994). Similar testing of a crack-and-seat pavement at Hunter Army Airfield in Georgia yielded an average modulus of 590,750 psi (4,073 MPa) for the 6-inch (150-mm) fractured PCC layer (Buncher et al., 2008).

f. The Mechanistic Empirical Pavement Design Guide (MEPDG) produced under National Cooperative Highway Research Program (NCHRP) Project 1-37A recommends the design moduli (E_{fs}) shown below for break/crack-and-seat layers (ARA-ERES, 2004) based on a 75% reliability level. The MEPDG states that the values given for Level 3 are conservative and not for break-and-seat unless ensuring full debonding of PCC from reinforcing steel (ARA-ERES, 2004).

6-3.1.1 High-Level (Level 1) Design Analysis.

- Good to excellent slab fracture control expected (COV=25%): Efs = 600,000 psi (4,137 MPa)
- Fair to good slab fracture control expected (COV=40%): Efs = 450,000 psi (3,103 MPa)
- Poor to fair slab fracture control expected (COV=60%): Efs = 300,000 psi (2,069 MPa)

6-3.1.2 Low-Level (Level 3) Design Analysis.

- 12-in crack spacing: Efs = 200,000 psi (1,379 MPa)
- 24-in crack spacing: Efs = 250,000 psi (1,724 MPa)
- 36-in crack spacing: Efs = 300,000 psi (2,069 MPa)

For HMA overlay design using the layered elastic design (LED) procedure, use the MEPDG Level 3 moduli above as minimum values, with adjustments made upward based on the expected quality control of the cracking operation, as shown in Table 6-1.

Table 6-1 Recommended Elastic Moduli for Cracked and Seated PCC Layers

	Modulus for Various Levels of Expected Slab Fracture Control		
	Poor to Fair	Fair to Good	Good to Excellent
12 inches (300 mm)	200,000 psi (1,379 MPa)	300,000 psi (2,069 MPa)	400,000 psi (2,758 MPa)
24 inches (600 mm)	250,000 psi (1,724 MPa)	375,000 psi (2,586 MPa)	500,000 psi (3,448 MPa)
36 inches (900 mm)	300,000 psi (2,069 MPa)	450,000 psi (3,103 MPa)	600,000 psi (4,137 MPa)

For HMA overlay design using the CBR procedure, use CBR equivalency factors (i.e., thickness equivalent ratios of an unbound base or subbase material) for the fractured PCC layer. Equivalency factors between 1.2 and 1.6 are reasonable maximum values, with the lower end representative of shorter crack spacing and lower fracture control and the upper end representative of longer crack spacing and greater fracture control.

The minimum recommended HMA overlay thickness for a crack-and-seat project is 4 inches (100 mm). The use of a reinforcing fabric or SAMI following placement of the first lift of HMA (leveling layer) delays reflective cracking. Considered for use if representative data are available to show their cost-effectiveness. The HMA material recommended for use in a break/crack-and-seat project is a standard dense-graded asphalt mixture, conforming to UFGS 32 12 15.13 for airfield pavement applications or UFGS 32 12 16.16 for roadway pavement applications.

A final consideration in the design of break/crack-and-seat projects is subsurface drainage. The installation of edge drains is highly recommended where drainage problems exist. Thus, if pavement condition or evaluation data indicate serious moisture-related issues and the existing pavement is either not equipped with a drainage system or has an ineffective system, it is strongly recommended that a new system be installed. A properly installed and maintained retrofit drainage system can play an important role in achieving the intended design life of the HMA overlay (ARA-ERES, 2004).

6-3.2 Rubblization and Overlay.

As with overlay structural design for broken/cracked-and-seated PCC, the structural response characteristics of the rubblized layer is an important parameter in determining the thickness of the overlay. Rubblized layer characteristics are unknown at the time of design. Directly test the rubblized layer after rubblization is complete and the first lift of HMA placed. Make initial estimates using the best information available.

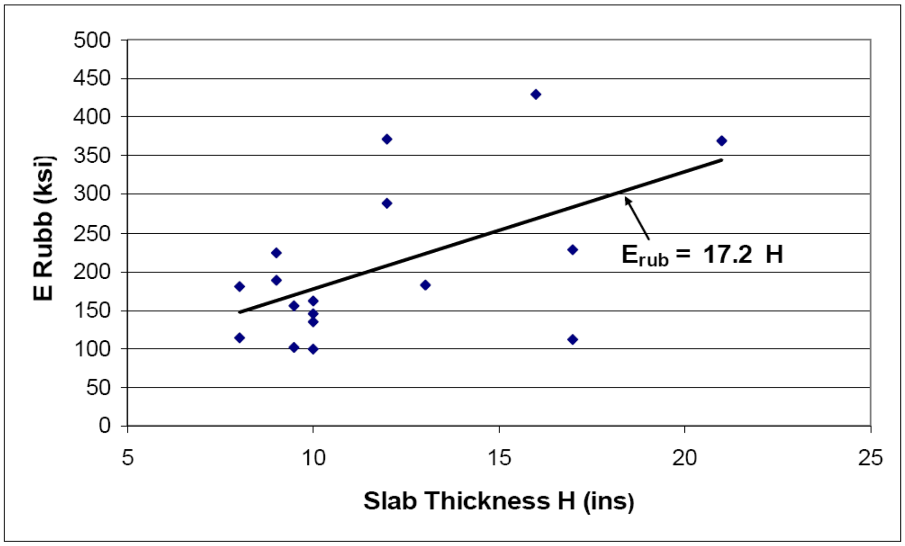
AAPTP Project 04-01, *Development of Guidelines for Rubblization*, is a comprehensive assessment on the rehabilitation of airfield pavements using rubblization. This report includes a very detailed assessment of back-calculated rubblized PCC moduli compiled from numerous studies and projects sponsored by agencies including USACE, FAA, Asphalt Institute, NAPA, FHWA, SHRP, airport authorities, state DOTs, and rubblization equipment manufacturers. Although it was acknowledged that various factors have an impact on the effective modulus of rubblized PCC (e.g., thicker slabs generally result in larger rubblized particles), results of the assessment indicated a general relationship between the modulus (E_{rub}) and slab thickness. Figure 6-1 shows this relationship. There is considerable scatter of the data points in the figure, and this sheds some concern as to its validity.

Combining this relationship with recommended moduli ranges given in the Asphalt Institute Manual Series No. 17, FAA *Engineering Brief No. 66* , American Association of State Highway and Transportation Officials (AASHTO) MEPDG, and other sources, the following ranges are recommended as design modulus values for rubblized PCC on airfield pavements (Buncher et al., 2008):

- For slabs 6 to 8 inches (150 to 200 mm) thick: moduli from 100,000 to 135,000 psi (690 to 931 MPa).

- For slabs 8 to 14 inches (200 to 350 mm) thick: moduli from 135,000 to 235,000 psi (931 to 1,620 MPa).
- For slabs >14 inches (>350 mm) thick: moduli from 235,000 to 400,000 psi (1,620 to 2,758 MPa).

Figure 6-1 Average Initial Modulus Versus Slab Thickness*



*Source: Buncher et al., 2008.

These moduli are substantially higher than that of crushed aggregate base (50,000 to 60,000 psi [345 to 414 MPa]) and are comparable to that of an asphalt-treated base (150,000 to 400,000 psi [1,034 to 2,758 MPa]). They are suitable for determining HMA overlay thickness when using LED procedures, including PCASE.

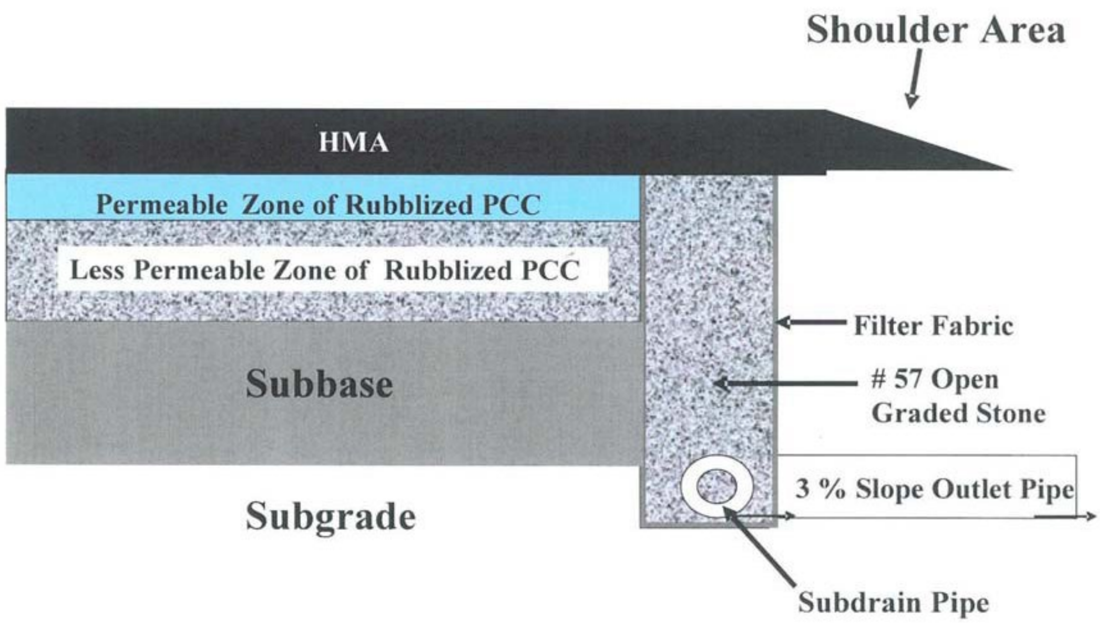
AAPTP Project 04-01 states that characterizing rubblized concrete as simply a crushed stone base layer with CBR = 100 is too conservative. The recommended method is to characterize the rubblized layer as a stronger material by using the following equivalency factors (EF) to convert the thickness of the rubblized layer to an "equivalent" thickness of crushed stone base:

- For rubblized layers 6 to 8 inches (150 to 200 mm) thick: EF = 1.2.
- For rubblized layers 8 to 14 inches (200 to 350 mm) thick: EF = 1.4.
- For rubblized layers >14 inches (>350 mm) thick: EF = 1.6.

The minimum recommended thickness of HMA overlay on a rubblized layer is 5 inches (125 mm) (Buncher et al., 2008). At least two lifts of HMA are necessary to meet grading and smoothness requirements. The minimum thickness of the first lift over the rubblized layer is 3 inches (75 mm) to prevent slippage at the interface between the HMA and the rubblized surface during compaction.

The issue of subsurface drainage is critical to the success of rubblization projects. Not only is it important in terms of the overall long-term performance of the pavement, but it can significantly affect the desired characteristics and long-term performance of the rubblized layer. A properly designed and installed edge drain system (Figure 6-2) facilitates the rubblization process by draining free water from the system, thereby yielding a stable platform for rubblizing the PCC.

Figure 6-2 Typical Longitudinal Edge Drain System for Rubblized PCC



6-3.3 Application.

When installing retrofit drains in conjunction with HMA overlays of fractured PCC slabs, consider the potential for fines generated during the slab fracturing process (particularly during rubblization) to clog the edge drain system. Carefully evaluate the potential for clogging. Choose the components of the drainage system to ensure the functionality of the drainage system. Further, since the slab fracturing process provides an open graded system, design the installed drains with adequate hydraulic capacity to handle the potential quantities of outflow. AASHTO MEPDG (ARA-ERES, 2004) provides additional guidance on edge drain systems for both break/crack-and-seat and rubblization projects.

6-3.4 RCA Applications.

Crush RCA and process to any desired grading (Saeed et al., 2006) to satisfy the intended application (unbound granular layer, lean concrete base, new PCC, etc.). Typical engineering and mechanical properties of RCA as compared to virgin aggregate materials are summarized in Table 6-2 (C). As can be seen, RCA possesses somewhat different properties than conventional virgin aggregates. Additionally, RCA typically has a lower dry density and higher optimum moisture content than virgin aggregate materials.

Table 6-2 Comparison of Typical Virgin Aggregate and RCA Properties[7]

Aggregate Property	Virgin Aggregate	RCA
Particle Shape and Texture	Well rounded, smooth (gravels) to angular and rough (crushed stone)	Angular with rough surface
Absorption Capacity, %	0.8 to 3.7	3.7 to 8.7
Specific Gravity	2.4 to 2.9	2.1 to 2.4
LA Abrasion Test Mass Loss, %	15 to 30	20 to 45
Sodium Sulfate Soundness Mass Loss, %	7 to 21	18 to 59
Magnesium Sulfate Soundness Mass Loss, %	4 to 7	1 to 9
Chloride Content, lb/yd^3 (kg/m^3)	0.00 to 2.03 (0.00 to 1.20)	1.01 to 12.00 (0.59 to 7.09)
California Bearing Ratio (CBR), %	25 to 100[a]	94 to 184[b]

[a]Typical CBR of crushed limestone is 100.

[b]Measured in lab to be up to 184, but set limit at 100 (UFC 3-250-01, UFC 3-260-02).

6-3.4.2 RCA as Unbound Base/Subbase Layer.

6-3.4.2.1 Mix Design.

UFGS 32 11 23 details the requirements for use of RCA (and other types of aggregate) as a base course in flexible pavements. Two different applications are covered, the first being an aggregate base course (ABC) having a CBR of 80 percent and the second being a graded-crushed aggregate (GCA) base course having a CBR of 100 percent.

In addition to meeting CBR, gradation, and density requirements, RCA under this specification requires the following:

- The subgrade soil contains less than 0.3 percent of sulfates to prevent expansive ettringite reaction with the RCA.
- The RCA material experience no greater than 0.08 percent expansion when tested for aggregate-alkali reactivity under ASTM C 1260 *Standard Test Method for Potential Alkali Reactivity of Aggregates (*mortar-bar method).

[7]Hoerner et al., 2001; Saeed et al., 2006.

RCA must meet all the same requirements as natural aggregates per UFGS 32 11 23.

Comparing these requirements with the typical values shown in Table 6-2, shows that abrasion resistance and soundness (sodium sulfate, in particular) are potential issues for RCA when it used as GCA base course in flexible pavements.

UFGS 32 11 20 details the requirements for use of RCA (and other types of aggregate) as a base course in rigid pavements (airfield and roadway) or as a subbase course in flexible pavements (airfield and roadway). In addition to meeting respective gradation requirements for subbase for flexible pavement, the combined aggregate must also meet the requirements for CBR equal to or larger than 50 and LA abrasion equal to or less than 50.

6-3.4.2.2 Structural Design.

The structural design of flexible pavements using RCA as an unbound granular base/subbase layer requires either a CBR or resilient modulus estimate for the subject layer. As shown previously in Table 6-2, RCA material generally exhibits CBR values between 94 and 184 that is considerable higher than crushed stone. Based on the design guides for flexible pavements (UFC 3-260-02 and UFC 3-250-01), the CBR used for base course is limited to 100 and the CBR for subbase is limited to 50.

For flexible or rigid pavement design using LED procedures in PCASE, the following relationship developed by the Transport Research Laboratory (TRL) can be used to convert CBR values to resilient modulus (psi) (ARA-ERES, 2004):

Equation 6-1. Conversion of CBR Values to Resilient Moduli

$$M_r = 2{,}555 \times (CBR)^{0.64}$$

This equation yields modulus values between 31,240 and 48,685 psi (215 and 336 MPa) for CBR values of 50 to 100 percent. Use higher modulus values (up to 70,000 psi [483 MPa]) if supported by actual test data.

For Westergaard design of rigid pavements using modulus of subgrade reaction, k, the design k-value is that effective on top of the aggregate base layer (UFC 3-260-02 for airfields; UFC 3-250-01 for roads). Derive this value using various relationships established between field plate-bearing tests performed on the subgrade (i.e., subgrade k-values) and the design thickness of the base layer (minimum of 4 to 6 inches [100 to 150 mm]). These relationships are valid for RCA base layer applications.

6-3.4.3 RCA in PCC (and Lean Concrete Base).

The following discussion focuses on new concrete mixes using RCA as aggregate for use in surface courses. Although some differences exist, the information and guidelines presented are generally applicable to RCA used in lean concrete base mixes.

6-3.4.3.1 Mix Design.

Ensure that the RCA meets the specification for aggregates. Additionally, if the original pavement being recycled is D-cracked, then crush the concrete to a maximum size of 0.75 inches (19 mm). Prohibit RCA exhibiting ASR in any airfield pavement structure.

Table 6-3 lists the effects that RCA has on PCC properties when used as the aggregate for the mix. In general, if only the coarse portion of RCA is used in the new mix, no significant changes are necessary in the mix design and workability should be unaffected (Hoerner et al., 2001). However, if recycled fines are used, the resulting mix can have reduced workability due to the highly angular nature of the recycled fines, and the mix can have a lower compressive strength due to higher water/cement ratio (greater demand for water caused by the higher absorption capacity of the recycled fines). Eliminate these problems by limiting the percentage of RCA fines to 20 percent and using natural sand for the remaining percentage.

Table 6-3 Effects of RCA on Properties of New Concrete[8]

Property	Range of Expected Changes from Similar Mixtures using Virgin Aggregates	
	Coarse RCA Only	Coarse and Fine RCA
Fresh Concrete Properties		
Water Demand	greater	much greater
Drying Shrinkage	20 to 50% more	70 to 100% more
Finishability	more difficult	more difficult
Mechanical Properties of Hardened Concrete		
Compressive Strength	5 to 24% less	15 to 40% less
Flexural Strength[a]	8% less	>8% less
Strength Variation	slightly greater	slightly greater
Modulus of Elasticity	10 to 33% less	25 to 40% less
Creep	30 to 60% greater	30 to 60% greater
Tensile Strength	10% less	10 to 20% less
Permeability	200 to 500% greater	200 to 500% greater
Specific Gravity	5 to 10% lower	5 to 10% lower

[a]From Hoerner et al., 2001. Assumes same water/cement ratio as conventional PCC.

[8]FHWA, 2007.

Other mix design considerations include:

- Crushing operations that are more effective at removing mortar from aggregate are desirable from the standpoint that the resulting RCA material performs more like a natural aggregate (Sturtevant et al., 2007).
- The higher mortar contents of RCA PCC mixes and the lower amounts of natural aggregate result in an increased coefficient of thermal expansion and a higher level of drying shrinkage. To reduce the potential for cracking due to drying shrinkage, shorter slab lengths (<18 feet [<5.5 m]) are used when using RCA PCC mixes (Sturtevant et al., 2007).
- Keep RCA material in a moistened state to help maintain uniformity of absorbed water during PCC production (FHWA, 2007).
- Where D-cracked pavement requires that the top size of RCA be reduced to 0.75 inches (19 mm), it is recommended that only short-jointed JPCP be constructed with this type of aggregate and that dowels be included at transverse joints (Hoerner et al., 2001). This reduces the potential for faulting and spalling at joints due to poorer aggregate interlock. As an alternative, supplement RCA with virgin aggregate with a larger maximum size.
- For applications involving ASR-infected RCA, employ proper ASR mitigation techniques, such as mandatory use of low alkali cement, use of Class F fly ash (25 to 30 percent) or ground granulated blast-furnace (GGBF) slag (40 to 50 percent), or blending of RCA with natural aggregates (HQUSACE, 2006; Sturtevant et al., 2007). Consider alkalis from deicing salts within the RCA.

6-3.4.3.2 Structural Design.

The structural design of PCC pavements using RCA is covered by UFC 3-260-02 and UFC 3-250-01. In addition to possible slab length reductions to prevent shrinkage cracking, the pavement designer must account for expected reductions in both the strength and modulus of elasticity of the RCA PCC. As seen in Table 6-3, these reductions depend significantly on whether only the coarse portion of RCA is included in the mix or both coarse and fine portions are included.

The lower effective modulus of the RCA reduces the modulus of elasticity for RCA PCC (Hoerner et al., 2001). The decreased compressive and flexural strengths of RCA PCC are primarily due to the following (Hoerner et al., 2001):

- Inherently weaker structure of the RCA (due to its cement paste–aggregate structure).
- Greater porosity of RCA PCC, due to the presence of the porous mortar component.

- Greater number of bonded interfaces in RCA PCC (i.e., between natural aggregate and the mortar [both old and new] and between the new and old mortars).
- Lower resistance of RCA concrete to mechanical action.

6-4 CONSTRUCTION.

This section describes the construction processes of each PCC recycling method. The following documents provide guide specifications covering the use of RCA in subbase and base layers or as aggregate in new PCC or lean concrete base mixtures:

- UFGS 32 11 20
- UFGS 32 11 23
- UFGS 32 11 36.13
- UFGS 32 13 14.13
- UFGS 32 13 13.06

TSPWG M 3-250-04.06-2 and 07-6 provide additional guidance concerning the use of PCC recycling methods when ASR is present in the existing PCC pavement.

6-4.1 Break/Crack-and-Seat and Overlay.

The major steps in performing rehabilitation via the break/crack-and-seat and overlay method are as follows (modified from Thompson, 1989):

1. Remove any existing HMA surfacing.
2. Isolate adjacent pavements.
3. Break/crack the existing PCC slabs.
4. Seat the fractured PCC pieces.
5. Apply special treatments.
6. Construct the HMA or PCC overlay (HMA leveling layer required for PCC overlays).

6-4.1.1 Step 1—Remove Existing HMA Surfacing.

In the case of breaking/cracking and seating of composite HMA/PCC pavements, remove the HMA surface layer for better efficiency and control of the slab fracturing process. The softer HMA layer may dissipate facture energy and slow the fracturing operation. Remove any HMA patches and any existing sealant and incompressible materials from joint reservoirs.

6-4.1.2 Step 2—Isolate Adjacent Pavement.

Prior to commencing with break/crack-and-seat operations, isolate adjacent pavement sections not subject to the fracturing work with full-depth saw cuts to prevent damage. All load-transfer devices (dowel bars, tie bars) between the pavement planned for fracturing and the adjacent pavement sections must be fully severed. At the same time, make transverse saw cuts at regular intervals along each fracture slab to ensure breakage of the reinforcing steel and disrupt continuity.

6-4.1.3 Step 3—PCC Slab Breaking/Cracking.

The purpose of slab breaking/cracking is to reduce existing PCC slabs into segments small enough to reduce movements caused by thermal stresses, yet segments are large enough to maintain structural stability (Hoerner et al., 2001). To achieve optimum success, the cracking must extend fully through the slab. In the case of JRCP, rupture/shear the reinforcing steel at the pavement breaks and debond the concrete from the steel. To ensure that JRCP slabs are broken to size, the typical breaking pattern is somewhat smaller (nominal 1.5 to 2 feet [0.5 to 0.6 m]) than the pattern for crack-and-seat (nominal 2 to 4 feet [0.6 to 1.2 m]) (Morian et al, 2006). In addition, a significantly higher level of energy is required with breaking compared to cracking.

Various types of equipment are available for breaking/cracking PCC pavements, including impact hammers, gravity-drop hammers (Figure 6-3), guillotine hammers (Figure 6-4), and pile hammers (Figure 6-5). As Table 6-4 shows, some pieces of equipment are more suited for breaking operations than cracking operations. The effectiveness and production rates of breaking/cracking operations are highly dependent upon the equipment type and pavement thickness and other factors, such as, concrete strength and quality, foundation support conditions, presence and amount of reinforcing steel, and slab temperature.

Figure 6-3 Single-Head Hydraulic Drop Hammer*

*Source: Arrowmaster.

Figure 6-4 Guillotine Hammer

Figure 6-5 Trailer-Mounted Pile Hammer*

*Source: Buncher, et al; TRB Circular No. E-C087.

Table 6-4 Summary of Equipment for Break/Crack-and-Seat Applications[9]

Type of Equipment	Operating Procedure	Manufacturer	Type of Concrete	Advantages/ Disadvantages
Gravity Drop Hammer (single-head)	Operates by lifting a mass mechanically or hydraulically, and then releasing the mass. The impact force is delivered to the pavement through an impact foot.	Arrow-Master 1350T	JPCP and wire mesh-reinforced JRCP	▪ Effective on JRCP ▪ Can develop unusual cracking patterns on JRCP ▪ Several passes required
Gravity Drop Hammer (multi-head)	Same as single-head gravity drop hammers, only multiple hammers equipped on machine	Antigo MHB Badger Breaker®	JPCP and wire mesh-reinforced JRCP	▪ Fairly high productivity ▪ More break-up at surface

Type of Equipment	Operating Procedure	Manufacturer	Type of Concrete	Advantages/ Disadvantages
Guillotine Hammer	JPCP and JRCP	Antigo 8600 Badger Breaker®, Antigo T8600 Badger Breaker®	JPCP and JRCP	▪ Versatile-effective with JPCP and JRCP ▪ Preferred by many agencies ▪ High productivity ▪ Covers full lane width ▪ Impacts adversely affected by uneven PCC surfaces
Impact Hammer	Hydraulic or pneumatic hammer commonly mounted on backhoes or skid steers	Brokk 250 Various skid steer models with hammer attachments	JPCP	▪ Low productivity ▪ Less effective on thicker PCC ▪ Typically used for localized removal of pavement
Pile Hammer (i.e., modified pile-driver)	Trailer-mounted diesel hammers		JRCP	▪ Covers full lane width ▪ Low productivity

[a]Breaking width = 8 feet (2.4 m)

Successful breaking/cracking largely depends on the equipment and the type and thickness of the pavement. The most common fracturing device, the guillotine hammer (Figure 6-4), typically requires one or two passes to break/crack the full width of a 12-ft or 12.5-ft (3.7- to 3.8-m) wide slab. Other breakers such as pile hammers and hydraulic drop hammers require multiple passes to deliver the grid pattern of strikes on the pavement. A test strip will define the desired breaking/cracking process (see the QC/QA section later in this chapter).

6-4.1.4 Step 4—Seat the Fractured PCC Pieces.

In the fourth step of the break/crack-and-seat technique, seat the PCC pieces with rolling equipment to ensure they are in contact with the supporting layer and achieve a relatively uniform grade for subsequent paving operations (Thompson, 1989; Freeman, 2002). During this process, identify unstable or soft areas (rocking or deflecting pieces) for appropriate action under Step 5.

[9]Hoerner et al, 2001; Antigo, 2009; Thompson, 2006.

Seating uses a heavy pneumatic-tire roller that “massages” each PCC piece into the foundation, while maintaining aggregate interlock (Hoerner et al., 2001). Steel-wheel static and vibratory rollers are generally not appropriate, as they tend to bridge over the high spots on the fractured PCC surface. Good results have been obtained with two passes of a 50-ton (45.4-metric ton) pneumatic roller for crack-and-seat operations and a minimum of five passes of the same equipment for break-and-seat operations. Employ additional passes for the latter since the slabs in the break-and-seat applications more thoroughly broken. For thin pavements on a weak foundation, use more passes (3 to 7) with a lighter roller (30 to 35 tons [27.2 to 31.8 metric tons]) (Buncher et al., 2008).

Avoid excessive rolling and rolling on wet subgrade. Excessive rolling breaks down the aggregate interlock between slab segments and overstress the foundational layers, leading to excessive deflection. Rolling in wet conditions causes non-uniform or excessive deformation of the fractured slabs. It can in turn result in some mixing of the subgrade and base, ultimately reducing the structural capacity of the final pavement.

6-4.1.5 Step 5—Apply Special Treatments.

The fifth step involves final preparations to the broken/cracked-and-seated pavement prior to placement of the HMA overlay. Repair or stabilize weak areas, punch-throughs, and shift-prone pieces detected during seating operations by surface patching or removal and replacement with HMA. Clear or sweep all sizeable loose debris atop the fractured pavement surface (Thompson, 1989). On projects designed to include a new edge drain system, install all system components (longitudinal edge drain, lateral outlets, etc.) as part of this step. Install underdrains at least two weeks prior to the cracking process.

6-4.1.6 Step 6—Construct HMA or PCC Overlay.

The sixth and final step is placement of the HMA or unbonded PCC overlay. Conventional construction procedures are used in this step, beginning with the application of a bituminous tack coat (0.07 to 0.10 gal/yd^2 [0.32 to 0.45 L/m^2] application rate) for use with an HMA overlay or an HMA leveling or bond breaker course (1 to 2 inches [25 to 50 mm] thick) for use with an unbonded PCC overlay.

To avoid incremental cracking of partial overlays carrying construction or other forms of traffic, it is recommended that the full HMA overlay thickness be placed promptly after application of the tack coat and the installation of edge drains (Thompson, 1989). For projects designed to include reinforcing fabric or a SAMI as part of the HMA overlay, apply the material at the specified location within the HMA paving layers.

6-4.2 Rubblization and Overlay.

The construction process for rubblization and overlay is similar to that of break/crack-and-seat and overlay. Installing a longitudinal edge drain system is the primary exceptions and fracturing the existing pavement into smaller sizes requires more time. In addition, the type of rolling equipment used to seat the rubblized layer may differ.

Rubblization and overlay consists of the following major steps (AI, 2000; Thompson, 2006; Buncher and Jones, 2006; Buncher et al. 2008):

1. Remove any existing asphalt surfacing.
2. Install drainage system (if specified).
3. Isolate adjacent pavement.
4. Rubblize PCC pavement.
5. Roll rubblized PCC.
6. Construct the HMA or PCC overlay.

6-4.2.1 Step 1—Remove Existing Asphalt Surfacing.

When rubblizing composite HMA/PCC pavements, first remove the HMA surfacing layers to allow application of the optimal amount of energy. Remove any HMA patches.

6-4.2.2 Step 2—Install Drainage System (If Specified).

On projects designed to include an edge drain system, install all system components including longitudinal edge drains and lateral outlets as part of this step. Ensure the installed drainage system is properly functioning for a minimum of 2 weeks prior to rubblization activities.

If no edge drains are specified, remove shoulders to the level of the PCC pavement base to allow water to drain from problem areas.

6-4.2.3 Step 3—Isolate Adjacent Pavement.

To prevent damage, isolate adjacent pavement sections that are not subject to the fracturing work with full depth saw cuts. Fully sever all load-transfer devices between the rubblized pavement and the adjacent pavement sections severed prior to rubblization.

6-4.2.4 Step 4—PCC Slab Rubblization.

Rubblization fractures existing PCC into small aggregate-sized pieces to eliminate the underlying slab integrity and movement that cause reflection cracking in HMA overlays. As with break/crack-and-seat operations, the cracking must extend fully through the slab and, in the case of JRCP and CRCP, debond the concrete from the reinforcing steel to achieve optimum success.

Rubblization is performed using two different types of equipment—the resonant pavement breaker (RPB) and the multi-head breaker (MHB). The RPB (Figure 6-6) typically applies a 2,000-lb (8,900-N) impact force at a frequency of 44 impacts/sec to the pavement surface through a breaking shoe attached to a massive steel beam (Hoerner et al., 2001). The vibrating beam acts like a “giant tuning fork,” shattering the pavement in narrow strips (6 to 12 inches [150 to 300 mm]) as the machine moves forward along the unfractured edge of the existing pavement (Buncher and Jones, 2006). The impact loads delivered through the shoe, induce diagonal cracks that extend the depth of the PCC slab, as illustrated in Figure 6-7.

The MHB (Figure 6-8) fractures concrete by lifting and dropping rows of steel hammers onto the pavement (Hoerner et al., 2001). The hammers are mounted laterally in pairs, with half the hammers in a forward row and the remainder diagonally offset in a rear row (Thompson, 2006). The MHB is a low-frequency, high-amplitude process (Buncher and Jones, 2006). It produces irregular-shaped PCC pieces, as compared to the highly angular, sheared pieces generated by the RPB.

Table 6-5 provides additional information about each type of equipment. The effectiveness and production rates are highly dependent upon the pavement type and thickness, and foundational support conditions and other factors, such as, concrete strength, presence and amount of reinforcing steel, and slab temperature.

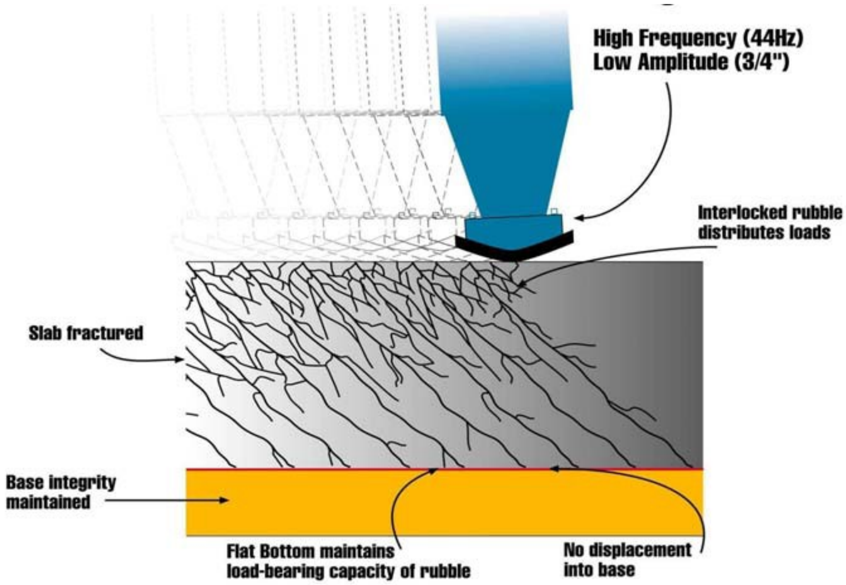
The equipment defines the rubblizing process. RPB rubblization starts at a free or unfractured edge and continues with successive passes until the equipment has moved transversely across the width of the pavement (Buncher and Jones, 2006).

MHB rubblization entails a single pass covering the width of the slab.

Figure 6-6 Rubblization Using RPB*

*Source: Buncher et al, 2008

Figure 6-7 Illustration of Rubblized PCC Using Resonant Breaking Process*



*Source: RMI, 2009.

Figure 6-8 Rubblization Using MHB*

*Source: Thompson, 2006.

Table 6-5 Summary of Pavement Rubblization Equipment[10]

Equipment	Manufacturer	Concrete Type	Advantages/ Disadvantages
Resonant Pavement Breaker (RPB)	RMI™	JPCP, JRCP, CRCP	▪ High degree of angular particle interlock due to diagonal (near 45° angle) fracturing. ▪ Potential for rutting by RPB tires on thin PCC/weak subgrade combinations
Multi-Head Breaker (MHB) (i.e., multi-head gravity drop hammer)	Antigo MHB Badger Breaker®	JPCP, JRCP, CRCP	▪ Equipment operates off of unfractured pavement, thereby minimizing operational problems associated with rubblizing pavements with thin PCC and/or weak foundation ▪ For slabs over 14 inches (350 mm) thick, pre-fracturing using guillotine hammer may be needed

On marginally stable and thin PCC pavements, the rubblization is not always effective. The deficient structural conditions cause problems with achieving full-depth fractures and result in overly large, disoriented PCC segments that make a very rough, uneven surface. In these instances, try a “modified rubblization” technique using the MHB with lowered drop heights and greater separations between impacts (achieved by increasing the equipment speed) (Buncher et al., 2008). Although this process produces larger pieces (nominal 8 to 18 inches [200 to 450 mm]) than specified with conventional rubblization, fracturing is more complete and the pieces remain better oriented for subsequent seating and overlay operations.

Pavements with thickened edges require adjustments to the RPB fracture energy or to the MHB hammer drop height to achieve the specified fracture size. Upon completion of the rubblization process, cut flush any exposed reinforcing steel at the surface or slightly below the surface, so that subsequent rolling operations are not adversely impacted.

6-4.2.5 Step 5—Roll Rubblized PCC.

In the fifth step, roll the rubblized layer to tighten the surface by seating loose particles and to smooth the surface in preparation for the HMA overlay (Buncher and Jones, 2006). During the rolling process, identify weak or unstable areas by observing significant deflection or settlement and repair by removing and replacing. Such

[10]Hoerner et al, 2001; Antigo, 2009, RMI, 2009; Buncher et al., 2008; Thompson, 2006.

detection is particularly important for MHB rubblization, since the rubblizing machine operates on the non-fractured portion of PCC pavement. With RPB rubblization, some level of detection is possible since the machine operates in a straddle position over the fractured and non-fractured portions of the pavement.

The rubblization equipment used dictates the rolling process. Start with the following standard rolling processes (roller weights as per Buncher and Jones [2006]):

6-4.2.5.1 RPB—Minimum of three passes with a vibratory steel-drum roller (minimum 10 tons [9.1 metric tons]) following completion of step 4.

6-4.2.5.2 MHB—Two passes with Z-grid roller (i.e., a vibratory steel-drum roller with Z-pattern grid on the drum face) (minimum 14 tons [12.7 metric tons]) and one pass with pneumatic-tired roller (25 tons [22.7 metric tons]), following completion of step 4. Immediately prior to HMA overlay, apply one pass with a vibratory steel-drum roller (10 tons [9.1 metric tons]).

Use of the Z-grid roller for MHB applications helps reduce the size of “flaky” particles (Thompson, 2006), leading to a tighter, smoother surface (Figure 6-9).

Figure 6-9 Z-Grid Roller Used on MHB Rubblized Pavement*

*Source: Thompson, 2006.

For the RPB process, apply a limited amount of water to the rubblized layer during the rolling process. The moisture lubricates particle surfaces and facilitates particle orientation (Buncher et al, 2008), leading to a tighter, more interlocked layer.

It is important to avoid excessive rolling and rolling in wet conditions. The former can destroy particle interlock and cause a weakening of the rubblized layer, while the latter can cause non-uniform or excessive deformation of the rubblized layer.

6-4.2.6 Step 6—Construct HMA or PCC Overlay.

The sixth and final step is placing the HMA or PCC overlay. In general, construction of the HMA overlay will proceed in the same manner as for a new or reconstructed HMA pavement structure. Two key exceptions are as follows:

6-4.2.6.1 Where marginally stable pavements are involved, such as a thin rubblized layer on a weak foundation, or there is difficulty in achieving a relatively smooth rubblized layer, consider applying a minimum 4-in (100-mm) thick aggregate leveling course (Buncher et al., 2008). Such a layer comprised of dense crushed aggregate, RAP, or RCA, provides a more stable and smoother platform for constructing the overlay.

6-4.2.6.2 A tack/prime coat on the rubblized layer is not needed (Buncher et al., 2008). The use or lack of use of a tack/prime coat has not been reported to impact pavement performance (Buncher et al, 2008), and its use increases project costs.

Depending on the overlay thickness and traffic control requirements, place the HMA overlay in two or three lifts (Buncher et al, 2008). Start with a minimum lift thickness of 3 inches (75 mm) for the first lift of HMA to increase the probability of achieving the in-place density requirements (Buncher et al., 2008). Windrow feeding the first lift of HMA is prohibited, due to the risk of disturbing/dislodging particles at the surface of the rubblized layer (Buncher et al., 2008).

If a PCC overlay is used, place a 1 to 2-in (25 to 50-mm) thick HMA leveling course or bond breaker on the rubblized layer.

6-4.3 RCA.

The construction process for RCA recycling involves the following seven steps:

1. Remove any existing asphalt surfacing.
2. Demolish existing PCC pavement.
3. Load and transport PCC material to crushing plant.
4. Crush PCC material.
5. Remove steel.
6. Size the aggregate.
7. Stockpile for use in aggregate subbase, base, lean concrete base, and/or PCC

The following sections review each step and discuss construction considerations for pavements using RCA materials.

6-4.3.1 Step 1—Remove Existing HMA Surface Layer.

Prior to breaking up the existing PCC pavement, remove any HMA patches or HMA surface layers (Hoerner et al., 2001). These materials slow the demolition process and contaminate the RCA material, which is especially important if using RCA in PCC or lean concrete. Although the amount of joint sealant material, if present, in the total volume of concrete rubble is very small, remove it as well.

6-4.3.2 Step 2—Demolish Existing PCC Pavement.

Pavement demolition breaks the PCC pavement into 18- to 24-in (450 to 600 mm) pieces small enough to lift and load into trucks (Hoerner et al., 2001). Typical equipment includes the excavator with ram hoe attachment shown in Figure 6-10. Table 6-6 lists the various types of equipment and their attributes.

Figure 6-10 Excavator W/Hydraulic Impact Hammer (Ram Hoe) Attachment*

*Source: Saeed et al., 2006.

Table 6-6 Summary of Equipment Used for Pavement Demolition[11]

Equipment	Description	Manufacturer	Pavement Type	Advantages/ Disadvantages
Drop Ball	A crane hoists and drops a heavy steel ball (2 to 7 tons [1.8 to 6.3 metric tons) onto pavement.		JPCP, JRCP, CRCP	▪ Not generally recommended because it breaks the pavement into excessively small pieces that are less salvageable

Equipment	Description	Manufacturer	Pavement Type	Advantages/ Disadvantages
Spring-Arm Whip Hammer	Uses a flexible arm made up of leaf springs that increase the velocity of the tool head and insulates the machine from reverse shock.		JPCP	▪ Covers full lane width through arc-like striking pattern ▪ Not particularly effective on thick PCC or on JRCP
Gravity Drop Hammer (single- head)	See Table 6-4	Arrow-Master 1350T	JPCP and wire mesh-reinforced JRCP	▪ Effective on JRCP ▪ Can develop unusual cracking patterns on JRCP ▪ Several passes required
RPB	See Construction-Rubblization section	RMI™ RB600	JPCP, JRCP, CRCP	▪ Rapid process but lower coverage rate (multiple pass) ▪ Good quality control
MHB (i.e., multi-head gravity drop hammer)	See Construction-Rubblization section	Antigo MHB Badger Breaker®	JPCP, JRCP, CRCP	▪ Relatively rapid process with higher coverage rate (single pass) ▪ Good quality control
Impact Hammer (i.e., ram hoe)	Hydraulic or pneumatic hammer commonly mounted on excavators	Brokk 250 Various models with hammer attachments	JPCP	▪ Limited power that can only be used with JPCP ▪ Typically used for localized removal of pavement
Impact Roller	Towed roller with heavy (19,000 to 29,000 lb. [8,597 to 13,122 kg]) cam-shaped drum that delivers impacts to pavement through its rotations	Impact Roller Technology (IRT) Impactor 2000/3000	JPCP and JRCP	▪ Rapid process with high coverage rate ▪ Quality control not as good
Pile Hammer (i.e., modified pile-driver)	See Table 6-4	???	JRCP	▪ Covers full lane width ▪ Low productivity

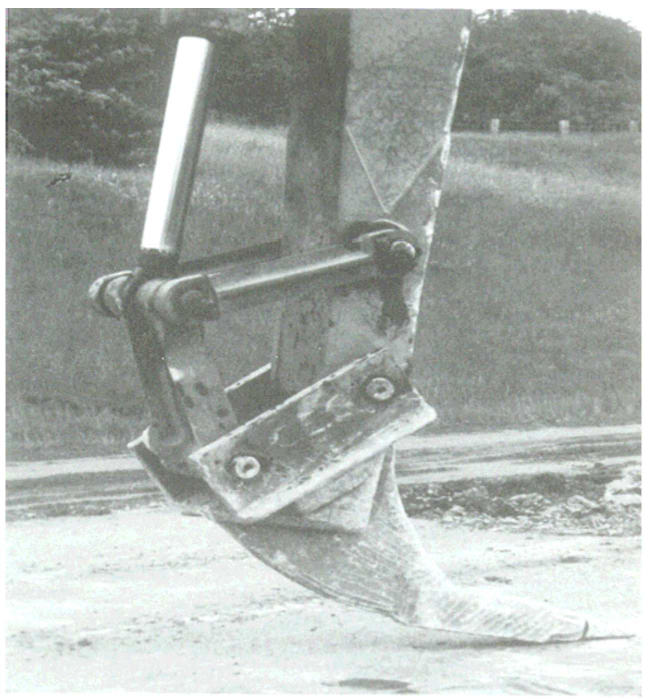
Besides the equipment itself, the most notable factors affecting production are slab thickness, concrete strength, quantity and type of steel reinforcement, and foundation support (Buncher, et al; TRB Circular No. E-C087.). Apply greater impact energy to thicker, stronger, and more heavily reinforced pavements as well as pavements resting on weaker foundations. Some control of the break energy is necessary to minimize damage to the subgrade and any underlying drainage features or utilities and to avoid pushing PCC pieces into the underlying granular layers (Buncher, et al; TRB Circular No. E-C087.). Keep disturbance of the foundation to a minimum.

[11] Hoerner et al., 2001; Antigo, 2009; IRT, 2009.

The breaking operation for CRCP pavement requires breaking rebar free of the concrete and removing prior to loading. Excavators with multi-processor attachments such as pulverizer jaws, shear jaws, and rakes effectively handle rebar as they can easily break concrete away from steel, rake steel from concrete rubble, and cut steel to size. A backhoe or front-end loader equipped with a rhino horn attachment (Figure 6-11) hooks and pulls the steel from the concrete rubble, but is less productive than equipment with multi-processor attachments.

Demolition operation generally severs mesh reinforcement (ACPA 1993). Break pieces too large for the primary crusher with multi-processor attachments or the rhino horn. Dowel bars and tie bars are typically removed during the crushing operation (Hoerner et al., 2001). However, during the demolition many of these pieces are loose and pop out.

Figure 6-11 Close-Up of Rhino Horn Attachment*



*Source: Buncher, et al; TRB Circular No. E-C087.

6-4.3.3 Step 3—Load and Transport PCC Material to Crushing Plant.

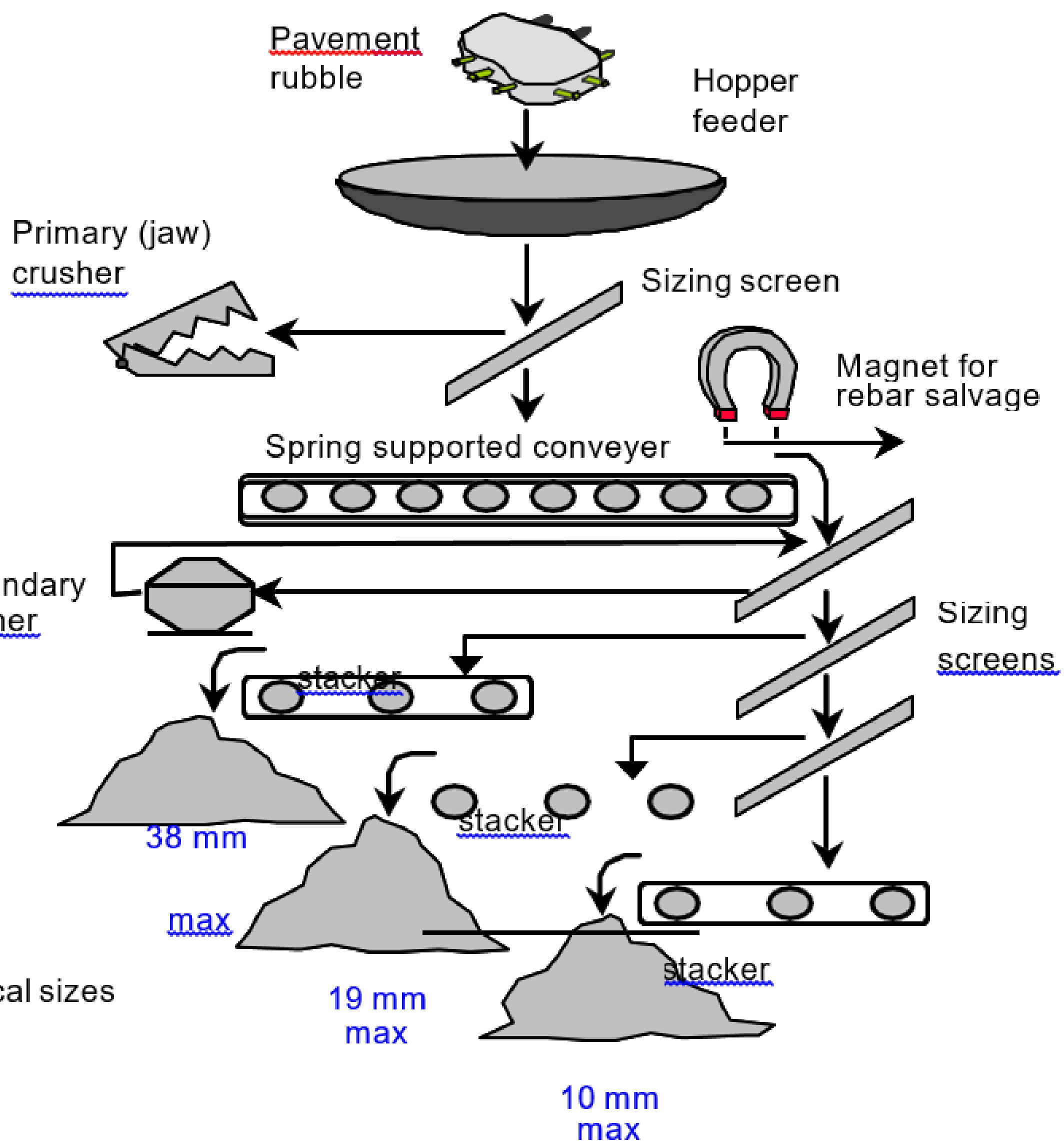
In off-site crushing and processing operations, load pavement rubble into dump trucks using an excavator with a shovel attachment or a front-end loader. Transport the material and stockpile at the crushing plant. During the loading operations, limit the amount of base material scooped up with the PCC rubble. Rubber-tired loaders are better at minimizing base disturbance than tracked loaders (Buncher, et al; TRB Circular No. E-C087.).

On-site crushing and processing operations negates the need for loading and hauling, as the excavators and/or front-end loaders perform the stockpiling work.

6-4.3.4 Steps 4 to7—Crush PCC Material, Remove Steel, Size Aggregate, and Stockpile for Use.

Process pavement rubble at the crushing plant to produce RCA. Figure 6-12 depicts the processes discussed in Steps 4 through 7 of RCA recycling (Hoerner et al., 2001).

Figure 6-12 Illustration of Operation Sequence at a PCC Recycling Plant*



*Source: Hoerner et al., 2001.

In the crushing step, load pavement rubble into a hopper that regulates the flow of the rubble onto the sizing screen (Hoerner et al., 2001). Divert pieces larger than 1 inch (25 mm) to a primary crusher that breaks the concrete away from the reinforcing steel and into pieces of a maximum size of 3 to 4 inches (75 to 100 mm). As the material transfers to a secondary crusher, an electromagnetic separator removes any remaining steel. The secondary crusher further breaks down the PCC material for screening to the desired gradation.

The two basic types of crushers are compression crushers and impact crushers (see Figure 6-13) (Buncher, et al; TRB Circular No. E-C087.). Compression crushers are either jaw or cone designs, and typically serve as the primary crusher. The jaw crusher (see Figure 6-14) provides a cyclic compression force to fracture the PCC while the cone crusher uses an eccentric rotating cone to do the same. The jaw crusher is often preferred as it can handle large PCC pieces. Impact crushers are either vertical or horizontal rotary designs and typically serve as the secondary crusher. These crushers use repeated blows from the rotary blow bars to reduce the size of concrete fragments (Buncher, et al; TRB Circular No. E-C087).

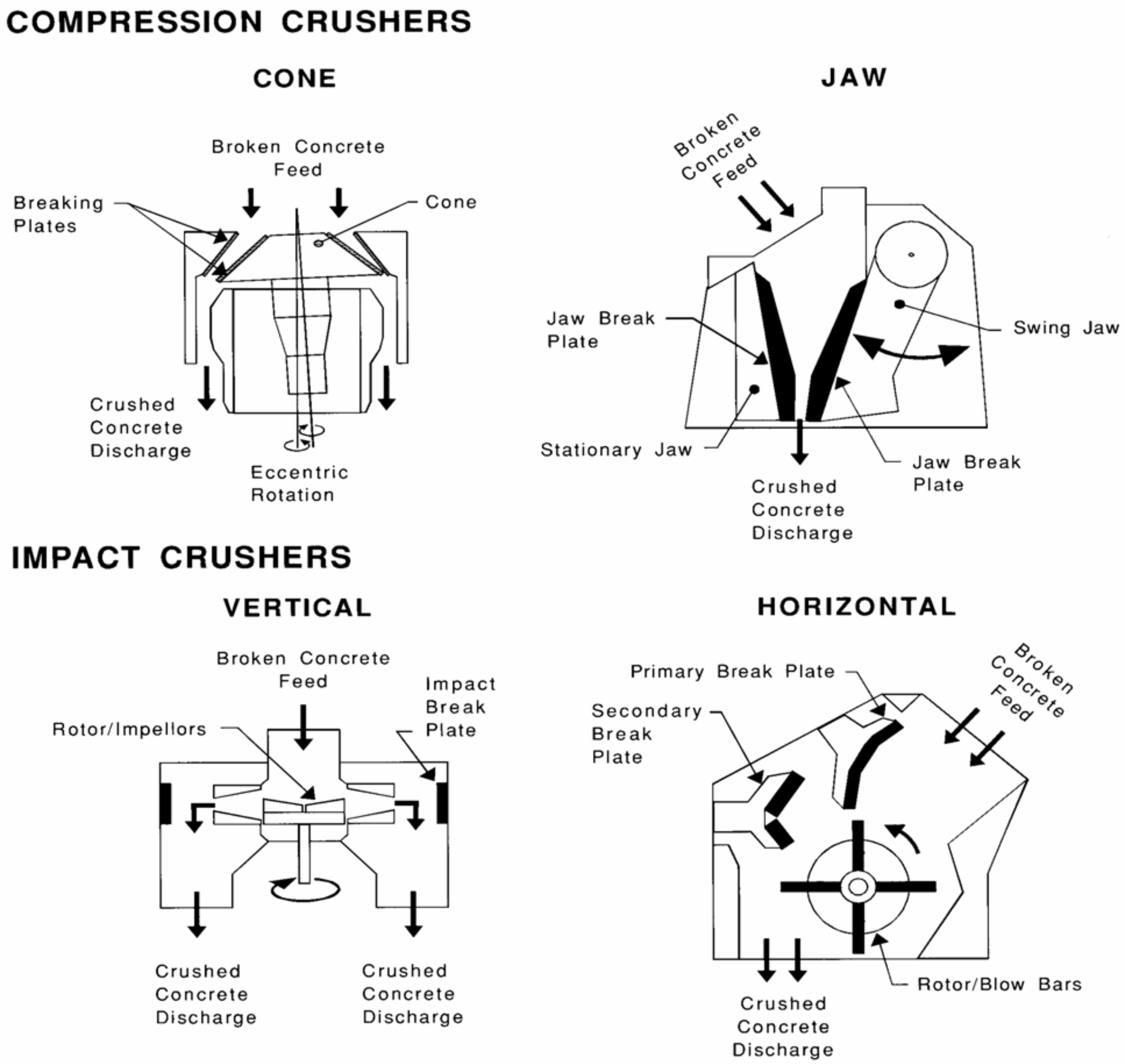
The primary crusher (e.g., jaw crusher) breaks the reinforcing steel from the concrete and reduces the concrete rubble to a maximum size of 3 to 4 inches (75 to 100 mm) (Buncher, et al; TRB Circular No. E-C087). The material processed by the primary crusher discharges onto a conveyor belt and moves to a screening dock. An electromagnetic separator removes virtually all steel present in the crushed material. Secondary crushing further breaks down the RCA for screening to the desired gradation. Pieces larger than the desired max size recirculate through a secondary cone crusher until all material passes through the screening sizes (Hoerner et al., 2001).

Typically, crushing operations yield about 75 percent coarse and 25 percent fine aggregate (Buncher, et al; TRB Circular No. E-C087). The ratio varies depending on the pavement type, broken concrete size, and the crushing plant design. When using RCA in new PCC, adjust the crushing operation to maximize the recovery of coarse aggregate, since the RCA fine aggregate is typically not used or is greatly limited in the new PCC. With a 0.75-inch (19-mm) top size, a coarse aggregate recovery of 55 to 60 percent is typical, while at a 1.5-inch (38-mm) top size, up to 80 percent or more can be recovered (Hoerner, et al., 2001).

6-4.3.5 Construction Considerations for Pavements Utilizing RCA.

Once processed, use the RCA material in an aggregate base or subbase layers or feed into a portable or central-plant mixer to produce lean concrete base material or new PCC. Listed below are several construction considerations for pavements that utilize RCA materials.

Figure 6-13 Types of Crushers used for PCC Recycling*



*Source: Buncher, et al; TRB Circular No. E-C087.

Figure 6-14 Jaw-Type Compression Crusher

6-4.3.5.1 RCA Unbound Base/Subbase.

To prevent segregation problems, use proper stockpiling and spreading techniques. Box spreaders or HMA pavers are preferred over motor graders (Saeed et al., 2006). Avoid excessive working of the RCA base or subbase material.

Ensure RCA base or subbase is in a saturated state to aid in compaction and migration of fines throughout the mix.

Suitable compaction equipment for RCA base and subbase layers includes static and vibratory steel-wheeled rollers and pneumatic-tire rollers.

6-4.3.5.2 RCA Used in New PCC or Lean Concrete Base.

Constructing PCC pavements containing RCA requires no special techniques or paving equipment (Hoerner et al., 2001). Use conventional mix plants, paving equipment, and normal paving and finishing practices.

The use of RCA in new PCC creates problems with mix workability, due to the high absorption capacity of the aggregate and the difficulty in maintaining a consistent and uniform saturated surface dry condition of the RCA. Overcome this problem by keeping stockpiles moist and by frequently testing aggregate for moisture content.

6-5 QUALITY CONTROL/QUALITY ASSURANCE.

6-5.1 Break/Crack-and-Seat.

6-5.1.1 Use a test strip to establish an acceptable breaking/cracking pattern for moderate to high-level projects. Examining the pavement and extracted cores resulting from varying degrees of energy and various strike patterns helps identify the procedure that best meets the design requirements.

6-5.1.2 Check crack patterns created by breaking/cracking operations at least twice a day by wetting the concrete surface with water and observing the appearance of cracks as the surface dries. If adjusting the crack pattern, consider coring to verify the full penetration of cracking.

6-5.1.3 Use NDT equipment to monitor the construction quality of cracking operations. Perform NDT testing on all broken-and-seated concrete to verify destruction of the bond between concrete and reinforcing steel in JRCP. Assure that the back-calculated modulus for broken JRCP (based on NDT performed directly on the fractured layer) is greater than 500,000 psi (3,448 MPa) and less than 1,000,000 psi (6,895 MPa) for 95 percent or more of the project area.

6-5.1.4 In the absence of NDT testing protocols conduct such testing every 500 to 1,000 feet (150 to 300 m) per paving lane with a typical width of 12 ft or 12.5 ft (3.7 or 3.8 m) wide directly on the fractured layer. Also, test that portion of the test strip in which the formal breaking/cracking pattern was established. Use test data to back calculate the elastic moduli for QC/QA purposes.

6-5.1.5 In the event that a break/crack-and-seat project includes an edge drain system, whether pre-existing or retrofit, visually inspect the system outlets for clogging issues. Properly clean and flush any segments with clogging problems.

6-5.2 Rubblization.

6-5.2.1 Use a test strip to optimize equipment operations and establish acceptable rubblizing and rolling practices on moderate to high-level projects. Use a test pit within the test strip to determine if a) the rubblizing procedure is producing pieces of the specified size, b) the fracturing is extending fully through the slab, and c) concrete is debonding from steel reinforcement. Use multiple test strips and test pits on projects with varying pavement structure conditions (Buncher et al., 2008).

6-5.2.2 Typical rubblization criteria are as follows:

- Resonate Pavement Breaker—Break slabs into pieces ranging from sand-sized to 6 inches. Ensure the majority of pieces are between 1 and 3 inches (25 and 75 mm) and ensure no individual piece exceeds 8 inches (200 mm). For JRCP, debond steel from concrete and leave in place and ensure no individual PCC piece exceeds 8 inches (200 mm).

- Multi-Head Breaker—Break slabs into pieces, with sizes in the top half of the slab generally ranging from sand-sized to 3 inches (75 mm) and sizes in the bottom half not exceeding 9 inches (225 mm). For reinforced PCC, debond steel from concrete and leave in place and ensure no individual PCC piece exceeds 9 inches (225 mm).
- Both RPB and MHB—Due to lack of edge support, the maximum size of PCC pieces below steel in reinforced PCC is 12 inches (300 mm).

6-5.2.3 The surface of the rubblized pavement is difficult to test and leads to wide levels of test variability. If the opportunity for NDT testing on a particular project exists, use the equipment on the pre-rubblized pavement to identify potential areas and localized weak spots that affect the rubblization process.

6-5.2.4 In the event that a rubblization project includes an edge drain system, visually inspect the system outlets for clogging. Properly clean and flush any segments with notable clogging problems to restore flow.

6-5.3 RCA Production.

QC/QA of the RCA production process focuses primarily on pavement demolition, the removal of steel and other contaminants, and the proper sizing and stockpiling of RCA material. Key considerations or measures to ensure the production of quality RCA for re-use in pavement structures are as follows:

- Evaluation and testing (ASTM C1260, ASTM C1293, ASTM C1567) of the old concrete is important in determining the severity of aggregate or mix problems, such as D-cracking and ASR.
- Careful monitoring of the pavement demolition operation to minimize the disturbance of the existing base and severely limit the amount of base material removed.
- Ensuring RCA consists of clean, sound, and durable crushed particles and is free of silt, clay, organic matter, AC, steel reinforcement, and other objectionable material (Saeed et al., 2006). While incidental amounts of AC, soil, base aggregates, or joint sealant are allowable for RCA used as unbound base or subbase, much tighter restrictions are necessary for RCA used in new PCC or lean concrete base.
- Monitoring crushing operations to ascertain that the yield of coarse aggregate is sufficient for the intended re-use application. Additionally, in the case of RCA PCC, monitor the amount of mortar retained on the coarse aggregate fraction to minimize the adverse effects of the mortar on PCC performance.
- To avoid segregation of the RCA material, use conveyor belts to create RCA stockpiles and carefully control stockpile heights.

6-5.4 RCA Re-Use.

QC/QA of re-used RCA material entails a variety of laboratory and field tests that are specific to the paving application. See the pertinent UFGS documents for further discussion of these tests. Key material and construction quality parameters are as follows:

6-5.4.1 RCA Base or Subbase.

- UFGS 32 11 20; RCA gradation, abrasion/wear, compaction/density (percent of laboratory maximum dry density), and thickness.
- UFGS 32 11 23: RCA gradation, wear, soundness, shape, angularity, density, and thickness.

6-5.4.2 RCA in Lean Concrete Base.

- UFGS 32 11 36.13: RCA gradation, slump, air content, temperature, compressive strength (7- and 28-day cylinders), and thickness (cores).

6-5.4.3 RCA in New PCC.

- UFGS 32 13 13.06: RCA gradation, workability and coarseness factors, unit weight, temperature, slump, air content, flexural strength (28- or 90-day values converted from compressive strength values on 7-day cylinders or from flexural strength values on 7-day beams), and thickness (cores).
- UFGS 32 13 14.13: RCA gradation, slump, air content, flexural strength (28- and 90-day beams), and thickness (cores).

This Page Intentionally Left Blank

APPENDIX A BEST PRACTICES

A-1 RESERVED FOR FUTURE USE.

This Page Intentionally Left Blank

APPENDIX B SUPPLEMENTAL RESOURCES

OTHER

A Pocket Guide to Asphalt Pavement Preservation
www.pavementpreservation.org/toolbox/links/PPGuide.pdf

Resonant Machines, Inc. (RMI)
www.resonantmachines.com.

This Page Intentionally Left Blank

APPENDIX C GLOSSARY

C-1 ACRONYMS

°C	degree(s) Celsius
°F	degree(s) Fahrenheit
AAPTP	Airfield Asphalt Pavement Technology Program
AASHTO	American Association of State Highway and Transportation Officials
AC	asphalt concrete
ACPA	American Concrete Pavement Association
ARRA	Asphalt Recycling and Reclaiming Association
ARRA	American Recovery and Reinvestment Act
ANG	Air National Guard
ASR	alkali silica reaction
ASTM	American Society for Testing and Materials
CBR	California bearing ratio
CCPR	cold central plant recycling
CIR	cold in-place recycling
CM	cold milling
COV	coefficient of variation
CRCP	continuously reinforced concrete pavement
DCP	dynamic cone penetrometer
DOT	Department of Transportation
EF	equivalency factor
Efs	design moduli for break/crack-and-seat layers
FAA	Federal Aviation Administration
FDR	full-depth reclamation

ft	foot
FHWA	Federal Highway Administration
FOD	foreign object debris
FWD	falling weight deflectometer
g	gram
gal	gallon
GCA	graded-crushed aggregate
GGBF	ground granulated blast furnace
GPR	ground penetrating radar
HFMS	high float medium setting
HMA	hot mix asphalt
HIR	hot in-place recycling
HR	hot recycling
HWD	heavy-weight deflectometer
in.	inch
IPRF	Innovative Pavement Research Foundation
JMF	job mix formula
JPCP	jointed plain concrete pavement
JRCP	jointed reinforced concrete pavement
kg	kilogram
km	kilometer
km/h	kilometer per hour
ksf	thousand square feet
L	liter
L&T	longitudinal and transverse (cracking)

lb	pound
lb/in^2	pound per square inch
LCCA	life cycle cost analysis
LED	layered elastic design
M&R	maintenance and rehabilitation
m	meter
MEPDG	Mechanistic Empirical Pavement Design Guide
MHB	multi-head breaker
mm	millimeter
MPa	megapascal
mph	mile per hour
MTV	material transfer vehicle
N/A	not applicable
NAPA	National Asphalt Pavement Association
NAVFAC	Naval Facilities Command
NCHRP	National Cooperative Highway Research Program
NDT	nondestructive deflection testing
NHI	National Highway Institute
NPW	net present worth
PCASE	Pavement-Transportation Computer Assisted Structural Engineering
PCC	Portland cement concrete
PCI	pavement condition index
PG	performance grade
PI	plasticity index
PIARC	World Road Association (originally “Permanent International Association of Road Congresses”)

PMS	Pavement Management System
POL	petroleum, oil, lubricants
psi	pound per square inch
QA	quality assurance
QC	quality control
RAP	reclaimed asphalt pavement
RAS	reclaimed asphalt shingle
RCA	recycled concrete aggregate
RPB	resonant pavement breaker
SAMI	stress absorbing membrane interlayer
SCI	structural condition Index
SS	slow-setting
TSMCX	Transportation Systems Center
TSPWG	Tri-Service Pavements Working Group
TSR	tensile strength ratio
UFC	Unified Facilities Criteria
UFGS	Unified Facility Guide Specification
U.S.	United States
USACE	United States Army Corps of Engineers
VFA	voids filled with asphalt
VMA	voids in mineral aggregates
VTM	voids total mix
yd	yard

C-2 TERMS

Additive Stabilization: Achieve stabilization by adding the proper percentages of additives to the soil. Select the type and determine the percentage of an additive depends on; the soil classification, amount of deleterious materials, such as, sulfates and organics, and the degree of soil quality improvement desired. Non-traditional additives, such as, polymer, fiber, lignin derivatives, enzymes, acids, etc. are addressed where appropriate. This UFC does not define specific criteria for all additives. Generally, smaller amounts of additives are required when only modifying soil properties, such as, gradation, workability, and plasticity. Obtaining significant strength and durability improvement requires greater quantities of additive. After mixing the additive with the soil at the optimum moisture content, spread and compact by conventional means.

Additives: Manufactured commercial products, when added to the soil in the proper quantities, improve some engineering characteristics of the soil such as strength, texture, workability, and plasticity are termed “traditional” additives and include materials such as lime, cement, fly ash, and asphalt emulsions. “Non-traditional” additives such as polymer emulsions, fiber, lignin derivatives, enzymes, acids, and other materials used to improve soil qualities are newer with little history of use. Additives addressed in this UFC are portland cement, lime, fly ash, bitumen, polymer emulsion, fiber, and select combinations of these.

Durability: Durability refers to the resistance of the soil to weathering, primarily by the action of water and abrasion after wet-dry and freezing and thawing cycles (ASTM D559 and D560).

Mechanical Stabilization: Mechanical stabilization mixes or blend soils of two or more gradations to obtain a material meeting the required specification. Soil blending may take place whenever convenient. Spread and compact the blended material to required densities at the optimum moisture content by conventional means. Compaction and fiber addition are also mechanical stabilization methods. Compaction consists of the mechanical rearrangement of soil particles into a denser configuration, typically resulting in increased strength and/or durability. The addition of fibers into a soil can mechanically stabilize the soil by creating interlock between particles.

Modification: Modification refers to the stabilization process that improves some material property of the soil, such as, the plasticity index (PI) but does not, by design, result in a significant increase in soil strength and durability.

Optimum Moisture Content: The optimum moisture content of soil is the water content, measured as a percentage by unit weight, that achieves the maximum dry unit weight for a given compactive effort. (See ASTM D1557 for further information.) A higher or lower moisture content produces a lower maximum dry unit weight after compaction.

Soils: Soils are naturally occurring materials used for the construction of all layers of concrete and asphalt pavements, except the surface, and is subject to classification tests (ASTM D2487) to provide a general concept of their engineering characteristics.

Stabilization: Stabilization is the process of blending and mixing materials with a soil to improve engineering properties of the soil. The process may include blending soils to achieve a desired gradation or mixing additives to alter the; chemistry, gradation, texture, plasticity, or water absorption or act as a binder for cementation of the soil. Stabilization significantly increases the strength and/or durability of the stabilized material.

Strength: In the context of this UFC, “strength” refers to the unconfined compressive tests measured using ASTM D1633.

APPENDIX D REFERENCES

FEDERAL LAW

https://www.govinfo.gov/app/details/PLAW-111publ5

Public Law 111-5, *American Recovery and Reinvestment Act (ARRA)*, 17 February 2009

AIRFIELD ASPHALT PAVEMENT TECHNOLOGY PROGRAM

http://www.eng.auburn.edu/research/centers/ncat/research/aaptp

Use of Reclaimed Asphalt Pavements and *Development of Guidelines for Rubblization,* July 2008

AIR FORCE

https://wbdg.org/ffc/dod/supplemental-technical-criteria

TSPWG 3-260-03.02-19, *Airfield Pavement Evaluation Standards and Procedures*

TSPWG M 3-250-04.06-2, *Alkali-Aggregate Reaction In Portland Cement Concrete (PCC) Airfield Pavements*

TSPWG 3-250-07.07-6, *Risk Assessment Procedure For Recycling Portland Cement Concrete (PCC) Suffering From Alkali-Silica Reaction (ASR) In Airfield Pavement Structures*

AMERICAN SOCIETY FOR TESTING AND MATERIALS (ASTM)

https://www.astm.org/

C136-06, *Standard Test method for Sieve Analysis of Fine and Coarse Aggregate*

D558, Method B, *Moisture-Density Relations of Soil-Cement Mixtures*

D559, Test Method B, *Wetting and Drying Compacted Soil-Cement Mixtures*

D698 or D1557, *Moisture Density Relations of Soils and Soil- Aggregate Mixtures*

D1557, *Moisture-Density Relations of Soils and Soil- Aggregate Mixtures*

D2041, *Standard Test Method for Theoretical Maximum Specific Gravity and Density of Asphalt Mixtures*

D2396, *Standard Test Methods for Powder-Mix Time of Poly (Vinyl Chloride) (PVC) Resins Using Torque Rheometer*

D3203, *Percent Air Voids in Compacted Dense and Open Bituminous Paving Mixtures*

D3633, *Compressive Strength of Molded Soil-Cement Cylinders*

D4123, *Indirect Tension Test for Resilient Modulus Bituminous Mixtures*

D4318, *Liquid Limit, Plastic Limit and Plasticity Index of Soils*

D4867, *Effect of Moisture on Asphalt Concrete Paving Mixtures*

D5101 Procedure B, *Unconfined Compressive Strength of Compacted Lime Mixtures*

D5297, *Standard Test Method for Drop Test of Loaded Containers by Free Fall*

D5505-14 (Reapproved 2020), *Standard Practice for Classifying Emulsified Recycling Agents*

D5821, *Standard Test Method for Determining the Percentage of Fractured Particles in Coarse Aggregate*

D6307, *Standard Test Method for Asphalt Content of Hot-Mix Asphalt by Ignition Method*

ASPHALT RECYCLING AND RECLAIMING ASSOCIATION

https://www.arra.org/

Basic Asphalt Recycling Manual, 1st Edition, 2001

Basic Asphalt Recycling Manual, 2nd Edition, 2015

“Full Depth Reclamation” (PowerPoint presentation)
https://cdn.ymaws.com/arra.site-ym.com/resource/resmgr/files/ARRA_Full_Depth_Reclamation_.pdf

FEDERAL HIGHWAY ADMINISTRATION

https://www.fhwa.dot.gov/resources/pubstats/

Pavement Recycling Guidelines for State and Local Government, 1997.

FHWA National Highway Institute (NHI):

4R Participant’s Manual (Course 131008)

HMA Pavement Evaluation and Rehabilitation Reference Manual (Course 131063)

PCC Pavement Evaluation and Rehabilitation Reference Manual (Course 131062)

Asphalt Pavement Recycling Technologies Manual (Course 131050)

FEDERAL AVIATION ADMINISTRATION (FAA)

https://www.faa.gov/airports/engineering/engineering_briefs/

Engineering Brief No. 66, *Rubblized Portland Cement Concrete Base Course*

INNOVATIVE PAVEMENT RESEARCH FOUNDATION (IPRF)

http://www.iprf.org/

Evaluation, Design, and Construction Techniques for Airfield Concrete Pavement Used as Recycled Material for Base, 2006

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM (NCHRP)

http://www.trb.org/NCHRP/NCHRP.aspx

Project 1-37A Report, *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures*

Project 4-31, NCHRP 452, *Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method—Technician's Manual*

Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method: Guidelines

Report 567, *Volumetric Requirements for Superpave Mix Design*

NATIONAL HIGHWAY INSTITUTE

https://www.nhi.fhwa.dot.gov/

NHI Course No. 131063, *HMA Pavement Evaluation and Rehabilitation Reference Manual*

NHI Course No. 131062, *PCC Pavement Evaluation and Rehabilitation Reference Manual*

Asphalt Pavement Recycling Technologies-Participants Workbook, NHI Course No. 131050, Bozkurt, D., M. Grogg, and S. Seeds, 2002

Superpave Mix Design
www.pavementinteractive.org.

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY (NIST)

www.wbdg.org/resources/lcca.php

Whole Building Design Guide (WBDG) LCCA

PERMANENT INTERNATIONAL ASSOCIATION OF ROAD CONGRESSES (PIARC)

https://www.piarc.org/en/

2003 Road Safety Manual

Proceedings of 22nd World Road Congress, Durban, South Africa, PIARC Committee C7/8, *Pavement Recycling*, 2003

TRANSPORTATION RESEARCH BOARD (TRB)

Circular No. E-C087, "Rubblization of Portland Cement Concrete Pavements," January 2006

UNIFIED FACILITIES CRITERIA

https://www.wbdg.org/ffc/dod/unified-facilities-criteria-ufc

UFC 3-250-01, *Pavement Design for Roads and Parking Areas*

UFC 3-250-04, *Standard Practice for Concrete Pavements*

UFC 3-250-07, *Standard Practice for Pavement Recycling*

UFC 3-260-02, *Pavement Design for Airfields*

UFC 3-260-03, *Airfield Pavement Evaluation*

UFC 3-260-16, *O&M Manual: Standard Practice for Airfield Pavement Condition Surveys*

UFC 3-270-08, *Pavement Maintenance Management*

UNIFIED FACILTIES GUIDE SPECIFICATIONS

https://www.wbdg.org/ffc/dod/unified-facilities-guide-specifications-ufgs

UFGS 32 01 13 64, *Bituminous Pavement Liquid Rejuvenating*

UFGS 32 01 16.70, *Cold-Mix Reused Asphalt Paving*

UFGS 32 01 16.71, *Cold Milling Asphalt Paving*

UFGS 32 01 16.74, *In-Place Hot Reused Asphalt Paving*

UFGS 32 01 16.75, *Heater Scarifying of Asphalt Paving*

UFGS 32 11 16.16, *[Base Course for Rigid] and [Subbase Course for Flexible][Subbase Course for Pervious] Paving*

UFGS 32 11 20, *[Base Course for Rigid] [and] [Subbases for Flexible] Paving*

UFGS 32 11 23, *Aggregate Base Course*

UFGS 32 11 26.19, *Bituminous Stabilized Base and Subbase Courses*

UFGS 32 11 36.13, *Lean Concrete Base Course*

UFGS 32 12 15.13, *Asphalt Paving for Airfields*

UFGS 32 12 16.16, *Road-Mix Asphalt Paving*

UFGS 32 13 13.06, *Portland Cement Concrete Pavement for Roads and Site Facilities*

UFGS 32 13 14.13, *Concrete Paving for Airfields and Other Heavy-Duty Pavements*

USACE ENGINEER RESEARCH AND DEVELOPMENT CENTER

https://www.erdc.usace.army.mil/

Pavement- Transportation Computer Assisted Structural Engineering (PCASE), User Manual, Version 2.08

Users Guide: Cracking and Seating of PCC Pavements

WORLD ROAD ASSOCIATION (PIARC)

https://www.piarc.org/en/

2003 Road Safety Manual

Proceedings of 22nd World Road Congress, Durban, South Africa, PIARC Committee C7/8, *Pavement Recycling*, 2003

OTHER

Antigo, 2009, Antigo Construction, Inc. (ACI)
www.antigoconstruction.com

Bardesi, A., *Cold Recycling With Emulsion, A Great Technique for Rehabilitating Pavements*, Repsol Asphaltic Products, August, 2000, Madrid, Spain, 15 pp (in Spanish).

Buncher, M., G. Fitts, T. Scullion, and R. McQueen, 2008. *Development of Guidelines for Rubblization*, AAPTP Project 04-01.

Ceylan, H., R. Mathews, T. Kota, K. Gopalakrishnan, and B.J. Coree. 2005. "Rehabilitation of Concrete Pavements Utilizing Rubblization and Crack and Seat Methods," Final Report for IHRB Project TR-473, Iowa Department of Transportation, Ames, Iowa.

Emery, J., *Practical Experience with In-Place Asphalt Recycling, CIR – FDR – HIR*, ARRA 2007 Semi-Annual Meeting, Las Vegas, October 2007.

Freeman, T.E. 2002. "Evaluation of Concrete Slab Fracturing Techniques in Mitigating Reflective Cracking Through Asphalt Overlays," VTRC 03-R3 Final Report, Charlottesville, Virginia.

Hoerner, T. E., K. D. Smith, H. T. Yu, D. G. Peshkin, and M. J. Wade. 2001. PCC Pavement Evaluation and Rehabilitation. Reference Manual, NHI Course 131062. National Highway Institute, Arlington, VA.

Huang, H. and T.D. White. 1995. "Concrete Pavement Crack and Seat Performance and Overlay Design," Final Report for Joint Highway Research Project No. C-36-52P, Purdue University.

Impact Roller Technology (IRT)
www.impactor2000.com/pavement.html

Kandhal, Prithvi S. and Rajib Mallick, "Pavement Recycling Guidelines for State and Local Governments Participant's Reference Book," Report No. FHWA-SA-98-042, Federal Highway Administration (FHWA) [Washington, D.C.], 1997
https://www.fhwa.dot.gov/pavement/recycling/98042/

Ken, H., *Cold In-Place Recycling in Tampa*, Asphalt Recycling & Reclaimed Association, ARRA, 2008 Semi-Annual Meeting, November, 2008, 64 pp.

Lee, H.D. and Kim, Y, *Validation of the Mix Design Process for Cold In-Place Rehabilitation Using Foamed Asphalt*, Final Report, IHRB Project TR 474, Research Sponsored by Iowa Highway Research Board, 2007, 261 pp.

Morian, D.A., S. Sadasivam, J.W. Mack, and S.M. Stoffels. 2006. "Pavement Rehabilitation Using Fractured Concrete Pavement Techniques," In *ASCE Airfield and Highway Pavements: Meeting Today's Challenges with Emerging Technologies*, American Society of Civil Engineers (ASCE), Reston, Virginia.

Mueller, S.R. 2008. "Sustainability Issues: Materials, Energy, and the Environment," FHWA presentation made at 2008 California Pavement Preservation Conference.

Reference Manual of Pavement Preservation Treatments, 2005, Hajek, J. Hein, D.K. and Olidis, C., Applied Research Associates, Inc., Toronto, Ontario

Saeed, A., M.I. Hammons, D.R. Feldman, and T. Poole. 2006. "Evaluation, Design, and Construction Techniques for Airfield Concrete Pavement Used as Recycled Material for Base," Report No. IPRF-01-G-002-03-5, Innovative Pavement Research Foundation (IPRF), Skokie, Illinois.

Shuler, S. and Schmidt, C., Performance Evaluation of Various HMA Rehabilitation Strategies, Colorado State University, Final Report CDOT-2008-9, Sponsored by Colorado Department of Transportation, December, 2008, 140 pp.

Sturtevant, J.R., D.L. Gress, and M.B. Snyder. 2007. "Performance of Rigid Pavements Containing Recycled Concrete Aggregates-2006 Update," Paper Presented at 86th Annual Meeting of the Transportation Research Board (TRB), Washington, D.C.

Katie Zimmerman, Applied Pavement Technology, "Integration of Pavement Management and Preservation"

https://www.pavementpreservation.org/wp-content/uploads/presentations/Integration%20of%20Pavement%20Management%20and%20Preservation.pdf