CHAPTER 8. END-OF-LIFE CONSIDERATIONS

Introduction

Chapter 2 defines pavement end-of-life as the "final disposition and subsequent reuse, processing, or recycling of any portion of a pavement system that has reached the end of its useful life." When the pavement reaches its end-of-life, it may: 1) remain in place and be reused as part of the supporting structure for a new pavement, 2) be recycled, or 3) be removed and landfilled. Each of these activities has economic and environmental costs that should be considered (e.g., consumption of raw materials, energy input, emissions), just as there are economic and environmental costs to the other more highly visible portions of the pavement life cycle (i.e., production of pavement materials, initial pavement construction, and the use phase). Therefore, end-of-life activities can impact sustainability factors such as waste generation and disposition, air and water quality, and materials use, and must be considered in a comprehensive LCA.

Asphalt Pavement End-of-Life (EOL) Options:

- ✓ *Central Plant Recycling (hot and cold)*
- ✓ *Full-Depth Reclamation*
- ✓ *Landfilling*

Concrete Pavement End-of-Life (EOL) Options:

- ✓ *Recycling*
- ✓ *Reuse*
- ✓ *Landfilling*

This chapter introduces the methods and definitions associated with the EOL phase, drawing from ISO standards and practices and from case studies in the literature. Various EOL considerations for asphalt and concrete pavements and the associated challenges to quantify the EOL contribution in the pavement life cycle are also presented.

Recycling and Reuse Statistics of Pavements

As quality aggregate sources are depleted, there is growing importance given to incorporating RCWMs even more aggressively in new and rehabilitated pavements. An ideal goal would be to use recycled materials to produce a long-lived, well-performing pavement, and then at the end of its life be able to use those materials again into a new pavement, effectively achieving a zero waste highway construction stream. This would not only produce distinct cost advantages, but it would also provide significant reductions in energy consumption and GHG emissions, eliminating the need for landfill disposal.

Asphalt and concrete pavements are commonly recycled and reused construction materials (EPA 2009), with an overall description of reclaimed asphalt and concrete pavements and their reuse in highway applications provided by Chesner, Collins, and MacKay (1998). According to industry data, in 2012 less than 1 percent of RAP was sent to landfills, with 68.3 million tons (62.0 million mt) of RAP being used in new asphalt concrete mixtures. This is a 22 percent increase in the use of RAP in 2012 compared to 2009 (Hansen and Copeland 2013). The total amount of recycled concrete used in the U.S. is estimated to be 140 million tons (127 million mt) in 2014, including materials recycled from both pavements and other sources (CDRA 2014). These recycled materials can be used back in new asphalt or concrete mixtures or used as aggregates in base layers, or even in a number of other uses such as fill, riprap, and ballast. A distribution of the use of recycled asphalt and concrete materials is shown in figure 8-1.

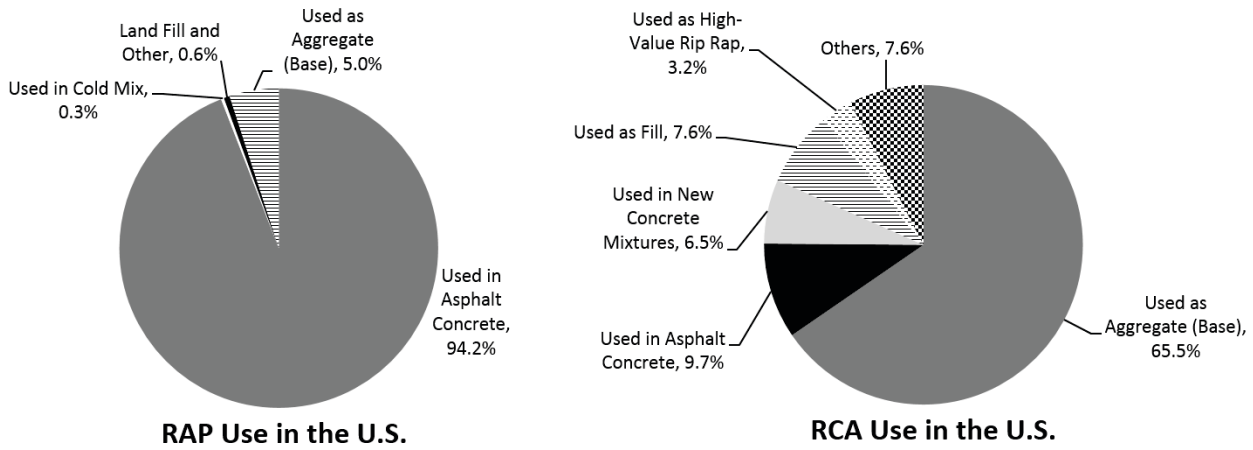


Figure 8-1. Recycling and reuse statistics of asphalt and concrete materials (data compiled from Hansen and Copeland (2013) for RAP and Wilburn and Goonan (1998) and USGS (2000) for RCA).

Economic and Environmental Considerations of EOL Options

Using materials from a pavement at the end of its life is accepted as one of the most effective ways to improve pavement sustainability. However, a comprehensive economic and environmental analysis for recycling and reusing pavement materials must be done in order to fully quantify the effects of the various EOL options. For example, pavement recycling is highly affected by material transportation costs as compared to the cost of new virgin material delivered to the construction site (Horvath 2004).

Different options are available for recycling asphalt and concrete pavement materials. However, in order to assess realistic benefits of recycling, all recycling options and their associated costs should be evaluated. Figure 8-2 illustrates a detailed characterization of the environmental cost determinants, including the potential factors contributing to the cost of pavement recycling and environmental implications. The important factors are technology (on site or off site), disposal costs (if the pavement is going to be landfilled), transportation, and the quality of the recycled material. These are expanded upon below:

- *Technology* – This can be an important driving determinant for on-site and off-site recycling. This includes the construction equipment used for on-site recycling, such as cold in-place recycling, hot in-place recycling, and full-depth reclamation. On the other hand, if the pavement is recycled in a central plant, the environmental costs include demolition at the job site, crushing, screening, and stockpiling at the plant.
- *Disposal costs* – If the recycled pavement materials are disposed of at a landfill, the total disposal costs include demolition, transportation, and landfill tipping fees. According to Horvath (2004), landfill tipping fees can be $10 to $70 per ton ($11 to $78 per mt) of material, varying widely even over relatively small distances. A very important consideration for landfill disposal is the diminishing number of landfills.

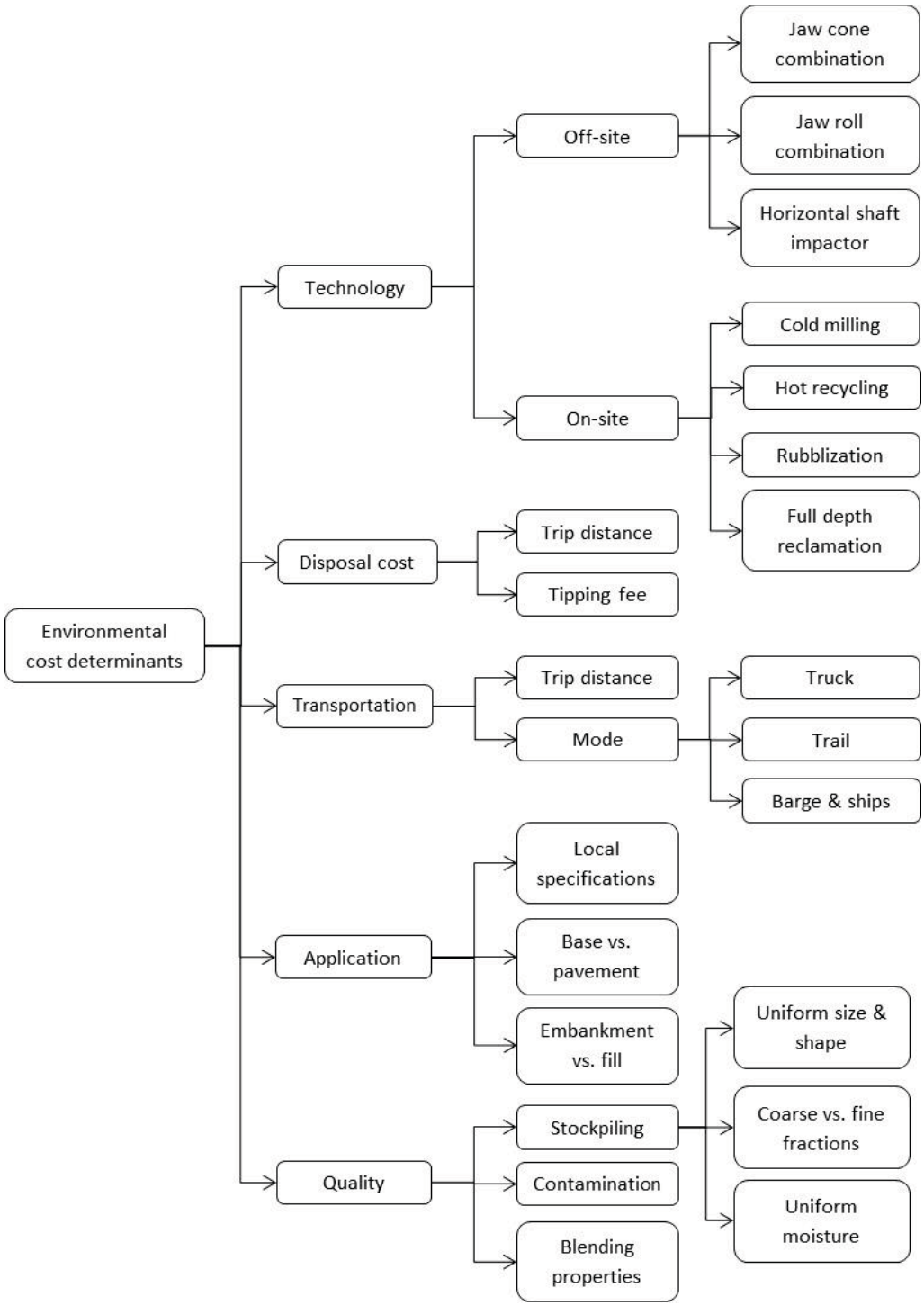


Figure 8-2. Environmental cost determinants for pavement EOL considerations (adapted from Horvath 2004).

- *Transportation* – For recycled materials, transportation can have a major impact on the environmental burden. This results from transportation from job site to a landfill, from job site to a central plant for processing, or from the plant back to the job site.
- *Application* – Recycled pavement can be reused in pavements as base layers or surface layers, in addition to embankments, fills, and scores of other potential uses.
- *Quality* – The original quality of recycled pavement, its process, storage, and local specifications determine its final application. The quality requirements of using recycled pavement can be different for asphalt and concrete pavements, including surface and base layers. The potential contamination risk of recycled pavement can also limit its use and application.

A Strategy for Optimizing the Use of Recycled Materials

Chapter 3 discusses approaches for highest use of recycled materials in pavements. While experience shows that using recycled aggregate in a base can be cost effective, other costs must be considered including material handling, preparation for reuse, and transportation. Transportation is usually a relevant aspect from both a cost and environmental perspective; in general, on-site recycling or transporting recycled materials within a small radius is feasible. However, it may not be optimal to transport recycled materials over a long distance when a local primary source or sometimes subprime materials are available. An LCA provides the means to determine the optimized distance for transporting recycled materials compared to using local virgin materials to ensure efficiency and sustainability. Hence, applying all four concepts of sustainability assessment (functional performance, LCCA, LCA and rating systems, as described in chapter 10) would provide a quantitative measure of the optimized use of recycled materials. It should be noted that the highest use is usually context defined, and may change over time as technologies continue to evolve and alternative recycling material implementation methods are developed.

Closed-Loop or Zero-Waste Thinking for Pavement Systems

There is a growing interest among infrastructure professionals, such as urban planners, architects, and engineers, in the application of *zero-waste* or *closed-loop* concepts. In closed-loop systems, a high proportion of energy and materials will need to be provided from reused waste and water from wastewater. This can be realized by transforming existing urban development design and construction philosophy to create or upgrade recycling infrastructure. Such thinking is encouraged for application at small scales of urban development such as planning for city districts. For instance, one of the critical planning considerations for more sustainable city districts is to have recycling facilities in close proximity to avoid transporting materials for longer distances. For pavements, closed-loop or zero-waste thinking will promote standardization of the recycling processes and improve the overall quality, the result of which will improve the overall sustainability of pavements.

Closed-loop system thinking can deliver a series of advantages (compiled from Lehmann 2013):

- Avoids waste being generated in the first place.
- Creates closed-loop economies with additional employment opportunities in recycling industries.
- Transforms industries toward a better use of resources, cleaner production processes, and, importantly, extends the initial producer's responsibility.

- Delivers economic benefits through more efficient use of resources.
- Conserves landfill space and reduces the need for new landfill spaces.

It is very important to place some level of responsibility of the pavement's future on the initial producer (this can be the contractor or the owner/agency) instead of the last owner only. This will lead to practices where an increasing number of contractors or agencies consider future recovery and processing of the materials at the end of its useful life (Lehmann 2013). Economic incentives in the last decades have been the major driver of the increased use of recycled pavement and recycled materials or co-products (for example, shingles, slag, fly ash, tire rubber) from other industries. A detailed discussion of some of these materials is given in chapter 3.

It is critical in a closed-loop pavement system to quantify and measure the benefits to incentivize contactors and owner/agencies. Some of the relevant questions that need to be addressed to generate robust, realistic, and scalable assessment of pavement recycling include (Horvath 2004):

- How much environmental "credit or burden" should be given to recycled materials (i.e., what is the environmental impact of recycled materials)?
- Where should these credits be counted?
- How should transportation be counted in the model?
- Which life-cycle stage should it be assigned to?

LCA deals with these issue through allocation rules. Allocation is defined by ISO 14044 (ISO 2006) as the partitioning the input or output flows of a process or a product system between the product system and one or more product systems. Several allocation rules and procedures are applicable to reuse and recycling.

ISO 14044 defines a closed loop as being when a material from a product is recycled into the same product system, while defining the open loop as being when a material from one product system is recycled in a different product system (ISO 2006). As far as the allocation procedures, similar categorization exists for both open- and closed-product systems. Closed-loop allocation procedures apply to materials from a product recycled into a material of the same product system (closed loop) or to a material in a different product system (open loop) without inherent property changes. On the other hand, open-loop allocation procedures apply to only open-loop product systems where the material is recycled into other product systems with substantial change in the inherent properties.

According to another definition of open- and closed-loop recycling and allocation procedures by Boguski, Hunt, and Franklin (1994), open-loop recycling can be defined as recycling of a post-consumer product into another useful product that will be disposed of or recycled only for limited number of cycles due to material degradation. An example for this is the recycling of old newspapers to the cereal box system where the cereal boxes are ultimately discarded. Boguski, Hunt, and Franklin (1994) go on to define closed-loop recycling as recycling of a material from a virgin product into another product that can be recycled over and over, theoretically endlessly. For example, used aluminum containers can be recycled into containers or other aluminum products virtually to no end. The key difference in the recycling definitions is the degradation of the recycled material, which can limit the number of recycling cycles. If the properties of the

recycled product are not degrading, it can be recycled endlessly in the same or different product system (closed-loop recycling).

There is no trivial answer to the question of allocation for pavement materials. When pavement materials (asphalt concrete and concrete) are recycled, they can be reused in another pavement application. The two critical questions that need to be answered to determine the type of recycling definition applies to RAP and RCA: Do the properties of pavement materials degrade, and is there infrastructure to collect RAP and RCA? The answer to both of these questions is generally yes. However, there is always some measurable value left in the recycled pavement that can make it reusable multiple times. Therefore, pavement recycling is more analogous to closed-loop recycling due to its potential for being reused many times.

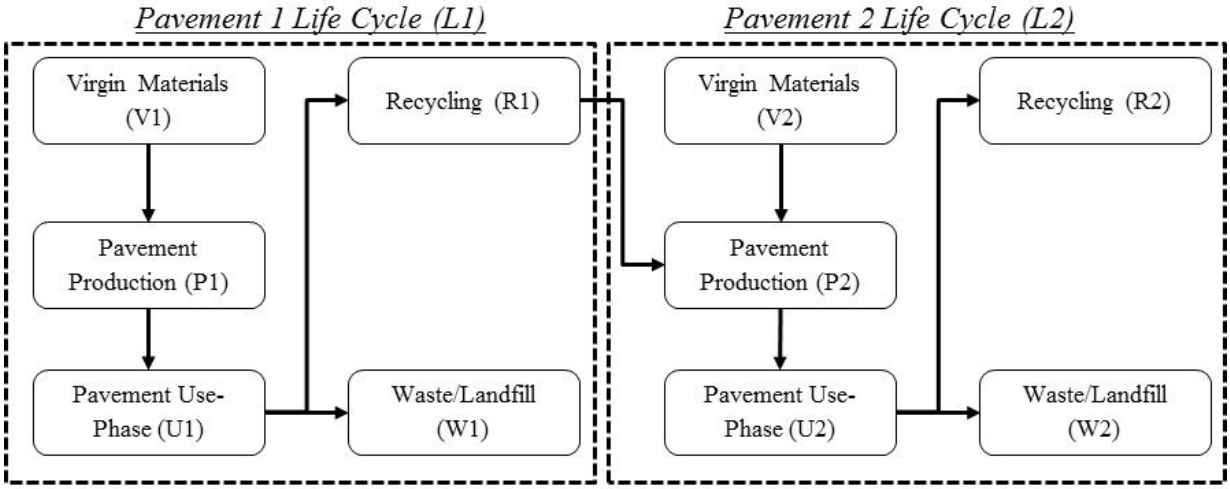
A comprehensive definition of a different class of allocation rules for different industrial products is discussed by Boguski, Hunt, and Franklin (1994); Ekvall and Tillman (1997); Ekvall and Finnveden (2001); and Nicholson et al. (2009). A schematic description of the three allocation rules is shown in figure 8-3.

The most commonly used allocation method is the cut-off and substitution method for pavements (Horvath 2004; Nicholson et al. 2009; Huang, Spray, and Parry 2013). According to the cut-off method, each product is assigned only the burdens directly associated with it; in other words, all benefits of recycling are given to using recycled materials. The cut-off method is usually applied when a "waste" material (negative economic value) turns into a product (positive economic value). The life of the recycled materials starts with its removal from the old pavement followed by transportation to a depository place for processing and transportation to a job site to be reused. All benefits are given to the pavement using the recycled materials by reduction in the use of virgin materials without any *a priori* knowledge about the rate of recycling at the end of its life.

Allocation Issues Related to Recycling at the End-of-Life of Pavements

Recycled materials can be produced during pavement rehabilitation (for example when a top layer of asphalt concrete is milled before adding a new layer). However, most recycled material is produced during a full pavement reconstruction or possibly from the demolition of some other civil structures (e.g., recycled asphalt shingles and crushed concrete from buildings). When the material is recycled, a system boundary is crossed from one pavement life cycle to another. For example, RAP can be recycled back into new asphalt concrete where it can function as aggregate and also as a source of binder, reducing the need for virgin aggregate and asphalt binder. Another example is recycling crushed concrete for use as aggregate in the base or as an aggregate in a new concrete pavement. Hence, it is important to determine the allocation of processing and handling to the producing and receiving life cycles.

Several approaches have been and are being investigated to ensure that the "benefits" of using secondary materials or fuel resources are properly reflected in LCA for pavements. Most EPD approaches use a strict and conservative approach in that all processes and transportation needed to reuse or recycle the material are assigned to the product utilizing the recycled content. The allocation of environmental impact to the new application is cut off from the previous use at the start of the processes and transport to prepare it for use in the new application.



Cut-off Method:

Benefits and burdens of recycling to downstream (Pavement 2 is responsible for the impacts of R1 and no credit for pavement producing recyclable material)

50/50 Method:

Half impact to using recycled pavement life cycle (L2) and half impact to producing recycled materials (L1)

Substitution Method:

The first pavement producing recycled product (R1) is given full benefits.

V1: Primary material burden for pavement L1

V2: Primary material burden for pavement L2 (V1 < V2 due to using recycling content from L1)

R1: Recycling burden

W1: Waste management burden

P1, P2: Burden associated with production (plant + construction) of each pavement

U1, U2: Burden associated with use-phase of each pavement

Note: Impacts associated with one product only should be allocated to that product such as P1, P2, U1, and U2 (Ekvall 1998).

Figure 8-3. An illustration of EOL allocation rules potentially applicable for pavements (cut-off method, 50/50 method, and substitution method).

The substitution method, on the other hand, gives new pavement full benefits of recycling at EOL. In other words, since the pavement is recyclable at the end of its life, it will replace the use of virgin material in another pavement. Therefore, the pavement under study can be rewarded *a priori* if the rate of recycling is known at present time. This approach requires appropriate accounting rules for the percentages of recycled content used in the pavement itself and the recycling at EOL. Double counting of benefits should be prevented. Another important consideration is the material to be substituted, whether it is virgin aggregate, binder, or a combination, and to what extent.

The cut-off method and the substitution method are the two extremes of allocation rules. A third option is the 50/50 method in which one-half of the benefits of recycling are allocated to the pavement using recycled materials and the other half are allocated to the pavement producing the recyclable material. Some of the available strategies most applicable to pavement EOL scenarios are summarized by Santero, Masanet, and Horvath (2011).

EOL Considerations for Asphalt Pavements

Asphalt pavement recycling has played a significant role in the pavement rehabilitation and preservation strategies employed by highway agencies since the energy crisis of the 1970s. With the more recent emphasis on sustainability considerations in pavement design and construction,

effective pavement recycling strategies are sought even more by agencies interested in reducing energy usage, lowering material and transportation costs, and reducing GHG emissions. Asphalt pavement recycling can be done through central plant or in-place recycling techniques. Both of these EOL techniques are discussed in the following section along with best practices, procedures, and opportunities to improve sustainability at this stage of pavement life cycle.

Central Plant Recycling

Central plant recycling (CPR) is the process of producing hot or cold asphalt mixtures in a central plant by combining virgin aggregates with new asphalt binder and recycling agents along with a certain amount of RAP. RAP is most commonly generated through cold milling or by ripping and crushing of existing pavements and then transported to asphalt plants. RAP from different source is usually kept in different stockpiles, and is usually screened into two, or sometimes three, different sizes at the asphalt plant.

In hot central plant recycling (HCPR), heat transfer is used to soften RAP for mixing instead of direct heating. This means it is important that the moisture content of RAP be kept to a practical minimum as high moisture contents can significantly hamper the plant production as the heat will turn the moisture into steam instead of softening the RAP. Heat transfer is carried out by overheating the virgin aggregates before introducing the RAP into the drum, and may lead to additional fuel and energy use, which may offset the economic and environmental benefits of using RAP. Heat radiation has also been used to heat RAP.

Cold central plant recycling (CCPR) combines RAP with emulsified asphalt/recycling agent without the use of heat; new aggregates can also be added if needed. Although not a common practice (Chesner, Collins, and Mackay 1998; Hansen and Copeland 2013), these mixtures can be used for surface, base, or subbase courses. Specifications for cold plant recycled mixtures are found in ASTM D4215.

Best Practices for Construction of Asphalt Concrete with RAP

Processing and fractionating RAP at the central plant increases product uniformity and, consequently, produces more consistent asphalt concrete containing RAP. However, there are costs involved in processing and fractionating RAP, and greater stockpiling areas (multiple sizes vs. one) are required, which may present issues in some urban plant locations. Moreover, the amount of RAP that ends up in a given fractionated stockpile is usually a function of the parent material and the sizes chosen for fractionation. This, in turn, dictates how much each fractionated size is available for use in the new asphalt concrete. Thus, while processing helps improve consistency, the amount of RAP that ends up (on average) in each fractionated stockpile drives how much it can be used. Al-Qadi, Elseifi, and Carpenter (2007) provide a comprehensive review of RAP use in central plant recycling.

Dust control is a critical issue with the use of RAP in a central plant facility. Plant production of mixtures with high RAP results in high dust contents and difficulties in meeting specifications (VMA and Dust/Effective Binder primarily). Very few plants are equipped to properly waste dust and even fewer have an outlet for that dust even if the plant is capable of wasting it. Without being able to address the increasing dusts, the use of a clean/washed aggregate material becomes more important in order to achieve VMA. Unfortunately, this type of product is not readily available in many locations.

Environmental and Economic Impact of RAP

The proponents of using high RAP contents in asphalt claim the benefit of resource conservation and waste reduction; however, it is necessary to corroborate such claims in a quantified way over the pavement life cycle. Horvath (2004), Ventura, Moneron, and Julien (2008), and, more recently, Aurangzeb and Al-Qadi (2014) and Aurangzeb et. al. (2014) discuss environmental benefits and trade-offs of using RAP in pavements from a pavement life-cycle perspective.

Pavements incorporating RAP should be evaluated using LCCA and LCA and should include the materials production and maintenance stages. For example, when asphalt binder mixtures with 30 percent, 40 percent, and 50 percent RAP are used, LCCA showed a net savings up to $94,000/mi ($58,000/km), whereas LCA showed energy savings of 800 to 1400 MBTU and GHG reductions of 70 to 117 ton (64 to 106 mt) when 30 percent to 50 percent RAP was added to the asphalt mixtures (Aurangzeb and Al-Qadi 2014). However, when the loss of inherent properties of recycled pavement materials is considered, it can be argued that the pavement with recycled mixtures may deteriorate faster in the field than pavements with less (or without any) RAP. The possible substandard performance of recycled mixtures will necessitate more maintenance and rehabilitation activities, thereby offsetting the economic and environmental benefits of using RAP. Figure 8-4 illustrates the potential for increasing costs and emissions as the percentage of RAP increases in the pavement. An "optimum performance level" is defined where the economic and environmental benefits of using RAP are counterbalanced by the project costs and environmental burden incurred from increased frequency of maintenance and rehabilitation activities (Aurangzeb and Al-Qadi 2014). For example, based on the total cost, the mixture with 50 percent RAP can have a performance margin of 11.5 percent (100 − 88.5 = 11.5).

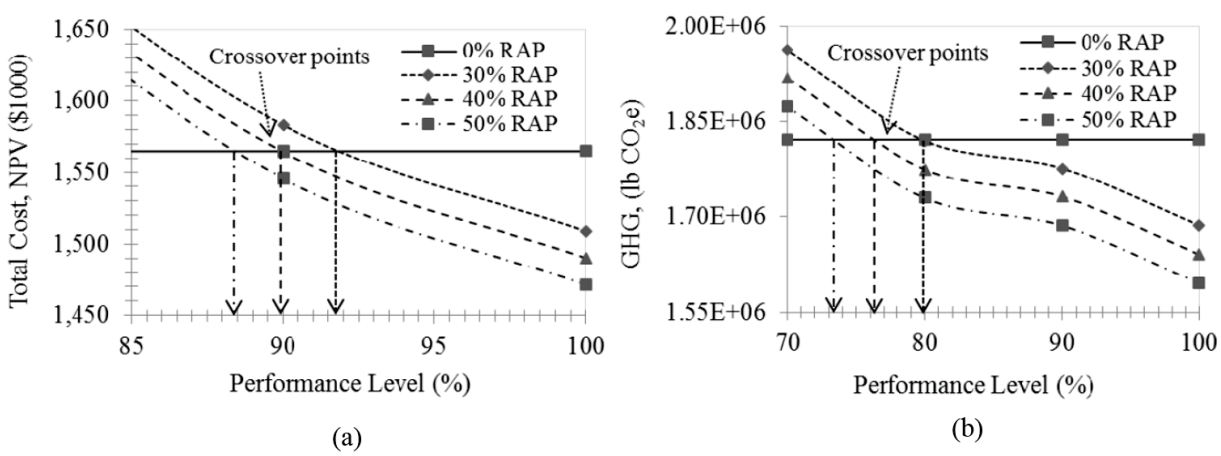


Figure 8-4. Optimal performance levels based on (a) total cost and (b) GHG emissions (Aurangzeb and Al-Qadi 2014).

One environmental concern about the use of reclaimed pavement is associated with leachate when RAP is stockpiled, placed in a landfill, or used in a surface layer exposed to water infiltration. Brantley and Townsend (1999) investigated this issue of leachate produced by RAP, and concluded that RAP samples in the study were not hazardous waste and did not leach chemical greater than allowed by typical groundwater standards. Horvath (2003) reported average metal concentrations for various recycled and co-product materials used in construction including RAP. The hazardous limits were slightly exceeded only for two metals (barium and lead) out of fifteen metals examined. Legret et al. (2005) also concluded that insignificant leaching occurred from RAP.

Full-Depth Reclamation (FDR)

FDR is a technique in which the full thickness of the existing asphalt pavement and a predetermined portion of the underlying materials (base, subbase, and subgrade) are uniformly pulverized and blended to provide a homogeneous material. The pulverized material is mixed with or without additional binders, additives, or water, and is placed, graded, and compacted to provide an improved base layer before placement of the final surface layers. Full-depth reclamation can be performed through single-unit trains, two-unit trains, or multi-unit trains (Thompson, Garcia, and Carpenter 2009). The FDR trains may include combinations of a reclaimer (milling, reclaimer, and stabilizer), pugmill mixer/paver, or a portable crushing and screening unit. Figure 8-5 illustrates a full-depth reclamation train, with more detailed information provided elsewhere (ARRA 2001b; Wirtgen 2004; Asphalt Academy 2009).

FDR is distinguished from other commonly used rehabilitation techniques, such as cold in-place recycling and hot-in place recycling, by its ability to recycle thicker pavement layers and to address specific problems rooted in different layers. FDR can recycle pavement depths up to 12 inches (305 mm), with depths of 6 to 9 inches (152 to 229 mm) more common (ARRA 2001b; Stroup-Gardiner 2011).

The FDR process varies between projects depending on needs of the owner/agency, the in situ material properties, and the required structural capacity after recycling. Three basic components of FDR processing are:

- *Pulverization* – Pulverization is the first stage of the FDR process where existing HMA and part of the granular layers are transformed into uniform granular material with a target gradation that can be used as base layer. Once the layers are pulverized, a compacted base layer can be obtained by adding proper moisture.
- *Stabilization* – Additives and stabilizers are commonly added to the pulverized materials to improve the strength and structural capacity of the compacted layers. Stabilization can be classified into four groups (ARRA 2001b).
  - Mechanical stabilization involves the incorporation of imported granular materials such as crushed aggregates, RAP, or RCA to achieve desired density and gradation and compaction.
  - Asphalt stabilization using asphalt emulsion or foamed asphalt binder (Wirtgen 2004; Jooste and Long 2007; Jones, Fu, and Harvey 2008; Fu, Jones, and Harvey 2011).
  - Chemical stabilization by adding additives such as fly ash, calcium chloride, magnesium chloride, lime, and portland cement. These additives can be added alone or in combination with other chemical additives.
  - Combination of asphalt and chemical additives is also a possibility to improve the properties of recycled layers. For example, Wirtgen (2004) indicates that cement is routinely used with emulsions to improve moisture resistance.
- *Overlay or Surface Treatment* – A structural asphalt concrete overlay is commonly used as the final wearing surface for a FDR project, although a number of surface treatments (chip seal, microsurfacing, slurry seal) may also be placed. These treatments are described in chapter 7.

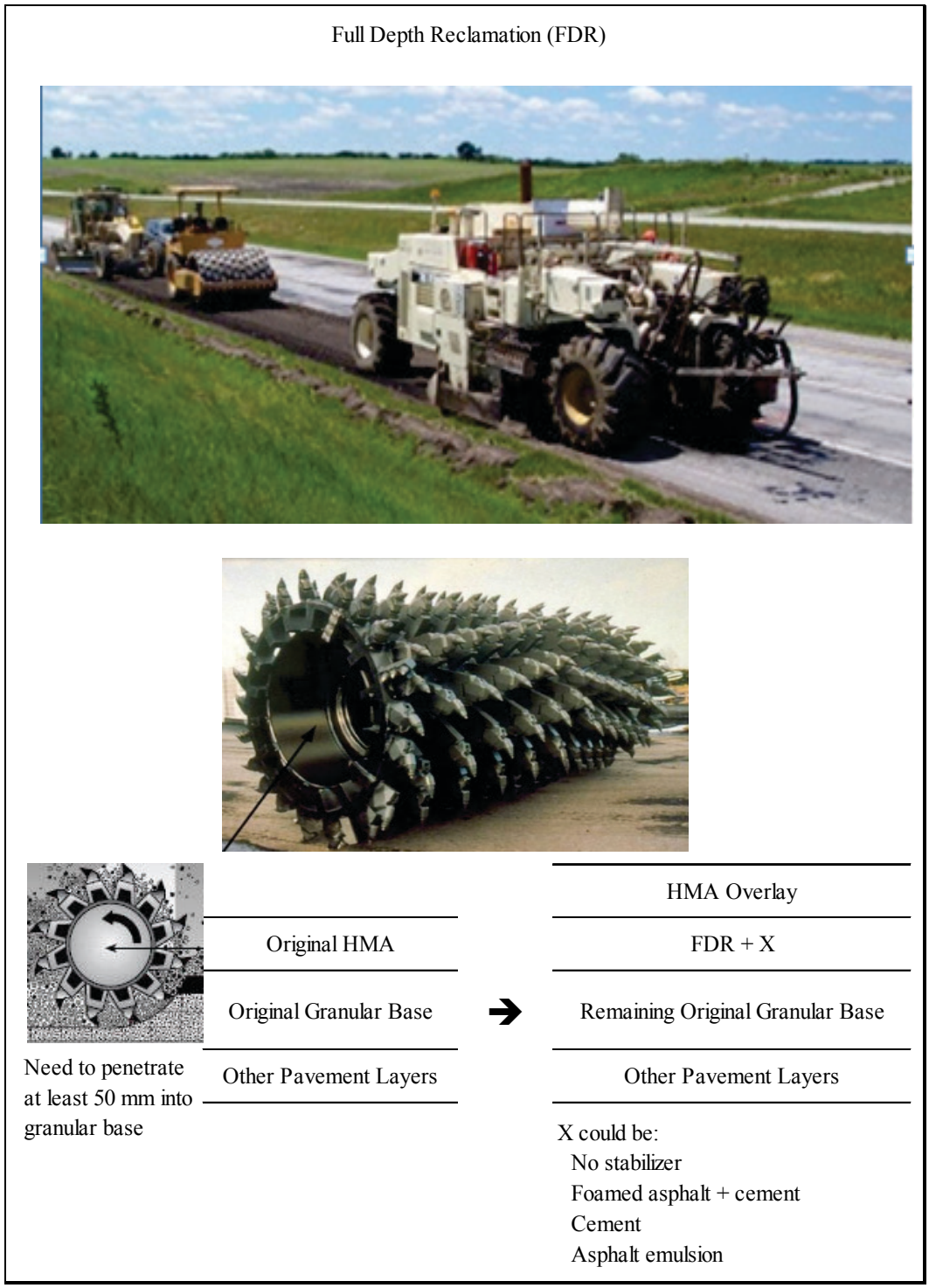


Figure 8-5. Full-depth reclamation train (courtesy of John Harvey).

Project selection, using the proper stabilizing agent, mixture design, and curing considerations, are critical for the performance of any recycling project. Some of these considerations for improving quality of FDR mixture design and construction are discussed next.

There are several comprehensive references that document best practices for FDR construction (e.g., Stroup-Gardiner 2011; Wirtgen 2004; ARRA 2001b). At the same time, the successful installation and performance of FDR projects has been well documented in the literature, including in Minnesota (Dai et al. 2008), Canada (Berthelot et al. 2007); Georgia (Smith, Lewis, and Jared 2008); Nevada (Bemanian, Polish, and Maurer 2006); and Indiana (Nantung, Ji, and Shields 2011). A summary of advantages, limitations, and candidate pavements for FDR projects is presented in table 8-1.

Table 8-1. Summary of FDR advantages, candidate pavements, and limitations.

Summary	Description
Advantages	• Provides significant structural improvement. • Can address most pavement distresses at different layers. • Can improve ride quality. • Minimizes hauling costs. • Reduction in energy use and emissions in material production. • Can correct smoothness deficiencies.
Candidates for FDR	• Pavements with severe longitudinal and transverse cracking. • Pavements with poor ride quality. • Pavements with permanent deformation problems. • Pavements with raveling problems and potholes. • Inadequate structural capacity.
Limitations	• Not recommended for high-volume roads (i.e., > 20,000 ADT). • Not recommended for roads with high percentage of trucks. • Not suitable for areas with drainage problems. • Soils with high plasticity can result in swelling.

Best Practices for FDR

Project selection, mixture design, the selection of appropriate additives for the project, and effective compaction are all critical to the effective construction of FDR. These are described in the following sections.

- *Project Selection* – Understanding key project details such as traffic, roadway geometry and features, and the ability of the existing pavement structure to support the equipment recycling train are all critical in identifying suitable FDR projects. According to a recent survey done with contractors, the lack of project selection criteria was a strong factor limiting the use of in-place recycling techniques (Stroup-Gardiner 2011). Commonly used project selection criteria include pavement condition (distress type and severity, ride quality), pavement thickness, roadway geometry, and identification of the needed surface type for structural capacity, the prevention of moisture infiltration, and protection from thermal cracking.
- *Mixture Design* – A mixture design is required for each FDR project. However, a unique mixture design could be impossible because the design depends on the properties of the in situ pulverized materials, which is often variable. The ultimate objective of mixture design is to determine the quantity and type of additive, water, and compactive effort. A standard mixture design specification does not currently exist for FDR mixtures, but guidelines have been developed by some states and agencies to aid the development of

good quality FDR layers (SEM Materials 2007; Caltrans 2012). Sieve analysis, extraction for binder content, soil plasticity, moisture susceptibility, critical low temperature cracking, resilient modulus, and triaxial compressive strength tests are usually conducted as part of the mixture design process. Material evaluation is primarily focused on the wet and dry strength of FDR mixtures and determination of the compaction curve for optimum moisture and additive content at a specified curing time. Compaction equipment and procedures and curing times can also vary depending on the additives and in situ climatic conditions. Table 8-2 summarizes the commonly used test methods used in the mixture design in addition to the standard ones. An on-going NCHRP study (Project 09-51) is currently studying the selection of material properties and the preparation of mixture designs for cold in-place recycling and full-depth reclamation of asphalt concrete for pavement design.

- *Additives* – The cost effectiveness of additives can vary based on the characteristics of the project. However, one study demonstrated that emulsion, cement, or a combination of emulsion and lime improves moisture susceptibility of FDR mixtures (Mallick et al. 2002). The same study indicated that emulsion-lime combination appears to be more cost-effective compared to water, emulsion, and cement stabilization. The critical issue for stabilized layers is the classification of the mixtures as "improved granular materials" (Anderson and Thompson 1995) or as bound materials such as HMA. The distinction between two material types governs the mixture design process as testing required will vary for each type of materials. Depending on the type and amount of additives, FDR mixtures can span a range of material behavior from very stiff (highly cemented) to very flexible (high emulsion content). The most commonly used additives are summarized in table 8-3 with their commonly reported and accepted advantages and limitations.
- Compaction – The importance of compaction and achieving target density is as critical as selecting the right amount and type of additive. Mallick et al. (2002) emphasize the selection of design number of gyrations and achieving the target density in the field. It was reported that 97 percent of the laboratory density or 92 percent to 98 percent of the theoretical maximum specific gravity is suitable for wide range of FDR mixtures (Thompson, Garcia, and Carpenter 2009).

Economic and Environmental Impact

A number of potential benefits can be listed for in-place recycling techniques that can be attributed to the increasing attention by agencies. Some of the major benefits are conservation of virgin materials; reduction in the cost of pavement preservation, maintenance, and rehabilitation; reduced lane closures; reduced fuel consumption; and reduced emissions. Of course, these are listed as potential benefits and they can only be realized when impacts over the complete life cycle of the pavement are considered.

Table 8-2. Commonly used test methods in the mixture design of FDR projects.

Test Method	Specification	Purpose
Extraction of Binder Content	ASTM D2172	Determine existing binder content in the HMA layers
Sieve Analysis	ASTM C136 or AASHTO T27-11	Determine gradation of pulverized materials
Plasticity	ASTM D4318 or AASHTO T90-00	Suitability for pavement layer and additive selection
Fines	ASTM C117 or AASHTO T11-05	Determine materials finer than 75 μm in the granular layer
Wet and Dry Indirect Tensile Strength	Similar to ASTM D4867 or AASHTO T283-07 (curing time may vary)	Moisture susceptibility of mixture design
Resilient Modulus	ASTM D4123 or AASHTO T307	Resilient modulus for thickness determination
Thermal Cracking	AASHTO T322	Determine critical cracking temperature
Cohesiometer Test	ASTM D1560 or AASHTO T246	Determine early mixture
Raveling Test	ASTM D7196	Determine resistance to raveling
Confined and Unconfined Triaxial	Similar to AASHTO T296	Determine cohesion and shear strength parameters

Table 8-3. Common additives used in FDR projects (recommended additive percentages from ARRA 2001a).

Additive	Advantages	Limitations
Liquid calcium chloride (1% by weight)	Improves freeze-thaw resistance	
Portland cement (3 to 6% by weight)	Increases compressive strength, improves moisture resistance	Works best with soils plasticity index less than 10% (Thompson, Garcia, and Carpenter 2009), increases risk of shrinkage cracking
Lime (calcium hydroxide) (2 to 6% by weight)	Works best with reactive clay (plasticity index > 8) and fine content > 10% (Mathews 2008; Franco et al. 2009); reduces plasticity of base material, improves moisture resistance	Too much lime can result in shrinkage cracking
Quicklime (calcium oxide)	Improves early strength	Can result in shrinkage cracking
Fly ash (8 to 14% by weight)	Improves strength and moisture resistance	
Asphalt emulsions (1 to 4% by weight)	Improves strength and soften aged asphalt binder in RAP, reduce shrinkage cracking	Less resistance to permanent deformations, vulnerable to moisture related stripping
Foamed asphalt (1 to 3% by weight)	Stockpile material for longer period (up to 1 month), deeper road stabilization (up to 14 inches), open roads to traffic faster	
Lime and cement	Improves stiffness, moisture resistance, and strength (Naizi and Jalili 2009)	
Fly ash and lime	Improves strength	Increased shrinkage cracking
Emulsion and lime slurry	Provides flexibility for low temperature cracking and shrinkage cracking	
Cement and emulsion	Improves strength, fatigue resistance, moisture resistance, accelerates curing time	

Strategies for Improving Sustainability

Some general approaches to improving sustainability with regard to pavement recycling at the end of its life along with associated environmental benefits and trade-offs are summarized in table 8-4. The specific strategies are discussed in the following sections.

Strategy No 1: Improve Plant Technology

There exist few asphalt plants that are equipped with positive dust control (PDC) systems. The PDC system allows the producer to "waste dust" by returning less dust to the mixture than is being generated and the system is able to account for the aggregate weight change and translate that to adding the "correct" amount of virgin binder. Other energy efficient technologies should be explored.

Strategy No 2: Increase Initial Quality of Pavement Materials and Construction

Improvement in the initial quality of paving materials and construction will increase the level of performance and the overall pavement life. The increase in pavement life will reduce the total cost of the pavement and the number of recycling phases, directly impacting the emission resulting from the total recycling process.

Strategy No 3: Use Rejuvenators or Softening Agents

Recycled asphalt concrete materials, including plant and hot in-place recycling, have different characteristics than the original materials. The recycled materials usually have relatively high stiffness due to the aged binder. Effective rejuvenators are needed to reduce the brittleness of these materials, and these also affect the fatigue and thermal cracking of the new pavements with recycled materials. A suitable rejuvenator added at an optimized amount would increase the new pavement life, thereby reducing life-cycle costs, the impacts on the environment, and the number of recycling phases within a specific period of time. However, the upstream environmental impacts of any rejuvenator or softening agent must also be considered.

Strategy No 4: Maintain and Manage RAP Stockpiles Fractionated and Moisture Free

It is important that the mixture design of asphalt concrete with RAP be developed to meet the design volumetrics. RAP fractionation is needed to accomplish that, which requires management of multiple stockpiles. This would allow achieving initial quality of the mixture that would result in extended performance. In addition, to reduce the cost of energy needed to process the RAP, the RAP stockpiles should be covered to protect them from exposure to moisture.

Strategy No 5: Selection of Proper Type and Amount of Additives or Stabilizers

It is critical to use the proper type and amount of additives or stabilizers. The selection should be made on geotechnical inspection of in situ properties of the granular materials. This strategy may have minimal impact on the environmental burden of construction and material procurement phase; however, the expected improvement in performance and service life of the FDR can easily offset the initial environmental burdens and costs.

Table 8-4. Approaches for improving sustainability of asphalt pavement recycling for pavement sustainability.

Asphalt Pavement Recycling Objective	Sustainability Improving Approach	Economic Impact	Environmental Impact	Societal Impact
Increase Central Plant Recycling Rate of Pavements	Improve plant technology (including heating time, positive dust control, double barrel etc.)	Requires initial capital investment for the producer. Can potentially reduce pavement production costs.	Can reduce GHG emissions if transportation burden will not offset.	Preserves virgin natural sources. Reduces need for landfills.
	Increase initial quality of pavement products and construction.	Can increase initial costs but may decrease life-cycle costs.	Can increase material production energy use but overall life-cycle energy and emissions may reduce.	Decline in natural resources.
	Use softening agents or rejuvenators	Can increase material production costs.	Can reduce GHG emission in overall life cycle if pavement quality is improved.	Preserves virgin natural sources. Reduces need for landfills.
	Maintain and manage RAP stockpiles (reduce moisture, fractionation)	Can increase material production costs slightly but may decrease life-cycle costs.	Can increase material production energy use but overall life-cycle energy and emissions may reduce.	Preserves virgin natural sources. Reduces need for landfills.
Increase In-Place Recycling Rate of Pavements	Use the proper type and amount of additive or stabilizers	Can increase material production costs but may decrease life-cycle costs.	Life-cycle energy and emissions may reduce.	Preserves virgin natural sources. Reduces need for landfills.
	Use structural asphalt overlays to improve weathering, cracking and fatigue resistance	Can increase material production costs but may decrease life-cycle costs.	Life-cycle energy and emissions may reduce.	Preserves virgin natural sources. Reduces need for landfills.
	Develop standards for mixture design and QA to improve quality	No costs.	Life-cycle energy and emissions may reduce since the quality is improved.	Preserves virgin natural sources. Reduces need for landfills

Strategy No 6: Structural Overlays

The type and thickness of an asphalt overlay can have considerable impact on the environmental burden of initial construction. However, their placement can protect the recycled layers from direct exposure to weathering and slow down the deterioration rate. LCCA and LCA can be used to demonstrate the potential benefits of different structural overlay alternatives.

Strategy No 7: Improve Construction Quality

Similar to any other highway construction works, the quality of construction is also critical for the long-term performance of recycled pavements using FDR. Inexperienced contractors and the relative complexity of FDR jobs are some of the factors that may increase risks for quality construction. Stringent quality assurance protocols are critical to improve the long-term performance of pavements constructed with FDR.

Future Directions and Emerging Technologies

Continued evaluation and eventual adoption of zero-waste strategy for all reconstruction projects should be considered, providing the primary benefit that none of the existing pavement materials is ever wasted. This will require innovative equipment and approaches to make sure that all the materials can be recovered and effectively recycled. In addition, in order to minimize the recycled materials transportation cost and environmental impact, innovative equipment and processes that recycle the pavement completely in place should be considered.

EOL Considerations for Concrete Pavements

Introduction

There are three primary end-of-life options for concrete pavement surfacing: reuse, recycling, and disposal. The sustainable aspects of each of these (and the impact that sustainable choices have on the necessary production and use processes of each) are introduced in this section and discussed in detail in following sections.

Recycling

Natural aggregate resources are vast, but finite; many high-quality, conveniently located aggregate resources are being depleted rapidly. In addition, environmental regulations, land use policies, and urban/suburban construction and settlement are further limiting access to known aggregate resources. As a result, natural aggregate costs can be expected to rise with scarcity and increased haul distances. Concrete pavement recycling is a proven technology that offers an economical and sustainable solution to these problems.

Concrete recycling is a relatively simple process. It involves breaking, removing, and crushing hardened concrete from an acceptable source to produce RCA, which a granular material that can be produced for use as a substitute for natural aggregate in almost any application.

Typical Uses of Recycled Concrete Products

Concrete recycling has been used extensively in Europe since the 1940s and in the U.S. since the 1970s (NHI 1998), with one of the first U.S. applications of RCA in pavement construction taking place in the 1940s on U.S. Route 66 (Epps et al. 1980). Production of RCA in the U.S. currently averages about 140 million tons (127 million mt) per year from all sources (CDRA 2014). USGS has reported that aggregate producers were responsible for approximately 100 million tons of all crushed concrete production in 2000 (USGS 2000). The primary applications

of RCA have been base and subbase materials, but it also has been used in both concrete and asphalt concrete paving layers, as well as in high-value riprap, general fill and embankment, and other applications.

The recycling of paving materials (including concrete pavement) into new paving applications is supported by the Federal Highway Administration, which states that "reusing the material used to build the original highway system makes sound economic, environmental, and engineering sense" (FHWA 2002; Hall et al. 2007). FHWA further states that "The engineering feasibility of using recycled materials has been demonstrated in research, field studies, experimental projects and long-term performance testing and analysis. When appropriately used, recycled materials can effectively and safely reduce cost, save time, offer equal or, in some cases, significant improvement to performance qualities, and provide long-term environmental benefits" (FHWA 2002).

The suitability of RCA products may be limited by the quality of the source concrete from which it is derived. For example, poorly controlled or highly variable sources (such as might be produced from building demolition stockpiles) or sources that include significant amounts of known materials-related distress (e.g., freeze-thaw durability cracking or alkali-aggregate reactivity [AAR] distress) will generally not be suitable for use in producing aggregate for new concrete mixtures; however, these products can often still be recycled into aggregate for subbase and backfill applications.

Benefits of Concrete Recycling

One major incentive for concrete pavement recycling is economics. Aggregate costs (for fill, foundation and surface layers) constitute one of the greatest costs of highway construction, comprising between 20 and 30 percent of the cost of materials and supplies (Halm 1980). Concrete pavement recycling saves much of these costs. The cost of producing RCA can be considered to be limited to the costs of crushing the demolished concrete and screening and backhauling the RCA (along with quality assurance costs). The costs of concrete demolition, removal, and hauling are required whether the pavement is recycled or simply discarded. RCA production costs may be offset by savings in hauling and disposal costs, especially if the RCA is produced on site.

The USGS reported that the average cost of RCA in 2005 was $6.93/ton ($7.62/mt), ranging from $3.41/ton ($3.75/mt) in New Jersey to more than $8.09/ton ($9/mt) in California, Louisiana, and Hawaii. Virgin aggregate was reported to cost an average of $6.52/ton ($7.16/mt), ranging from $3.54/ton ($3.89/mt) in Michigan to more than $10.01/ton ($11/mt) in Mississippi and Hawaii (Kuennen 2007). In considering these numbers, it must be remembered that the volume of any given mass of RCA is 5 to 20 percent greater than the volume of natural aggregate, so a ton of RCA "goes farther" than a ton of virgin aggregate. Cost savings from concrete pavement recycling vary but have been reported to be as high as $5 million on a single project (CMRA 2008).

In addition, concrete pavement recycling is a smart and environmentally sustainable choice that conserves aggregate and other resources, reduces unnecessary consumption of limited landfill space, saves energy, reduces greenhouse gas emissions, and captures CO_2 from the atmosphere. Concrete recycling can eliminate the need for mining or extracting new virgin aggregates, and can reduce haul distances and fuel consumption associated with both aggregate supply and concrete slab disposal.

Best practices for concrete pavement recycling and guide specifications for using RCA in new concrete and base materials can be found in many sources, including ACPA (2009).

Reuse

The reuse of a material can be considered to include applications where the material is used in its current form, often in its current placement or location, with minimal (if any) processing.

Typical Applications for Concrete Pavement Reuse

The most common example of reuse of concrete pavement is when it is used without significant processing as a base or subbase layer for an overlay or new pavement structure. Rubblization of concrete pavement in preparation for the placement of an asphalt overlay can be considered to be reuse of the concrete because the processing (rubblization) is not inherently necessary for the application but is one of several approaches for minimizing the potential for reflection cracking of concrete pavement joints and cracks in the asphalt (other options include the placement of various fabrics, membranes, and interlayer materials).

The suitability of a concrete pavement for reuse may be limited by the type, severity, and extent of the distresses that are present. Pavements that do not present relatively uniform quality (e.g., pavements with significant amounts of joint deterioration and other distresses that would result in "soft spots" or areas with significantly higher deflections) may require in-place processing (e.g., rubblization) in order to be reused successfully. Alternatively, such pavements may be better suited for recycling into an appropriate application or, in extreme cases, disposal.

Benefits of Concrete Pavement Reuse

The economic, environmental, and societal benefits of appropriately reusing the existing pavement structure are generally the highest of all end-of-life options for concrete pavements. There is great potential for material savings and conservation of resources, in terms of both the materials and energy required to produce and haul new materials, as well as reductions in the costs and energy associated with landfill disposal of old materials. In addition, construction duration is generally significantly shorter, resulting in reduced impacts to local users and businesses.

These benefits may be partially (or even wholly) offset by shorter performance life or more frequent maintenance requirements in some cases, particularly when a reconstruction alternative would address foundation or drainage deficiencies in the existing structure. LCA, LCCA, and pavement performance analyses are useful in determining whether reuse of the concrete pavement is appropriate for any given situation.

Disposal

Disposal refers solely to the removal and hauling of a paving material to a landfill where it serves no purpose or value. As was noted earlier in this chapter, disposal costs are associated with demolition, transportation (which varies with haul distance), and landfill tipping fees, which vary widely, even over relatively short distances, and are increasing rapidly as available landfill space decreases. The National Solid Wastes Management Association reports that tipping fees increased from an average of $8/ton ($8.79/mt) in 1985 to $34.29/ton ($37.68/mt) in 2004, with averages as high as $70.53/ton ($77.51/mt) in the Northeast region (Kuennen 2007). One can also consider the potential value of RCA product (which can vary significantly with the quality

of the source concrete and the availability of local natural aggregate) as a lost value or opportunity cost of disposal.

Clearly, the economic and environmental costs of disposal are generally quite high and disposal is not an end-of-life option that will not often be preferred over the recycling and reuse options. Therefore, this option will not be discussed further in this chapter.

Concrete Recycling

RCA can be used as a replacement for natural aggregate in many situations and applications, but it is a composite material comprising natural aggregate and hardened mortar. As such, RCA can have significantly different physical, mechanical, and chemical properties than natural aggregate, and these differences must be addressed in the material processing, pavement design, and construction phases of road projects. Some of the most important issues to consider are highlighted below, along with strategies for improving the sustainability of concrete pavement recycling activities.

Source Material

The quality and overall properties of the source concrete must be evaluated to determine the potential uses of the RCA. High-quality, durable concrete may be suitable for producing RCA for use in structural concrete or pavement surface layers. Lower quality materials may be best suited for subbases, fill, or other applications. Additional factors, such as availability of local materials and haul distances, will also be necessary to determine the highest *feasible* use for the RCA.

Original construction and mixture design records can be an excellent source of information concerning the component material sources and their qualities and proportions. If the pavement to be recycled is still in place, a condition survey should be performed to determine the type and extent of any distresses present and to retrieve samples for visual inspection and laboratory evaluation (FHWA 2007). If any material-related distresses (e.g., D-cracking or AAR) are observed in the source concrete, evaluations and tests should be conducted to ensure that mitigation measures will be effective in preventing recurrence of these distresses if the RCA is to be used in new concrete applications or the development of degradation-related problems in foundation or other applications. Techniques that may be effective in preventing recurrent ASR[1] for RCA to be used in new concrete applications include the introduction of lithium-based admixtures, the use of Class F fly ash or slag cement in place of a portion of the cement, a reduction in the total alkali loading in the concrete, or other ASR mitigation strategies applicable for virgin aggregate to be used in concrete. Recurrent D-cracking may be prevented by reducing the coarse RCA top size to 0.75 inches (19 mm) or less.

Stockpile Runoff and Drainage Effluent

The runoff from RCA stockpiles is initially highly alkaline, with one study finding median pH values of 9.3 and 9.8 for fine and coarse RCA stockpiles, respectively (Sadecki et al. 1996). The high alkalinity is the result of the leaching of calcium hydroxide from the freshly exposed mortar faces of the recycled aggregate. In addition, studies have shown the presence of trace amounts of

[1]Note that there is no effective way to mitigate alkali-carbonate reactivity (ACR) and RCA obtained from a pavement affected by ACR must not be used as aggregate in new concrete.

heavy metals and other naturally occurring contaminants in RCA stockpile runoff, although generally not at levels considered hazardous (Sadecki et al. 1996).

Similarly, the effluent from RCA foundation layers is initially highly alkaline (an effect that diminishes with time in service), and it is not uncommon to see very small regions of vegetation kill in the immediate area of associated pavement drain outlets for a short time after construction (Snyder 1995). Nevertheless, stockpile runoff and drainage effluent alkalinity usually decrease rapidly within a few weeks as the exposed calcium hydroxide is depleted through neutralization, dissolution, and reaction with carbon dioxide in the air; in addition, the concentrations of other contaminants in the runoff or effluent can also be expected to decrease rapidly with time (Snyder 1995).

Runoff and effluent alkalinity is generally not considered to be an environmental hazard because it is effectively diluted and partially neutralized at a very short distance from the stockpile or drain outlet with much greater quantities of rainwater runoff (Sadecki et al. 1996; Reiner 2008), which is typically slightly acidic (in the range of 5.2 to 5.4 inches some regions of the U.S). Furthermore, the effects of soil buffering and equilibration with atmospheric CO_2 during transport from the RCA source to local surface waters may further reduce pH levels. Washing and selectively grading the RCA (as described in the next section) is also generally effective in reducing initial pH levels in RCA stockpile runoff and drainage effluent (Snyder and Bruinsma 1996).

The bottom line is that there appear to be no negative environmental effects from using RCA that significantly offset the positive environmental effect of reduced use of virgin aggregate and landfills (Reiner 2008).

Impact of RCA on Pavement Design and Construction

Because RCA typically has different physical, mechanical, and chemical properties than most natural aggregates, the properties and behavior of materials and layers comprising RCA can be significantly different from those of similar materials and layers comprising only natural aggregate. It is important to consider these differences in the design and construction of systems containing RCA components. Some of the key impacts of RCA on the design and construction of pavement foundation and concrete surface layers are described herein, along with generally accepted techniques for mitigating the effects.

Mitigation of Calcareous Tufa in RCA Base Materials

One major concern with using RCA in drained pavement layers is the potential for calcium carbonate precipitate in edge drainage structures and on associated filter fabrics. The mechanism of precipitate formation is presented completely in Bruinsma, Peterson, and Snyder (1997), where it is described as the dissolution of calcium hydroxide (an important cement hydration phase) into water from freshly exposed crushed mortar surfaces and the subsequent precipitation of calcium carbonate as the dissolved calcium hydroxide reacts with atmospheric CO_2. The availability of calcium hydroxide increases with increasing surface area of recycled concrete (i.e., with finer particle sizes) and decreases over time as the available calcium hydroxide is depleted.

Bruinsma (1995) and Tamarisa (1993) also determined that as much as 50 percent of the material deposited in drainage structures and on associated filter fabrics may be dust and insoluble residue

produced by the crushing operation. Bruinsma (1995) found that washing the product prior to use minimized the presence of this material.

There have been many lab and field studies to characterize and identify solutions to this potential problem. The following conclusions, drawn from these reports, are useful in preventing problems with pavement drainage systems when using RCA in drained pavement layers:

- Consider using "daylighted" subbase designs that provide broad paths for drainage (rather than concentrating all residue in outlet structures) (ACPA 2009).
- Unbound RCA layers that can pass water to pavement edge drainage systems or are "daylighted" should contain no more fine material than is necessary for stability. This will minimize the movement of dust and the formation of calcium carbonate precipitate. Blending with virgin aggregate will also reduce precipitate potential, but may not represent a best sustainable practice. Unstabilized fine RCA may be suitable for placement in layers below the pavement drainage system.
- Wash RCA prior to its use in a drained layer to minimize the contribution of "crusher dust" to drainage system problems.
- Select filter fabrics with initial permittivity values that are at least double the minimum required so that adequate flow will be maintained even if some clogging takes place (Snyder 1995).
- When filter fabrics are used in pipe drain trenches, leave the top of the trench unwrapped to reduce deposits of residue on the fabric.
- Accumulations of precipitate and residue in drainage pipes can be significant and can reduce discharge capacity, but are rarely (if ever) observed to significantly impede drainage flow.
- RCA intended for use in cement- or asphalt-stabilized layers require none of the special treatment or handling required for unstabilized RCA layers.

Effects of Material Properties on Pavement Design and Construction

The use of RCA can significantly affect the properties and behavior of the materials and layers in which it is used. As a result, it may be necessary to modify certain pavement design and mixture proportions in order to obtain the desired behavior of the materials and performance of the pavement. Key considerations and possible design and construction modifications are provided below.

- Effects of Unbound RCA Layers on Pavement Design. When unbound RCA is used in pavement subbase layers, it may initially behave similarly to layers comprising unbound natural aggregate (although studies suggest that the angular, rough-textured nature of the particles may provide modest increases in layer stiffness). However, after time, the hydration of freshly exposed and previously unhydrated cement grains (sometimes referred to as "secondary hydration") can result in a layer that behaves like a stabilized layer. The increased stiffness of this layer may allow for a slight reduction in the thicknesses of surface layers. However, it may also result in increased slab curling and warping stresses and the need to reduce panel dimensions to mitigate the effect.

- Effects of RCA on PCC Mixture Properties. Fresh concrete mixtures containing RCA may exhibit higher water demand and have poorer workability or finishing characteristics, depending upon the amount and properties of RCA used. These difficulties are related to the inclusion of reclaimed mortar (which is generally angular and relatively porous) and can be especially acute for high replacement levels of fine natural aggregate with fine RCA. Mixture design and proportioning modifications (for example, using chemical and mineral admixtures or using lower levels of RCA substitution) can partially offset or eliminate many of these issues. ACPA (2009) and FHWA (2007) provide specific guidance on the proportioning of concrete mixtures containing RCA.

  PCC mixtures comprising RCA may also be more susceptible to drying shrinkage problems due to the absorptive nature of the reclaimed mortar. These issues can be minimized with good RCA stockpile moisture management, mixture design modifications, and good construction and curing practices.

- Effects of RCA on Hardened PCC Properties and Related PCCP Design Parameters. When all other factors are held constant (i.e., no compensating mixture adjustments are made), hardened RCA concrete can be expected to have somewhat lower (but still acceptable) strength and elastic modulus values, significantly more permeability, drying shrinkage and creep potential, slightly lower specific gravity, and somewhat higher CTE values (ACPA 2009). The physical and mechanical properties of RCA concrete must be determined and considered in the development of RCA concrete pavement design details.

  For example, increased shrinkage and thermal response of concrete containing RCA can cause larger joint movements, requiring different sealant materials and reduced panel dimensions. They also may increase slab curling and warping deformations. Strength and elastic modulus reductions can impact stress distributions and fatigue damage and may cause increases in required pavement thickness. Some of these effects can be offset with mixture proportioning modifications (e.g., lower *w/cm*) to reduce shrinkage and increase strength) or modifications in the properties of the RCA (e.g., reductions in the use of fine RCA and using impact crushing processes that remove most of the mortar from the reclaimed natural aggregate particles).

  In some cases, the use of large amounts of coarse and fine RCA can have a beneficial effect on pavement behavior. Won (2007) describes the design and reconstruction of I-10 near Houston, TX in 1995 using 100 percent recycled concrete aggregate in a CRCP. The resulting pavement had a 28-day compressive strength of 4600 lb/in^2 (32 MPa), but an elastic modulus of only 2.6 million lb/in^2 (17,900 MPa); in other words, it was strong, but relatively compliant and not brittle, which is theorized to be at least partially responsible for the good behavior and excellent performance of the section to date.

Table 8-5 summarizes pavement design modifications that should be considered when using RCA concrete in new pavement construction.

Table 8-5. Design recommendations for RCA concrete pavements (ACPA 2009).

Concrete Pavement Design Element	Design Recommendations
Pavement Type	Use JPCP with panel length of 15 ft (4.6 m) or less to minimize potential for mid panel cracking. JRCP and CRCP may be considered if aggregate interlock is enhanced with larger aggregate top size or blending virgin and recycled, coarse aggregate. Additional reinforcement may be desirable to ensure that cracks are held tight.
Slab Thickness	Generally the same as for conventional concrete pavement provided that the RCA concrete mixture design provides adequate strength. For two-course construction using RCA concrete, the overall slab thickness might need to be greater than what is required for a conventional concrete pavement design, depending on the materials and mixture proportions used in each lift.
Joint Spacing	Panel length should be selected to minimize the incidence of mid panel cracks in JPCP or to keep crack width to a minimum in JRCP.
Load Transfer	The criteria used for using dowels in RCA concrete pavements should be identical to those used for pavements constructed using virgin aggregate. Reinforcing steel recommendations for crack load transfer are presented below.
Joint Sealant Reservoir Design	Dimensions must consider both the selected sealant material and expected joint movements caused by temperature and shrinkage effects, which may be higher for RCA concrete.
Subbase Type	Subbase material should be selected in consideration of the structural requirements of the pavement type selected (as for conventional concrete designs). Free-draining subbase layers should be considered for RCA concrete pavements produced from D-cracked or ASR-damaged concrete.
Reinforcement	Higher amounts of longitudinal steel reinforcing may be required in JRCP and CRCP to hold cracks tight so that aggregate interlock load transfer can be maintained.
Shoulder Type	Same as for conventional concrete pavement.

Concrete Pavement Reuse

In some situations, concrete pavements can be reused (without recycling) at the end of their natural service lives by treating them as a base layer for a new pavement that is constructed directly over them (i.e., an overlay). Unbonded concrete overlays are prime examples of this end-of-life strategy because they are typically placed over concrete pavements that have no other options besides reconstruction. Asphalt overlays of badly distressed concrete pavements are another example, although it may be necessary to rubblize the concrete in situ (or provide an interlayer of some type) to provide a more uniform support condition for the asphalt pavement and to prevent joint/crack reflection. Some of the most important issues to consider in reusing concrete pavements are highlighted below.

Evaluation of Existing Pavement Structure

The in situ reuse of a concrete pavement may not be a sustainable end-of-life option if there are significant structural or drainage issues in the underlying foundation that must be addressed. Like any other pavement structure, the sustainability of a new pavement structure being built on a reused concrete pavement foundation will depend in part upon the quality, strength, and durability of that pavement foundation. Failing to correct known structural deficiencies may result in a shorter life cycle with higher economic and societal costs, and increased environmental impacts. In addition, the reuse of concrete pavements may require that additional geometric and safety considerations be addressed in the new pavement design due to the increased elevation of the new pavement surface (e.g., reductions in overhead clearances, changes in foreslope and ditch bottom location, adjustment of guardrail).

Uniformity of Material

One of the most important aspects of concrete pavement reuse is the uniformity of support that the old pavement will provide to the new, particularly for new asphalt pavements, which are sensitive to foundation support. If the old pavement suffers from significant material-related distress (e.g., D-cracking, joint spalling), it may be necessary to construct or place interlayer materials (e.g., geotextile fabrics and constructed interlayers) or to rubblize the pavement (to reduce the stiffness of the entire pavement to levels comparable to those of the deteriorated areas).

If non-uniform pavement conditions necessitate interlayer or rubblization treatments (or the construction of thicker pavement overlay structures), then reuse of the original pavement may not be the most sustainable approach. The sustainability assessment techniques described in chapter 10 are useful in making such determinations and decisions.

Strategies for Improving Sustainability

The use of recycled concrete aggregate in lieu of natural aggregates is inherently sustainable when all other factors are equal. The following subsections describe strategies for improving the sustainability of concrete recycling by optimizing the production and use of the material, and these are also summarized in table 8-6. The ultimate goal for improving concrete pavement sustainability is the achievement of a zero-sized waste stream at the pavement end-of-life (as well as for rehabilitation operations).

Strategy #1: Optimize Use of Recycled Materials through Testing and Characterization

As was noted previously, the quality and overall properties of the source concrete must be evaluated to determine how best to use the resulting RCA products as completely as possible and in the highest feasible applications. RCA particles tend to be highly angular and are comprised of reclaimed virgin aggregate and reclaimed mortar. Reclaimed mortar generally has higher absorption, lower strength, and lower abrasion resistance than most virgin aggregates. As a result, RCA generally has lower specific gravity and higher absorption than virgin aggregate, particularly for smaller particle sizes, which tend to be comprised largely of mortar. The properties of a specific recycled concrete aggregate depend upon many factors, including the properties of the original concrete and the processes used to produce the RCA, particularly the crushing processes. Therefore, even when a preliminary assessment of product potential has been made, laboratory tests of product samples should be performed to further qualify the RCA for the selected applications, bearing in mind that higher type applications may require the use of higher test result thresholds.

Table 8-6. Approaches for improving sustainability of concrete pavement recycling.

Concrete Pavement Recycling Objective	Sustainability Improving Approach	Economic Impact	Environmental Impact	Societal Impact
Increase Use of Recycled Materials and Minimize Wastage	Optimize use of recycled materials through testing and characterization	Initial investments in research and development, will help understand material properties better	Optimized material usage will help reduce emissions and wastage	Preserves virgin natural sources. Reduces need for landfills
	Adjust RCA production operations	Initial investments to adjust production protocols	Reduced fuel consumption and minimizes wastage	Preserves virgin natural sources. Reduces need for landfills
	Customize preparation and breaking of source concrete: removal of asphalt overlays and patches and pavement breaking	Potential increase in production costs, higher production rate may reduce overall material costs	Minimizes material wastage	Preserves virgin natural sources. Reduces need for landfills
Reduce CO_2 Emissions over the Life Cycle	Sequestration of CO_2 by RCA	No economic impact.	Potential to offset CO_2 emissions from the raw materials used in cement production (not including fuels used in production)	Reduced impact on climate change.
Reduce Virgin Material Usage and Material Transportation needs	On-site recycling	Reduction in fuel and potentially labor costs, increased cost to setup up portable crusher at job site	Reduced GHG emissions due to reduction in haul traffic	Reduction in haul truck traffic and traffic congestions, reduces need for landfills

A good example of the use of several tests and varying criteria for use in different situations can be found in the final report for NCHRP Project 4-31 (Saeed 2008), which identifies several properties of recycled aggregate subbase materials that influence the performance of the overlying pavement, including aggregate toughness, frost susceptibility, shear strength, and stiffness. Table 8-7 is a matrix that was developed by Saeed (2008) to summarize their recommendations for critical test values to ensure good RCA subbase performance for specific traffic, moisture, and temperature conditions.

Table 8-7. Recommended RCA subbase quality tests and threshold values for various applications (Saeed and 2008).

Tests and Test Parameters	Medium-High Traffic Low or High Moisture Freeze climate	Low, Medium or High Traffic Low-High Moisture Freeze or Non-freeze climate	Low-Medium Traffic High Moisture Non-freeze climate	Low Traffic Low Moisture Non-freeze climate
Micro-Deval test (percent loss)	< 5 percent	< 15 percent	< 30 percent	< 45 percent
Tube Suction test (dielectric constant)	≤ 7	≤ 10	≤ 15	≤ 20
Static Triaxial Test (Max. Deviator Stress) OMC, s_c = 5 psi (35 kPa)	>100 psi (0.7 MPa)	>60 psi (0.4 MPa)	>25 psi (170 kPa)	Not required
Static Triaxial Test (Max. Deviator Stress) Sat., s_c = 15 psi (103 kPa)	≥180 psi (1.2 MPa)	≥135 psi (0.9 MPa)	≥60 psi (410 kPa)	Not required
Repeated Load Test (Failure Deviator Stress) OMC, s_c = 15 psi (103 kPa)	≥180 psi (1.2 MPa)	≥160 psi (1.1 MPa)	≥90 psi (620 kPa)	Not required
Repeated Load Test (Failure Deviator Stress) Sat., s_c = 15 psi (103 kPa)	≥180 psi (1.2 MPa)	≥160 psi (1.1 MPa)	≥60 psi (410 kPa)	Not required
Stiffness Test (Resilient Modulus)	≥60 ksi (0.4 MPa)	≥40 ksi (275 kPa)	≥25 ksi (170 kPa)	Not required

Note: Low traffic: < 100,000 ESALs/year, Medium traffic: 100,000 to 1,000,000 ESALs /year, High traffic: 1,000,000 ESALs/year

Strategy #2: Adjustment of RCA Production Operations

The intended use of the RCA products should drive production operations in ways that maximize production efficiency, which means maximizing product yield (i.e., producing as much of the desired particle sizes as possible and minimizing waste) and doing so with a minimum expenditure of effort and consumption of fuel). For example, the production of RCA for use in new concrete mixtures often requires additional care to prevent the inclusion of contaminants (e.g., joint sealant material, reinforcing steel, and perhaps asphalt materials) and should be produced using breaking and crushing equipment that maximizes the production of useful size fractions. Conversely, the use of RCA in base or backfill operations will be less sensitive to the inclusion of minor amounts of contaminants and may permit the use of different types of breaking and crushing equipment to produce properly graded materials.

Strategy 2A: Customize Preparation and Breaking of Source Concrete

Removal of Asphalt Overlays and Patches – Concrete pavements with asphalt concrete patches and overlays can be processed to produce RCA for use in new concrete mixtures or other applications. Historically, the asphalt and concrete components have been recycled separately in the U.S., but some European countries routinely recycle concrete with up to 30 percent coarse RAP into new concrete paving mixtures without any apparent detrimental effects (Hall et al. 2007), and the Illinois Tollway has recently begun utilizing fractionated reclaimed asphalt pavement (FRAP) as a partial replacement for virgin coarse aggregate in the lower course of two-layer concrete pavement construction. The sustainability of these practices must be

evaluated for any given situation to determine whether it is better to recycle the asphalt materials separately (thereby making high use of the RAP) or to simply recycle the asphalt and concrete together and save the costs of separate recycling.

Pavement Breaking – The main purpose of pavement breaking is to size the material for ease of handling and transport to the crushing plant. Slabs are typically broken into pieces small enough to be easily lifted, transported, and processed by the primary crusher (typically 18 to 24 inches [457 to 610 mm] in diameter). Breaking processes that produce an excessive amount of fines (e.g., drop balls and vibrating beam breakers or resonant breakers) are not recommended for off-site processing operations because they tend to produce a greater amount of excessively small fragments that are not easily salvaged. Pavement breaking equipment and slab cracking patterns should be selected after considering the intended crushing operation and desired product yield and gradation. For example, impact crushers typically can handle larger broken concrete pieces than compression (jaw or cone) crushers, allowing the use of a larger crack pattern and often resulting in higher breaking production rates.

Strategy 2B: Customize Crushing and Sizing Operations

The yield of coarse RCA from the recycling operation depends upon many factors, including the crushing processes used. Crushing for larger aggregate particles generally produces higher coarse RCA yields because less crushing is necessary and fewer fines are produced. For example, 55 to 60 percent coarse RCA yield is common when crushing to 0.75 inches (19 mm) top size, while 80 percent yield is common when crushing to 1.5 inches (38 mm) top size (NHI 1998).

Jaw crushers tend to produce fewer fines than impact or cone crushers, resulting in higher yields of coarse RCA, which often is more useful than fine RCA, particularly in new concrete mixtures. Figure 8-6 shows the results of one study of the impact of crusher type on RCA particle size distribution for a particular concrete source.

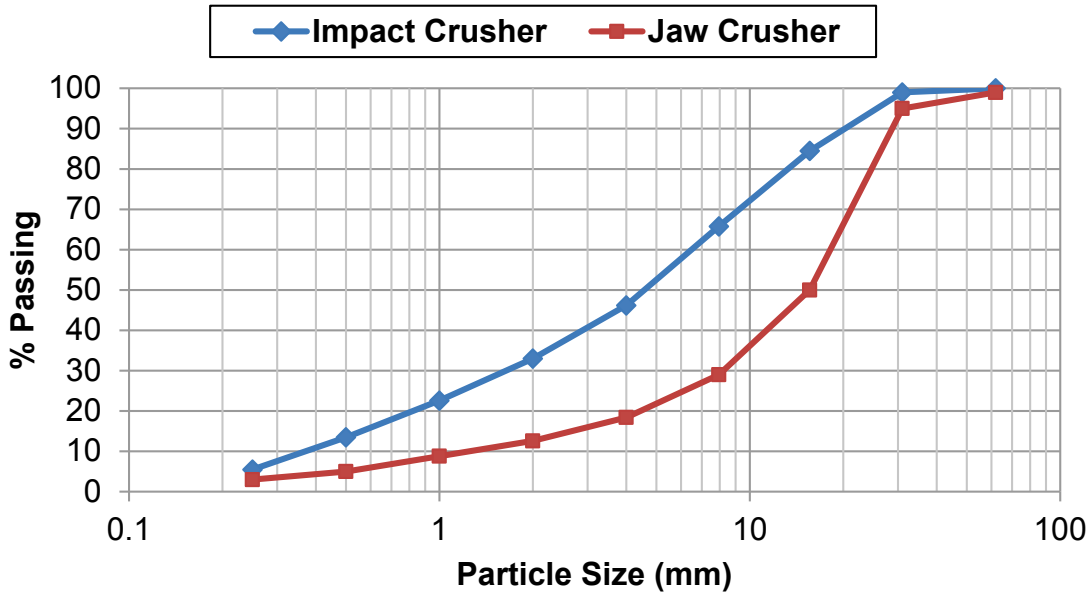


Figure 8-6. Example effect of type of crusher on RCA particle size distribution.

Impact and cone crushers often are more effective in removing most of the reclaimed mortar, producing RCA that looks and behaves similarly to the original virgin aggregate in the source concrete (although the yield of coarse RCA will be reduced). Impact crushers also can supply particle size distributions that are well suited for constructing unbound foundation layers (ACI 2001).

Strategy #3: Sequestration of CO2

Research has shown that RCA has significant value as a sink for CO_2 when atmospheric CO_2 reacts with calcium hydroxide ($Ca(OH)_2$), one of the principal phases resulting from cement hydration that is present in the concrete mortar, to produce calcium carbonate (Gardner, Leipold, and Peyranere 2006). The potential for carbon dioxide sequestration is equal to all of the CO_2 that was originally evolved from calcination of the raw materials used in the production of the cement (but not from the fuels used in production). Figure 8-7 shows an example of laboratory test results documenting CO_2 removal over time for various moisture conditions. This study suggests that the use of RCA in unstabilized applications (e.g., unstabilized subbases, embankment stabilization) has the potential to "scrub" the local atmosphere of significant quantities of CO_2.

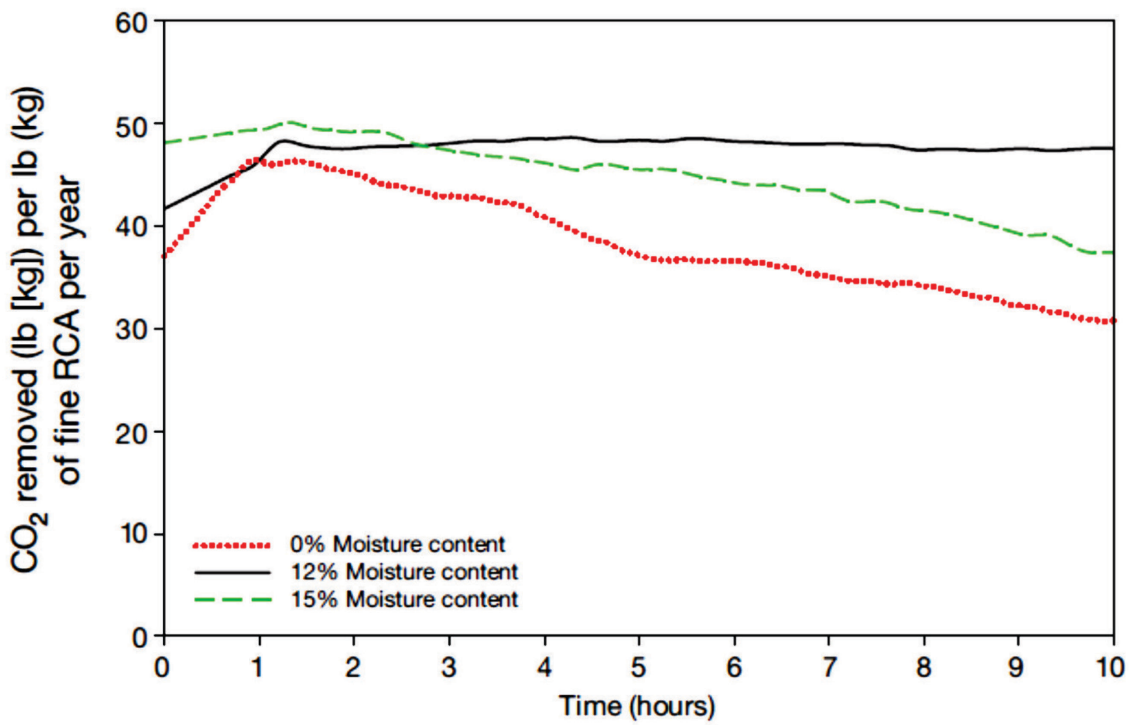


Figure 8-7. Carbon sequestration by fine RCA in laboratory column studies (Gardner, Leipold, and Peyranere 2006).

Strategy #4: On-Site vs. Off-Site Processing

When RCA is to be used in some component of the same project from which it was produced, substantial reductions in fuel consumption and emissions (as well as labor costs) can be achieved by processing the material at the construction site (as shown in figure 8-8) rather than by using an off-site facility. On-site processing also offers societal benefits (reductions in haul truck traffic and related traffic congestion and delays) and the potential for economic savings (which will be at least partially offset by the costs of setting up a portable crusher at the job site).

Figure 8-8. On-site concrete recycling operation.

When the RCA will be used in a foundation layer of the reconstructed pavement, additional sustainability benefits can be achieved through the use of a mobile crusher (an in-place concrete recycling train) that includes primary and secondary crushers that have been specially adapted for in-place recycling and are mounted on crawler tracks. Figure 8-9 shows a concrete recycling train working on a pavement recycling project.

Future Directions/Emerging Technologies

Current trends of increased and improved utilization of recycled concrete are expected to accelerate and continue for the foreseeable future, as highlighted in the following sections.

Increased Recycling (Reduced Disposal in Landfills)

Recent statistics on concrete recycling are difficult to find, but Wilburn and Goonan (1998) indicated that, while it is accepted that concrete pavement is 100 percent recyclable, only 50 to 60 percent of the 200 million tons (181 million mt) of concrete debris generated annually was being recycled in practice. This percentage has likely increased since 1998 due to national pushes by the FHWA and the development of a standard AASHTO specification for the use of RCA in new paving concrete. However, it is unlikely that 100 percent of all concrete paving demolition debris is currently being recycled or reused, so there is still room for concrete recycling initiatives to help in moving towards a zero-waste goal.

Figure 8-9. Recycling existing concrete pavement in place (photo courtesy of Jim Grove).

Improved Utilization of RCA Products

USGS (2000) reports that in 1997 only 15 percent of all recycled concrete aggregate were being used as aggregate in new concrete or asphalt concrete mixtures, which probably represents the highest type of application for recycled concrete aggregate. Seventy-eight percent was being used in base or landfill applications, which represents a relatively low value used for RCA.

It is understandable that many engineers are not comfortable with using RCA in higher type applications because of the ramifications of premature failures in a surface layer are usually more critical than when defects develop in lower pavement layers. In addition, there has not been widely accepted guidance on the use of recycled concrete aggregate in new asphalt and concrete mixtures. However, guidance on the production, characterization and use of recycled concrete aggregate has recently been developed in several forms, including:

- A technical bulletin from the American Concrete Pavement Association (ACPA 2009).
- A technical report by the American Concrete Institute (ACI 2001).
- Specifications from AASHTO.
  - AASHTO M319, “Reclaimed Concrete Aggregate for Unbound Soil-Aggregate Base Course.”
  - AASHTO MP16, “Reclaimed Concrete Aggregate for Use as Coarse Aggregate in Hydraulic Cement Concrete”
- Newer policies and technical advisories from the U.S. Federal Highway Administration (FHWA 2002 and FHWA 2007).

The advent of this level of technical support, combined with increased pressure for sustainable pavement construction, are certain to result in continued and improved high-type utilization of recycled concrete.

Concluding Remarks

This chapter describes the EOL phase of the pavement, particularly focusing on recycling, reuse, and disposal options for both asphalt and concrete pavements. Portions of the information presented in this chapter are also touched on in other chapters, including chapter 3 (materials), chapter 4 (design), chapter 5 (construction), and chapter 7 (maintenance and preservation).

Major issues associated with asphalt pavement EOL considerations are listed below:

- According to a survey conducted as part of an NCHRP Synthesis 421 (Stroup-Gardiner 2011), 33 out of 45 states have some experience with FDR. The implementation of in-place recycling—which includes cold in-place and hot in-place recycling in addition to FDR—is relatively low. Annual in-place recycling is less than 50 lane miles (80 lane km) in most of the states. However, central plant recycling is very common.
- Lack of mixture designs, specifications, and standards for project selection are some of the barriers for FDR applications.
- Uncertainty of future EOL consideration in the life-cycle assessment of pavements is a barrier for LCA calculations. Because of this uncertainty, pavements are not usually given credits for producing recyclable materials at the end of their life time.
- The quality of the recycled material remains a challenge for the pavement using recycled materials. The major question with pavement recycling is, how many times can a pavement be recycled without loss in the inherent properties?

Major issues associated with concrete pavement EOL considerations include:

- Source material: quality and overall properties of the source concrete must be evaluated to determine the potential uses of the RCA.
- Stockpile runoff and drainage effluent.
- Impact of RCA on pavement design and construction.
- Evaluation of existing pavement structure for concrete pavement reuse.

References

American Concrete Institute (ACI). 2001. *Removal and Reuse of Hardened Concrete*. ACI 555R-01. American Concrete Institute, Farmington Hills, MI.

Al-Qadi, I. L., M. Elseifi, and S. H. Carpenter. 2007. *Reclaimed Asphalt Pavement—A Literature Review*. FHWA-ICT-07-001. Illinois Department of Transportation, Springfield, IL.

American Concrete Pavement Association (ACPA). 2009. *Recycling Concrete Pavements.* Engineering Bulletin 043P. American Concrete Pavement Association, Skokie, IL.

Anderson, J. R. and M. R. Thompson. 1995. "Characterization of Emulsion Aggregate Mixtures." *Transportation Research Record 1492*. Transportation Research Board, Washington, DC.

Asphalt Academy. 2009. "Technical Guidelines 2: A Guideline for the Design and Construction of Bitumen Emulsion and Foamed Bitumen Stabilized Materials." Second Edition. *Bitumen Stabilized Materials.* Asphalt Academy, Pretoria, South Africa.

Asphalt Recycling and Reclaiming Association (ARRA). 2001a. *Full Depth Reclamation: A Century of Advancement for the New Millennium.* Asphalt Recycling and Reclaiming Association, Annapolis, MD.

Asphalt Recycling and Reclaiming Association (ARRA). 2001b. *Basic Asphalt Recycling Manual.* Asphalt Recycling and Reclaiming Association, Annapolis, MD.

Aurangzeb, Q. and I. Al-Qadi. 2014. "Asphalt Pavements with High Reclaimed Asphalt Pavement Content: Economic and Environmental Perspectives." *Transportation Research Record 2456*, Figure 3, p. 168. Copyright, National Academy of Sciences, Washington, DC. Reproduced with permission of the Transportation Research Board.

Aurangzeb Q., I. L. Al-Qadi, H. Ozer, and R. Yang. 2014. "Hybrid Life Cycle Assessment for Asphalt Mixtures with High RAP Content." *Resources, Conservation and Recycling*. Volume 83. Elsevier, Philadelphia, PA.

Bemanian, S., P. Polish, and G. Maurer. 2006. "Cold In-Place Recycling and Full-Depth Reclamation Projects by Nevada DOT: State of the Practice." *Transportation Research Record 1949.* Transportation Research Board, Washington, DC.

Berthelot, C., B. Marjerison, G. Houston, J. McCaig, S. Werrener, and R. Gorlick. 2007. "Mechanistic Comparison of Cement- and Bituminous-Stabilized Granular Base Systems." *Transportation Research Record 2026*. Transportation Research Board, Washington, DC.

Boguski, T. K., R. G. Hunt, and W. E. Franklin. 1994. "General Mathematical Models for LCI Recycling." *Resources, Conservation and Recycling*. Volume 12. Elsevier, Philadelphia, PA.

Brantley A. S. and T. G. Townsend. 1999. "Leaching of Pollutants from Reclaimed Asphalt Pavement." *Environmental Engineering Science*. Volume 16, Number 2. Elsevier, Philadelphia, PA.

Bruinsma, J. E. 1995. *Formation and Mitigation of Calcium Carbonate Precipitate and Insoluble Residue from Recycled Concrete Aggregate Bases.* M.S. Thesis. University of Minnesota Department of Civil Engineering, St. Paul, MN.

Bruinsma, J. E., K. R. Peterson, and M. B. Snyder. 1997. "A Chemical Approach to the Formation of Calcite Precipitate from Recycled Concrete Aggregate Base Layers." *Transportation Research Record 1577*. Transportation Research Board, Washington, DC.

California Department of Transportation (Caltrans). 2012. *Full Depth Reclamation Using Foamed Asphalt.* California Department of Transportation, Sacramento, CA.

Chesner, W., R. Collins, and M. MacKay. 1998. *User Guidelines for Waste and By-Product Materials in Pavement Construction*. FHWA-RD-97-148. Federal Highway Administration, McLean, VA. (Web Link).

Construction and Demolition Recycling Association (CDRA). 2014. *Good Economic Sense.* Construction and Demolition Recycling Association, Aurora, IL. (Web Link).

Construction Materials Recycling Association (CMRA). 2008. *Case Histories*. Construction Materials Recycling Association, Aurora, IL. (Web Link).

Dai, S., G. Skok, T. Westover, T. Labuz, and E. Lukanen. 2008. *Pavement Rehabilitation Selection*. Report No. MN/RC 2008-06. Minnesota Department of Transportation, St. Paul, MN. (Web Link).

Ekvall, T. and A. M. Tillman. 1997. "Open-Loop Recycling: Criteria for Allocation Procedures." *International Journal of Life Cycle Assessment*. Volume 2, Number 3. Springer, New York, NY.

Ekvall, T. and G. Finnveden. 2001. "Allocation in ISO 14041 – Critical Review." *Journal of Cleaner Production.* Volume 9, Issue 3. Elsevier, Amsterdam.

Environmental Protection Agency (EPA). 2009. *Recover Your Resources. Reduce, Reuse, and Recycle Construction and Demolition Materials at Land Revitalization Project.* EPA-560-F09-523. Environmental Protection Agency, Washington, DC. (Web Link).

Epps, J. A., D. N. Little, R. J. Holmgren, and R. L. Terrell. 1980. *Guidelines for Recycling Pavement Materials.* NCHRP Report 224. Transportation Research Board, Washington, DC.

Federal Highway Administration (FHWA). 2002. *Formal Policy on the Use of Recycled Materials.* Federal Highway Administration, Washington, DC. (Web Link).

Federal Highway Administration (FHWA). 2007. *Use of Recycled Concrete Pavement as Aggregate in Hydraulic-Cement Concrete Pavement*. Technical Advisory T 5040.37. Federal Highway Administration, Washington, DC.

Franco, S., S. P. Moss, D. Yuan, and S. Nazarian. 2009. *Design, Constructability Review and Performance of Dual Base Stabilizer Applications*. FHWA/TX-09/0-5797-1. Texas Department of Transportation, Austin, TX.

Fu, P., D. Jones, and J. T. Harvey. 2011. "The Effects of Asphalt Binder and Granular Material Characteristics on Foamed Asphalt Mix Strength." *Construction and Building Materials.* Volume 25, Issue 2. Elsevier, Amsterdam.

Gardner, K. H., J. Leipold, and S. C. Peyranere. 2006. *Concrete Carbonation*. Project 12 Final Report. Recycled Materials Resource Center, University of New Hampshire, Durham, NH.

Hall, K., D. Dawood, S. Vanikar, R. Tally Jr., T. Cackler, A. Correa, P. Deem, J. Duit, G. Geary, A. Gisi, A. Hanna, S. Kosmatka, R. Rasmussen, S. Tayabji, and G. Voigt. 2007. *Long-Life Concrete Pavements in Europe and Canada*. FHWA-PL-07-027. Federal Highway Administration, Washington, DC. (Web Link).

Halm, H. J. 1980. "Concrete Recycling." *Transportation Research News*. Volume 89. Transportation Research Board, Washington, DC.

Hansen K. R. and A. Copeland. 2013. *Asphalt Pavement Industry Survey on Recycled Materials and Warm-Mix Asphalt Usage: 2009–2012*. Information Series 138. National Asphalt Pavement Association, Lanham, MD. (Web Link).

Horvath, A. 2003. *Life-Cycle Environmental and Economic Assessment of Using Recycled Materials for Asphalt Pavements*. University of California Transportation Center, Berkeley, CA.

Horvath, A. 2004. *A Life-Cycle Analysis Model and Decision-Support Tool for Selecting Recycled Versus Virgin Materials for Highway Applications*. RMRC Research Project No 23. Federal Highway Administration, Washington, DC.

Huang Y., A. Spray, and T. Parry. 2013. "Sensitivity Analysis of Methodological Choices in Road Pavement LCA." *International Journal of Life Cycle Assessment*. Volume 18, Issue 1. Springer, New York, NY.

International Organization for Standardization (ISO). 2006. *Environmental Management – Life Cycle Assessment – Requirements and Guidelines*. ISO Standard 14044. International Organization for Standardization, Geneva, Switzerland.

Jones, D., P. Fu, and J. T. Harvey. 2008. *Full-Depth Pavement Reclamation with Foamed Asphalt in California: Guidelines for Project Selection, Design, and Construction*. UCPRC-GL-2008-01 CA101069D. University of California Pavement Research Center, Berkeley, CA.

Jooste, F. and F. Long. 2007. *A Knowledge Based Structural Design Method for Pavements Incorporating Bituminous Stabilized Materials*. Draft Technical Memorandum. Gauteng Department of Public Transport, Roads and Works and Southern Africa Bitumen Association (SABITA), Pinelands, South Africa.

Kuennen, T. 2007. "The Economics of Recycling." *Rock Products*. Volume 110, Number 10. Mining Media, International, Denver, CO.

Legret M., L. Odie, D. Demare, and A. Jullien. 2005. "Leaching of Heavy Metals and Polycyclic Aromatic Hydrocarbons from Reclaimed Asphalt Pavement." *Water Research*. Volume 39, Number 15. Elsevier, Philadelphia, PA.

Lehmann, S. 2013. "Optimizing Urban Material Flows and Waste Streams in Urban Development through Principles of Zero Waste and Sustainable Consumption." *Sustainable Solid Waste Management*. Apple Academic Press Inc., Point Pleasant, NJ.

Mallick, R. B., D. S. Bonner, R. L. Bradbury, J. O. Andrews, P. S. Kandhal, and E. J. Kearney. 2002. "Evaluation of Performance of Full-Depth Reclamation Mixes." *Transportation Research Record* 1809. Transportation Research Board, Washington, DC.

Matthews, D.M. 2008. "Contractors Perspective on Successful Construction of CIR and FDR." *Proceedings, First Western States Regional In-Place Recycling Conference*. Salt Lake City, UT.

Nantung, T., Y. Ji, and T. Shields. 2011. "Pavement Structural Evaluation and Design of Full-Depth Reclamation (FDR) Pavement." *Paper 11-2026, 2011 TRB Annual Meeting*. Transportation Research Board, Washington, DC.

National Highway Institute (NHI). 1998. *Techniques for Pavement Rehabilitation: A Training Course – Participant's Manual*. FHWA-HI-99-006. National Highway Institute, Federal Highway Administration. Washington, DC.

Niazi, Y. and M. Jalili. 2009. "Effect of Portland Cement and Lime Additives on Properties of Cold In-Place Recycled Mixtures with Asphalt Emulsion." *Construction and Building Materials*. Volume 23, Issue 3. Elsevier, Amsterdam.

Nicholson, A. L., E. Olivetti, J. R. Gregory, F. R. Field, and R. E. Kirchain. 2009. "End-of-Life LCA Allocation Methods: Open Loop Recycling Impacts on Robustness of Material Selection Decisions." *IEEE International Symposium*. Institute of Electrical and Electronics Engineers. (Web Link).

Reiner, M. 2008. *Evaluation of Potential pH Environmental Hazards and Mitigation Measures when Utilizing Recycled Concrete Aggregate in the Field*. Symbiotic Engineering Green Paper Number Six. Symbiotic Engineering, Boulder, CO.

Sadecki, R. W., G. P. Busacker, K. L. Moxness, K. C. Faruq, and L. G. Allen. 1996. *An Investigation of Water Quality in Runoff from Stockpiles of Salvaged Concrete and Bituminous Paving*. MN/PR – 96/31. Minnesota Department of Transportation, St. Paul, MN.

Saeed, A. 2008. *Performance-Related Tests of Recycled Aggregates for Use in Unbound Pavement Layers*. NCHRP Report 598. Transportation Research Board, Washington, DC.

Santero, N., E. Masanet, and A. Horvath. 2011. "Life-Cycle Assessment of Pavements Part II: Filling the Research Gaps." *Resources, Conservation, and Recycling*. Volume 55, Issues 9-10. Elsevier, Amsterdam.

SEM Materials. 2007. *Guidelines for Asphalt Emulsion Full Depth Reclamation (FDR)*. Version2a-3. SEM Materials, Tulsa, OK.

Smith, C. R., D. E. Lewis, and D. M. Jared. 2008. "Georgia's Use of Lime in Full-Depth Reclamation." *Transportation Research Record 2059*. Transportation Research Board, Washington, DC.

Snyder, M. B. 1995. *Use of Crushed Concrete Products in Minnesota Pavement Foundations*. 96-12. Minnesota Department of Transportation, St. Paul, MN.

Snyder, M. B. and J. E. Bruinsma. 1996. "A Review of Studies Concerning the Effects of Unbound Crushed Concrete Bases on PCC Pavement Drainage." *Transportation Research Record 1519*. Transportation Research Board, Washington, DC.

Stroup-Gardiner, M. 2011. *Recycling and Reclamation of Asphalt Pavements Using In-Place Methods*. NCHRP Synthesis of Highway Practice 421. Transportation Research Board, Washington, DC.

Tamirisa, R. 1993. *Study of Highway Base/Subbase Aggregates That Cause Depositions of Calcareous Tufa in Drains*. Master's Thesis. Department of Civil Engineering, University of Toledo, Toledo, OH.

Thompson, M. R, L. Garcia, and S. H. Carpenter. 2009. *Cold In-Place Recycling and Full-Depth Recycling with Asphalt Products*. FHWA-ICT-09-036. Illinois Center for Transportation, Rantoul, IL.

U.S. Geological Survey (USGS). 2000. *Recycled Aggregates – Profitable Resource Conservation*. USGS Fact Sheet FS-181-99. U.S. Geological Survey, U.S. Department of the Interior, Washington, DC. (Web Link).

Ventura A., P. Monéron, and A. Jullien. 2008. "Environmental Impact of a Binding Course Pavement Section, with Asphalt Recycled at Varying Rates." *Road Materials and Pavement Design*. Volume 9, Supplement 1. Taylor & Francis, London.

Wilburn, D. and T. Goonan. 1998. *Aggregates from Natural and Recycled Sources–Economic Assessments for Construction Applications*." Circular 1176. U.S. Geological Survey, U.S. Department of the Interior, Washington, DC. (Web Link).

Wirtgen. 2004. *Wirtgen Cold Recycling Manual*. Second Edition. Wirtgen GmbH, Windhagen, Germany.

Won, M. 2007. "Use of Crushed Concrete as Coarse Aggregates in Concrete Pavement." *Proceedings, International Workshop on Best Practices for Concrete Pavements*. Recife, Brazil. IBRACON. São Paolo, Brazil.