CHAPTER 7. MAINTENANCE AND PRESERVATION TREATMENTS TO IMPROVE SUSTAINABILITY

Introduction

Diminishing budgets and the recent recognition of the benefits of considering life-cycle costs have motivated changes in agency policies that advocate environmental and financial sustainability through the practice of pavement preservation. This is in stark contrast to the "worst-first" approach that was commonly practiced in the past, in which pavements were allowed to deteriorate to a highly distressed condition before performing major (and more intrusive) rehabilitation. In fact, the FHWA has been a strong proponent and supporter of the concept of cost effectively preserving the nation's pavement network. This has helped to spur a nationwide movement of pavement preservation and preventive maintenance programs, with an overall goal of improving safety and mobility, reducing congestion, and providing smoother, longer lasting pavements (Geiger 2005).

Incorporating Pavement Preservation into the AASHTOWare Pavement ME Design Software

A recently completed study for the National Cooperative Highway Research Program (Project 1-48) investigated different approaches for incorporating pavement preservation into the pavement design process, and specifically into the AASHTOWare Pavement ME Design software. The project identified several procedures and approaches for designing asphalt and concrete pavement structures so that they account for the effects of future scheduled preservation treatments (e.g., chip seals, thin overlays, diamond grinding, partial-depth repair) on pavement life. By designing a pavement to include preservation at key points in its life and carrying through with the application of those treatments once the pavement has been put into service, the pavement can be kept in better overall condition with less disruption to traffic because of delayed and less frequent rehabilitation treatments. This preservation-based design philosophy represents a sustainable approach to building and maintaining highway infrastructure, as it optimizes the use of pavement materials and minimizes the amount of energy and resources used in keeping the infrastructure in good condition.

Pavement preservation is inherently a sustainable activity. It often employs low-cost, low-environmental-impact treatments to prolong or extend the life of the pavement by delaying major rehabilitation activities. This conserves energy and virgin materials while reducing GHG emissions over the life cycle. Furthermore, as mentioned above, well-maintained pavements provide smoother, safer, and quieter riding surfaces over a significant portion of their lives, resulting in higher vehicle fuel efficiencies, reduced crash rates, and lower noise impacts on surrounding communities, which positively contributes to their overall sustainability. The philosophy of pavement preservation is often succinctly captured in terms of "applying the right treatment to the right pavement at the right time."

This chapter describes the impact that maintenance and preservation treatments have on the sustainability of pavement systems. It first describes the role that pavement management systems play in the pavement planning and decision making of highway agencies, and how they can incorporate preservation programs. This is followed by a review of common maintenance and preservation treatments for both asphalt and concrete pavements, and an assessment of how these various treatments impact sustainability. It is important to point out that only limited information exists in this regard, so much of the information is conjectural at this stage. This chapter does not delve into the details of the materials or the specific construction details of the various treatments, as there are a number of manuals and documents covering those aspects.

Pavement Preservation and Sustainability

Pavement Management Systems and Pavement Preservation

Since their conceptualization in the late 1960s and initial implementation by state highway agencies beginning in the late 1970s, the use of pavement management systems (PMS) has grown considerably. The benefits of pavement management are well documented, and include:

- Enhanced planning ability at all levels, including strategic, network, and project.
- Decision making based on observed and forecasted conditions rather than opinions.
- The ability to generate alternate scenarios for future pavement conditions based on different budget scenarios or management approaches.

Many state highway agencies have been using pavement management systems to demonstrate to legislators the benefits of pavement preservation in maintaining or improving the overall condition of the pavement network (Zimmerman and Peshkin 2003). Figure 7-1 shows a schematic that illustrates how pavement preservation can help extend the life of the pavement, delaying the need for major (and more costly) rehabilitation activities.

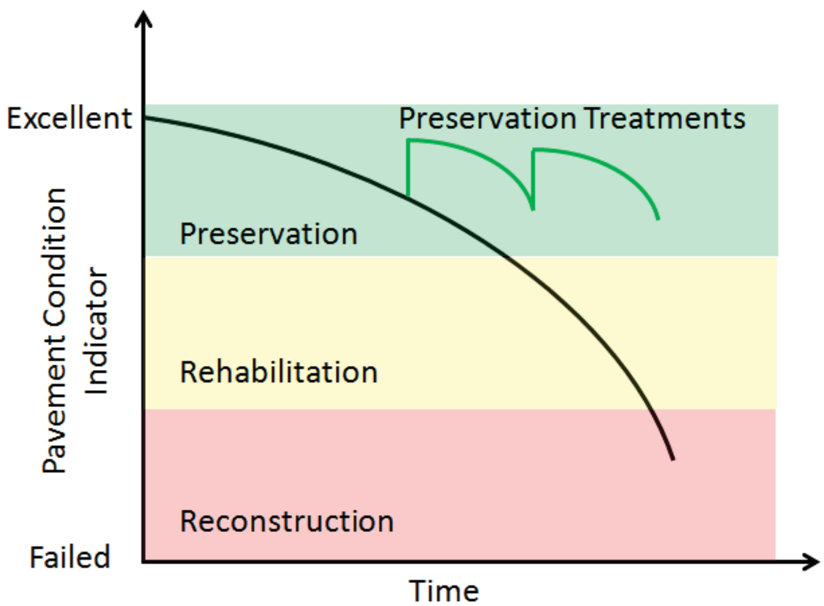

Figure 7-1. Illustration of the impact of pavement preservation.

Integrating PMS and Pavement Preservation

The integration of pavement preservation into pavement management requires a deliberate effort on the part of transportation agencies to reevaluate their existing data collection activities, to revise and update performance modeling approaches, and to improve overall program development activities. The desired outcome (and ultimate goal) is that the need for pavement preservation treatments, and their timing of application, can be identified within the pavement management system, and that the benefits realized from the application of the treatments can be accounted for in the system's optimization analysis. The critical steps involved in the integration of PMS and pavement preservation are summarized in figure 7-2.

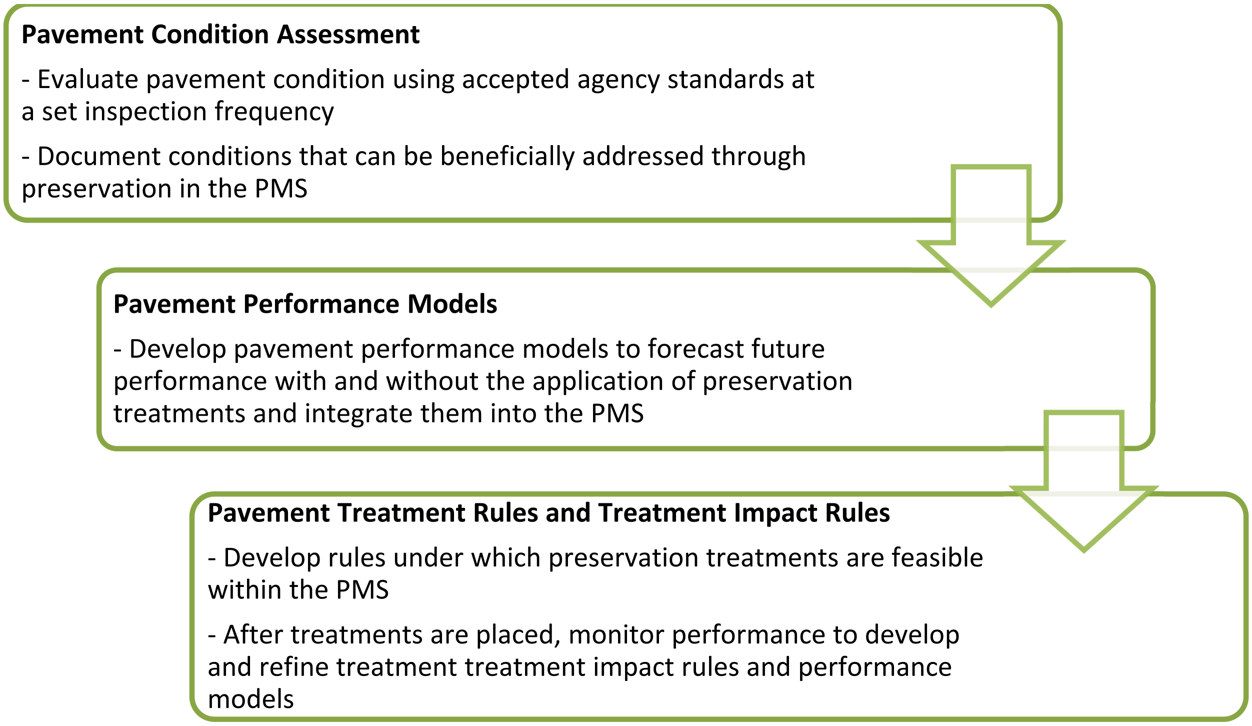

Figure 7-2. Steps in integrating PMS and pavement preservation (adapted from Zimmerman and Peshkin 2003).

General Pavement Preservation Strategies for Improving Sustainability

Major Issues:

- ✓ *Lack of life cycle inventories specific to maintenance and preservation activities.*
- ✓ *Cost effectiveness has been investigated and widely accepted.*
- ✓ *Impact of traffic.*
- ✓ *Treatment and material selection.*
- ✓ *Construction quality.*

Pavement preservation is primarily concerned with minimizing the project-level life-cycle cost of the agency. To minimize the agency life-cycle cost, only the materials and construction phases of the pavement life cycle are considered, since use-phase costs (primarily vehicle operating costs) are mostly borne by pavement users and not by the agency. For low-volume roads, where the environmental impact of vehicle operations is small, improvements in the agency life-cycle cost and improvements in sustainability are generally compatible, since the objective for both is to minimize the frequency of treatment applications and the amount of material used for each treatment. Assuming that preservation treatments all generally use combinations of aggregate, water, cement, and asphalt as construction materials and that internal combustion engines are used in their placement (e.g., the transport, removal, and application of the treatment and associated waste), the environmental impact of pavement treatments is roughly linearly proportional to the total thickness of the treatment, whether it is a milling/grinding activity, a surface treatment, or an overlay. Therefore, for low-volume routes, the general strategy for improving sustainability is to minimize the amount of materials used and the number of construction cycles over the life cycle by optimizing the treatment selection and timing to avoid major structural damage while minimizing costs.

For higher traffic volume roadways, the environmental impact of the use phase becomes more important, often to the point that, for very high-volume routes, the materials and construction phase impacts of maintenance and preservation become very small relative to the influence of the pavement smoothness, deflection, and macrotexture on vehicle operations (primarily in terms of fuel economy). Depending on the route, the optimization of the environmental benefit will require balancing the impacts incurred to keep the pavement in good condition (in order to reduce vehicle operating costs) with the impacts resulting from materials production and construction of the treatment. An example of this is provided in chapter 6, in which the optimization of ride quality (in terms of IRI) to minimize CO_2 emissions is presented for routes with different levels of traffic and considering materials, construction, and vehicle use. The optimization of environmental benefits for high-volume routes is, therefore, much more complex than it is for low-volume routes because it may increase agency economic life-cycle cost as the need for more frequent treatment is increased to maintain good condition to reduce road user costs and vehicle-produced emissions.

An example of this situation for high-volume routes is illustrated in figure 7-3 for asphalt concrete overlays placed at different recurring intervals on a high-volume interstate highway. The placement of the asphalt concrete overlays at different recurring intervals results in varying amounts of cumulative agency GHG emissions (expressed in terms of CO_2e). In the figure, it can be seen that the cumulative agency GHG emissions from materials production and construction decrease as the overlay interval increases from 10 years (when the IRI is expected to be 136 in/mi [2.2 m/km]) to 30 years (when the IRI is expected to be 273 in/mi [4.4 m/km]), while the cumulative user GHG emissions increase from vehicles operating on a rougher pavement. For this example, it is also observed that the net emissions are minimized at an overlay interval of 22 years; however, the IRI is 211 in/mi (3.4 m/km) at this age interval and the GHG emissions due to increased roughness may potentially offset any benefits obtained. This is but one example and the results change considerably depending on the expected overlay performance, the traffic levels, and the emissions from materials, construction, and end-of-life scenarios. Nevertheless, the application of such multi-criteria decision-making tools and approaches can be used as a way of balancing trade-offs between environmental goals and life-cycle cost goals.

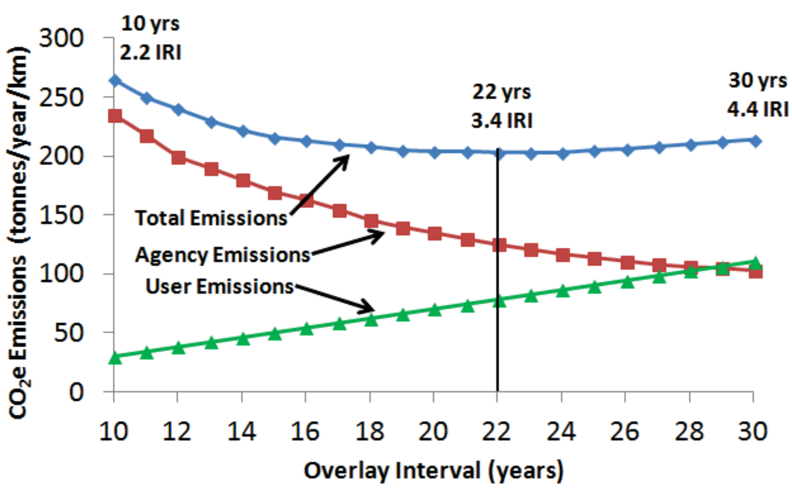

Figure 7-3. Effect of overlay interval on agency, user and total GHG (CO_2e) emissions (Lidicker et al. 2013*).

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To summarize, the selection of the right treatment for existing conditions is always important to improve sustainability. Most agencies are focused on minimizing agency economic life-cycle cost while preserving the pavement structure. For low-traffic-volume routes, minimization of agency life-cycle cost through the right timing of the right treatment also generally improves sustainability. The selection of the right treatment for existing conditions is also important for reducing agency life-cycle costs for higher traffic volume routes. However, as traffic levels increase, more frequent maintenance and preservation treatments can further reduce environmental impacts (in terms of its effect on the use phase), albeit at a higher agency cost.

Preservation Treatment Selection

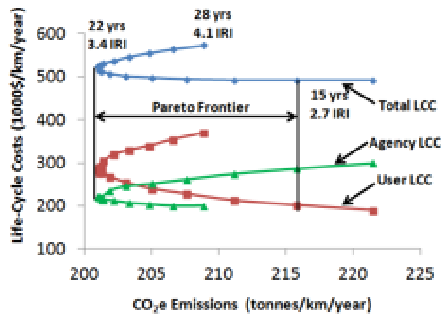
The selection of appropriate preservation treatments must consider the variables that are most important in the decision-making process. These variables may include factors that differ from those considered in identifying and selecting rehabilitation activities. The literature suggests that the following factors be considered in selecting appropriate pavement preservation treatments (Hicks, Seeds, and Peshkin 2000):

- Existing pavement type.
- Type and extent of distress.
- Climate.
- Cost of treatment.
- Availability of qualified contractors.
- Time of year of placement.
- Duration of lane closures.
- Traffic loading and expected life.
- Availability of quality materials.
- Pavement noise and surface friction.

A sequential approach for evaluating possible preservation treatments for an existing pavement and identifying the preferred alternative is provided in figure 7-4.

Reconciling Life-Cycle Costs and Environmental Impacts: A Quantitative Approach

One approach to evaluating both costs and environmental effects is to perform a Pareto analysis where the two criteria for decision making are plotted together. The example shown below illustrates the LCC and GHG emissions associated with several different overlay intervals/trigger roughness levels.



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Using this type of information, a final selection can be made from those alternatives that are on the "Pareto Optimal Frontier" where an increase in life-cycle cost results in a decrease in GHG emissions, or vice versa. In this example, this is the set of options on the lower portion of the life cycle cost (LCC) curves labeled "Pareto Frontier." The alternatives on the upper part of the curves are not optimal because there are alternatives with lower life-cycle costs with the same GHG emissions. The options on the lower portion of the Total LCC curve to the right of the Pareto Frontier (less than 15 years and 137 in/mi [2.7 m/km]) are not optimal because there is a slight minimum at that point. The point on the Pareto Frontier selected for overlay frequency for this pavement section would depend on the relative values placed on life-cycle cost and life-cycle CO_2e emissions by the agency, or specific cost or sustainability constraints placed on the project by the agency, which might narrow the range of acceptable values on the Pareto Optimal Frontier. Although simple tools for this type of analysis are not yet widely available, this example illustrates an approach for considering both life-cycle cost and sustainability (Lidicker et al. 2013).

*http://wwwcf.fhwa.dot.gov/exit.cfm?link=http://cedb.asce.org/cgi/WWWdisplay.cgi?302677

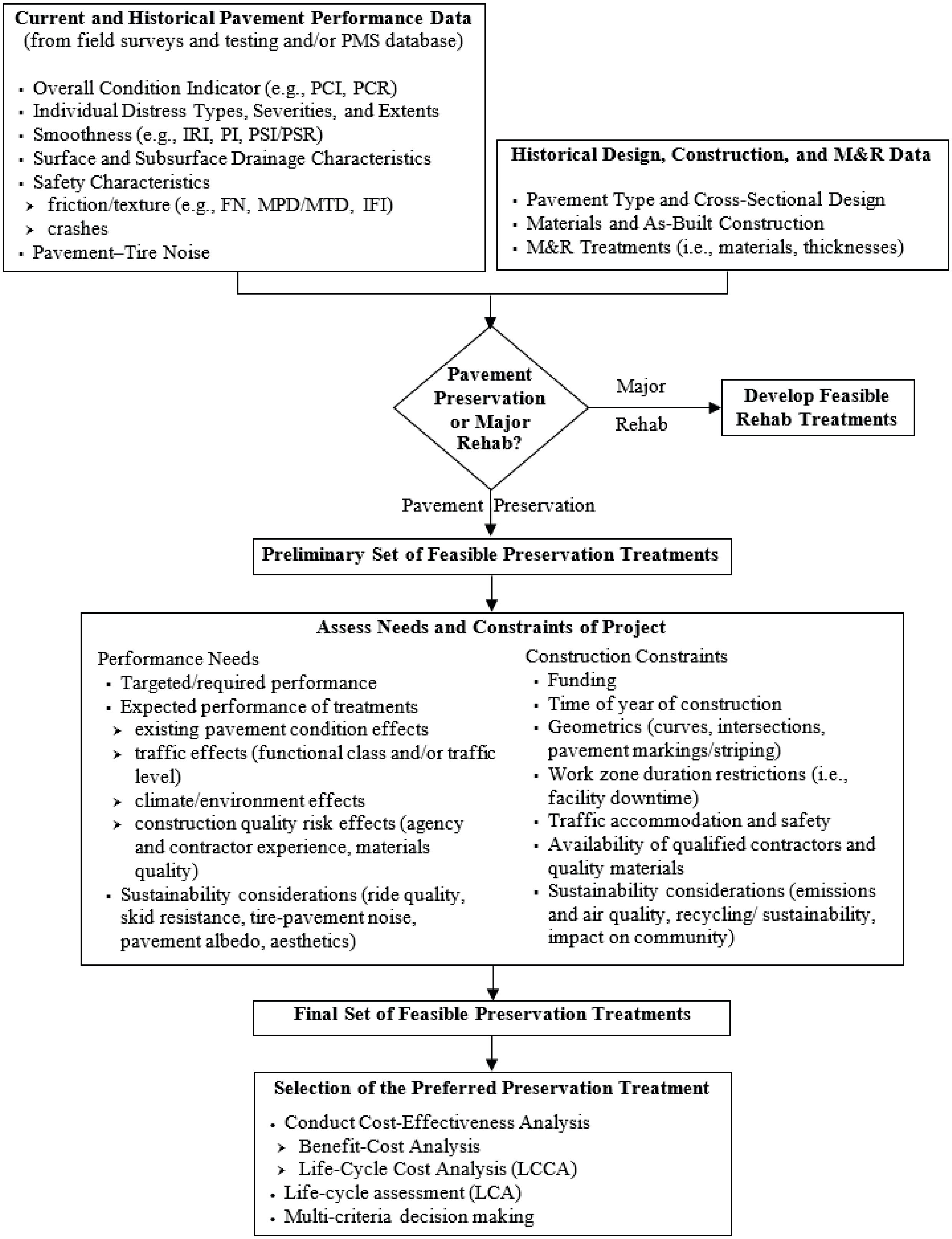

Figure 7-4. Process of selecting the preferred preservation treatment (adapted from Peshkin et al. 2011).

The rest of this chapter discusses various pavement maintenance and preservation techniques for asphalt and concrete pavements, particularly in terms of their associated benefits or costs with regards to enhancing sustainability. These benefits and costs are expressed in terms of the level of performance, performance longevity, congestion, lane closure durations, fuel consumption, as well as many others. Table 7-1 lists the maintenance and preservation treatments included in this discussion.

Table 7-1. Pavement maintenance and preservation techniques.

Asphalt	Concrete
Crack Filling/Sealing	Joint/Crack Sealing
Asphalt Patching	Slab Stabilization/Slab Jacking
Fog Seals/Rejuvenators	Diamond Grinding/Grooving
Chip Seals	Partial-Depth Repairs
Slurry Seals	Full-Depth Repairs
Microsurfacing	Dowel Bar Retrofit
Ultra-thin and Thin Asphalt Overlays	Slot/Cross Stitching
Hot In-Place Recycling	Retrofitted Edge Drains
Cold In-Place Recycling	Ultra-thin Bonded Wearing Course
Ultra-thin Bonded Wearing Course	Bonded Concrete Overlays
Bonded Concrete Overlays	

Whereas there is abundant literature available on the topics of how pavement materials, design, and construction influence sustainability, far less information is available on how pavement maintenance and preservation treatments and practices impact sustainability. One recent project (TRB 2012) concluded that environmental sustainability research related specifically to post-construction operations is an emerging field and that the consideration and quantification of the sustainability associated with pavement maintenance and preservation programs is not commonly practiced in the United States.

A concise summary of the potential applicability of RCWMs and other emerging techniques/materials for use in pavement maintenance and preservation treatments is shown in table 7-2 (TRB 2012). Although it is generally simply assumed that maintenance and preservation is inherently sustainable, the details of treatment type, placement frequency, and functional condition levels (especially roughness) affecting environmental impacts are not necessarily addressed.

Table 7-2. Potential use of non-traditional materials and techniques with potential pavement maintenance and preservation application (TRB 2012).

Material/ Technique	Literature Cited	Possible Preservation Uses	Possible Maintenance Uses	Remarks
Bio-Fluxing Agent	Denevillers (2010)	• Prime Coat • Chip Seal • Microsurfacing	• Overlay tack coat • Cold mix • Warm mix	Trade name is Vegeflux®
Bio Binder	Denevillers (2010)	• Chip Seal • Microsurfacing	• Cold in-place recycling • Chip seals • Road marking	Trade name is Vegecol®
Recycled Concrete Aggregate (RCA)	Gardner and Greenwood (2008)	• Bonded Concrete Overlay	• Full-depth patching • Partial-depth patching	RCA acts to sequester CO_2 in addition to recycling
Recycled Glass Gravel	Melton and Morgan (1996)	• Untried	• Unbound base courses	Potential use on gravel roads
Fly Ash	MnDOT (2005)	• Microsurfacing mineral filler • Slurry seal mineral filler • Concrete Overlays	• Concrete maintenance mixtures • Microsurfacing	Widely used in a variety of products
Bottom Ash	Carpenter and Gardner (2007)	• Microsurfacing mineral filler	• Subbase under gravel surfaces	
Flue Gas Desulfurization Gypsum	Benson and Edil (2009)	• Microsurfacing mineral filler • Slurry seal mineral filler	• Concrete maintenance mixtures	
Kiln Dust	MnDOT (2005)	• Prime coat • Microsurfacing	• Prime coat • Microsurfacing	
Baghouse Fines	Denevillers (2010)	• Microsurfacing mineral filler • Slurry seal mineral filler	• Untried	
Crushed Slag	Chappat and Bilal (2003)	• Chip seal aggregate	• Special binder road mixture	
Ultra-High Pressure Water Cutter	Pidwerbesky and Waters (2007)	• Restore macrotexture on chip seals	• Retexture chip-sealed roads prior to resealing	Uses no virgin material and the sludge can be recycled as precoating for chip seal aggregates
Shotblasting	Gransberg (2009)	• Restore microtexture on polished HMA and PCC pavements	• Restore skid resistance on resealed PCC bridge decks	Uses no virgin material and the steel shot is recycled for reuse in the process
Recycled Motor Oil	Waters (2009)	• Dust palliative • Otta Seals	• Otta seal as surface course	Motor oil is refined before use
Recycled Tire Rubber	Beatty et al. (2002)	• Chip seals • Thin overlay	• Chip seals • Thin overlays	Also found to reduce road noise

Asphalt-Surfaced Pavement Maintenance and Preservation Treatments

Introduction

Asphalt-surfaced pavements include any pavement surfaced with an asphalt material, whether asphalt concrete (i.e., HMA, WMA) or an asphalt surface treatment of some type. Although this represents a large family of different pavement types, the maintenance and preservation activities are identical.

Table 7-3 presents an overall summary of various maintenance and preservation treatments applicable to asphalt-surfaced pavements. First, it provides a brief description of the technique and then indicates its effect on a number of preventive and restorative benefits ("↑" indicates positive impact, "↓" indicates negative impact, and "↔" indicates both positive and negative impacts). This is followed by a general assignment of the relative life expectancy and cost, and the relative environmental and social impacts. It is noted that these relative comparisons are inherently non-specific, by definition, due to the general lack of available information and the broad number of variables that affect the performance, costs, life-cycle environmental impacts, and social impacts of each treatment. The relative comparisons will also vary depending on the traffic levels, climate region, and a host of other variables.

Various resources are available that discuss each treatment type, including the type of pavement conditions addressed, how each should be constructed, and their cost effectiveness. These include a series of three courses offered by the National Highway Institute (NHI Course Nos. 131115, 131103, and 131116), a series of webinars on key concepts and guidelines related to asphalt pavement maintenance, preservation, and recycling developed by the Asphalt Institute (http://www.asphaltinstitute.org/public/asphalt_academy/webinars/index.dot), and a manual on basic asphalt recycling and reclaiming concepts published by the Asphalt Recycling and Reclaiming Association (ARRA) and the FHWA, among others. As considerable information is readily available regarding the proper timing, cost effectiveness, and construction of the various treatments, the following sections specifically address the sustainability aspects of each treatment, focusing on the environmental and social impacts.

Crack Filling/Sealing

Crack filling (see figure 7-5) involves the process of placing an adhesive material (generally a lower quality, non-polymerized or polymerized cold-pour emulsion asphalt binder) into or over non-working cracks (cracks that are not expected to open and close with temperature changes) to reduce the infiltration of moisture and incompressible materials into the pavement structure (FHWA 1999; Peshkin et al. 2011). Typically very little preparation of the crack is performed prior to the installation of the filler material.

Figure 7-5. Installation of hot-applied sealant.

Table 7-3. Evaluation of sustainability impacts of treatments for asphalt-surfaced pavements.

Treatment	Description	Preventive		Restorative					Performance and Cost		Relative Environmental Impact based on life cycle energy use and GHG emissions, materials (Low, Medium, High, Variable)	Societal Impact
		Seal Pavement	Rejuvenate Surface	Addresses Surface Distress	Eliminate Stable Ruts	Improves Texture for Friction	Improves Ride Quality and Surface Profile	Improve Texture for Noise	Relative Treatment Life (✓ to ✓✓✓✓)	Relative Cost ($ to $$$$)		
Crack Filling	Placement of adhesive material into and/over non-working cracks, minimal crack preparation, lower-quality materials used	↑		↑ Cracking only		↓ Longitudinal overbanding can negatively impact friction	Overbanding may increase roughness; sealing cracks may slow development of roughness	↔ Overbanding increases noise	✓	$	Low	Reduced traffic delays, less pleasing aesthetics, potential roughness and noise issues
Crack Sealing	Placement of adhesive material into and/over working cracks, good crack preparation, high-quality materials used	↑		↑ Cracking only		↓ Longitudinal overbanding can negatively impact friction		↔ Overbanding increases noise, filling can reduce noise	✓	$	Low	Reduced traffic delays, less pleasing aesthetics, potential roughness issues
Asphalt Patching	Used to treat localized distresses; partial-depth patches address surface distresses and full-depth patches address structural distresses	↑		↑	↑				✓✓	$$	Variable Depends on amount of patching and improvement gained in structural life and ride quality	Reduced traffic delays compared to other treatments; negative impact on ride quality and noise, poor aesthetics (if patching is substantial)
Fog Seal/ Rejuvenators	Very light application of asphalt emulsion on pavement surface to seal the existing asphalt surface	↑	↑			↓ (May negatively impact skid resistance)			✓	$	Medium Depends in part on materials	Reduced traffic delays; improves aesthetics
Chip Seals	Sprayed application of asphalt (usually emulsion, heated asphalt cement and cutbacks also used) followed by aggregate chips roller to achieve 50 to 70% embedment. Cost and performance depends on whether it is single or multi-course, as well as binder type and aggregate quality	↑		↑		↑	↑ Depends largely on number of courses placed	↓ Depends on chip size	✓✓	$$	Medium to High Depends on number of courses and binder type	Increases safety by improving friction, reduced traffic delays due to faster construction and opening to traffic; reduced ride quality due to rough surface, potential vehicle damage due to loose aggregate chips
Slurry Seals	Mix of well-graded aggregate (fine sand and mineral filler) and asphalt emulsion spread over entire pavement surface	↑	↑			↑			✓✓	$$	Medium	Increases safety by improving friction, reduced traffic delays due to faster construction and opening to traffic; improves aesthetics. Lower albedo may negatively impact UHI effect

Table 7-3. Evaluation of sustainability impacts of treatments for asphalt-surfaced pavements (continued).

Treatment	Description	Preventive		Restorative					Performance and Cost		Relative Environmental Impact based on life cycle energy use and GHG emissions, materials (Low, Medium, High, Variable)	Societal Impact
		Seal Pavement	Rejuvenate Surface	Addresses Surface Distress	Eliminate Stable Ruts	Improves Texture for Friction	Improves Ride Quality and Surface Profile	Improve Texture for Noise	Relative Treatment Life (✓ to ✓✓✓✓)	Relative Cost ($ to $$$$)		
Microsurfacing	Mix of crushed, well-graded aggregate, mineral filler, and latex-modified emulsified asphalt spread over entire pavement surface. Cost and performance depends on whether single, double, or multiple-course	↑	↑	↑	↑	↑	↑	↑ Depends on system	✓✓✓	$$	Variable Highly dependent on system and materials used, longevity of treatment, and improvements gained in ride quality	Increases safety by improving friction and eliminating stable ruts; reduced traffic delays due to faster construction and opening to traffic; improves aesthetics. Lower albedo may negatively impact UHI effect
Ultra-thin and Thin HMA Overlay: Dense-Graded	Asphalt binder (may be polymerized) and dense-graded aggregate combined in central mixing placement and placed with paver in thickness ranging from 0.625 to 0.75 in. for ultra-thin and 0.75 to 1.5 in. for thin overlays. Cost and performance depends on binder type and whether milling is performed prior to treatment placement	↑		↑	↑	↑	↑	↑	✓✓✓✓	$$$	High Use of WMA may reduce construction impact (see Chapter 3)	Improved ride quality; improved safety through improved friction and drainage; improved aesthetics. Lower albedo may negatively impact UHI effect
Ultra-thin and Thin HMA Overlay: Open-Graded	Asphalt binder (often polymerized or rubberized) and open-graded aggregate combined in central mixing placement and placed with paver in thickness ranging from 0.625 to 0.75 in. for ultra-thin and 0.75 to 1.5 in. for thin overlays. Cost and performance depends on binder type and whether milling is performed prior to treatment placement			↑	↑	↑	↑	↑	✓✓✓	$$$	High Use of WMA may reduce construction impact (see Chapter 3)	Improved ride quality; improved safety through improved friction and drainage; reduces splash and spray; noise; improved aesthetics. Lower albedo may negatively impact UHI effect
Ultra-thin and Thin HMA Overlay: Gap-Graded	Asphalt binder and gap-graded aggregate, usually made with polymerized or rubberized binder and/or fibers, combined in central mixing placement and placed with paver in thickness ranging from 0.625 to 0.75 in. for ultra-thin and 0.75 to 1.5 in. for thin overlays. Cost and performance depends on binder type and whether milling is performed prior to treatment placement	↑		↑	↑	↑	↑	↑	✓✓✓✓	$$$	High Use of WMA may reduce construction impact (see Chapter 3)	Improved ride quality; improved safety through improved friction and drainage; highly rut resistant; improved aesthetics. Lower albedo may negatively impact UHI effect

Table 7-3. Evaluation of sustainability impacts of treatments for asphalt-surfaced pavements (continued).

Treatment	Description	Preventive		Restorative					Performance and Cost		Relative Environmental Impact based on life cycle energy use and GHG emissions, materials (Low, Medium, High, Variable)	Societal Impact
		Seal Pavement	Rejuvenate Surface	Addresses Surface Distress	Eliminate Stable Ruts	Improves Texture for Friction	Improves Ride Quality and Surface Profile	Improve Texture for Noise	Relative Treatment Life (✓ to ✓✓✓✓)	Relative Cost ($ to $$$$)		
Hot In-Place Recycling	Corrects surface distresses within top 2 in. of existing asphalt pavement by softening surface material through heat, mechanically loosening it, mixing with recycling agent, aggregate, rejuvenators, and/or virgin asphalt	↑		↑	↑	↑	↑		✓✓✓	$$$	Medium to High Re-use of existing materials reduces impact. Impact depends on whether it involves surface recycling, remixing, or repaving	Improved ride quality; improved safety through improved friction and drainage; improved aesthetics. Lower albedo may negatively impact UHI effect
Cold In-Place Recycling	Milling and sizing reclaimed asphalt pavement (RAP) and mixing in-place with recycling additive and new aggregate which is then relaid and compacted as new base course. CIR requires that a new surface be placed over it, usually an asphalt overlay or other surface treatment		↑	↑	↑	↑	↑		✓✓✓	$$	Variable Depends on additives used and type of surface applied; re-use of existing materials reduces impact	Increases safety through improved friction and drainage; improved ride quality; improved aesthetics. Lower albedo may negatively impact UHI effect
Ultra-thin Bonded Wearing Course	May be used as an alternative to chip-seals, microsurfacing, or thin overlays. Consists of a open-graded or gap-graded, polymer-or rubber-modified asphalt layer (0.4 to 0.8 in. thick) placed on a heavy tack coat	↑		↑		↑	↑	↑	✓✓✓✓	$$$	Medium Partly dependent on use of proprietary additives	Improved ride quality; improved safety through improved friction and drainage; improved aesthetics. Lower albedo may negatively impact UHI effect
Bonded Concrete Overlay	Placement of a thin (2 to 4 in.) PCC layer, with slab dimensions between 2 and 6 ft. over an existing asphalt-surfaced pavement	* Existing surface supports new concrete surface	* Existing surface supports new concrete surface	↑	↑ Also addresses unstable rutting	↑	↑	↔ Depends on surface texture and joint condition	✓✓✓✓	$$$$	Medium Virgin materials and concrete materials increase impact, thinner cross section reduces impact	Increases safety through improved friction and drainage; improved ride quality; improved aesthetics. Increase in albedo may positively impact the UHI effect

Note: Relative Environmental Impacts discussed in tale 7-3 provide rough comparisons; reliable estimates will be available only after new assessments are conducted.

Key:
↓ decreased
↑ increased
↔ no trend

In applications where significant crack movement is expected, crack filling is not expected to perform particularly well and crack sealing should be considered. Crack sealing is a more rigorous process than crack filling, and thus is more energy and emission intensive than crack filling. It begins with more preparation of the crack (e.g., routing, cleaning) before the placement of a higher quality adhesive and elastic material (typically polymerized or rubberized hot-poured asphalt materials) into or over prepared working cracks to minimize the infiltration of moisture and incompressible materials into the pavement structure.

Crack filling and crack sealing do not add any structural benefit to the pavement, but they do slow the rate of moisture ingress, which will slow the rate of pavement deterioration by preventing moisture from infiltrating and degrading the pavement layers (FHWA 1999; Peshkin et al. 2011).

Positive Sustainability Attributes of Crack Filling/Sealing

- Crack filling/sealing is expected to extend the life of the pavement by keeping the pavement sealed against water infiltration.
- Crack filling/sealing uses relatively small material quantities and thus does not have large material-related environmental impacts (but LCAs are not readily available).
- Crack filling/sealing generates little construction waste.
- Crack filling/sealing construction operations use relatively little energy.
- Crack filling/sealing can be conducted using moving traffic control operations, thus minimizing traffic disruptions and delays.

Potential Negative Sustainability Attributes of Crack Filling/Sealing

- Crack filling/sealing has a relatively short life compared to the pavement and thus must be repeated multiple times over the pavement life cycle.
- Crack filling/sealing configurations that apply material on the surface of the pavement on either side of the crack (i.e., overband configurations) can negatively impact ride quality and tire-pavement noise.
- Crack filling/sealing can negatively impact the pavement aesthetics.
- Overutilization of filling/sealing of longitudinal cracks using an overband configuration can negatively impact surface friction, especially for motorcycles.
- Construction operations (specifically the crack routing and cleaning processes) are typically noisy and produce particulates that can be a potential issue in a community setting.

Asphalt Patching

Figure 7-6. Full-depth asphalt patch.

The placement of an asphalt patch (see figure 7-6) is a common maintenance procedure used to treat localized distresses. Patching can be performed with limited preparation and using a cold-mix material (such as under winter conditions) or may employ a more rigorous approach consisting of milling or saw cutting, application of a tack coat, and placement of a high-quality asphalt concrete patching material. Patching may be partial depth or full depth, depending on the type and severity of the distresses being addressed. Patching is typically used to fix potholes and severely cracked areas. Patching is also commonly done in preparation for (or in conjunction with) other forms of maintenance activities or preservation treatments, or as a pre-treatment for an asphalt overlay. The primary materials used for patching are asphalt concrete, cold-mix asphalt, aggregate/asphalt emulsions, and various proprietary patching mixtures.

Positive Sustainability Attributes of Asphalt Patching

- The replacement of localized pavement failures restores structural integrity and ride quality. If done correctly, this is a long-term repair that should last for the life of the pavement.
- For isolated repairs, patching uses relatively little material and thus does not have large material-related impacts.
- Construction operations associated with patching use relatively little energy (when compared to a more substantial treatment like asphalt overlays).
- Although some construction waste is generated from the removed material, it can be recycled as RAP.
- Patching can be completed in a relatively short period of time, thus minimizing traffic disruptions and delays.

Potential Negative Sustainability Attributes of Asphalt Patching

- Poorly constructed asphalt patching can negatively impact ride quality and tire-pavement noise.
- Patching becomes costly with increasing environmental impact as the density of patching increases.
- Large quantities of asphalt patching can negatively impact the overall aesthetics of the pavement.

Fog Seals/Rejuvenators

Fog seals or rejuvenators (see figure 7-7) are treatments used to add fresh asphalt binder or more volatile asphalt constituents to the surface of an existing pavement to seal the pavement surface, prevent or slow oxidation, and prevent further loss of aggregates from the pavement surface. Fog seals/rejuvenators are not effective in treating cracking or other surface distresses that may compromise the structural integrity of the pavement.

Figure 7-7. Fog seal application.

Positive Sustainability Attributes of Fog Seals/Rejuvenators

- Fog seals/rejuvenators restore the pavement surface with minimal application of material, effectively sealing it and preventing further loss of aggregate.
- Fog seals/rejuvenators improve pavement aesthetics creating the impression of a new pavement.
- Construction operations associated with the placement of fog seals/rejuvenators use relatively little energy.
- The application of fog seals/rejuvenators can be completed in a relatively short period of time, thus minimizing traffic disruptions and delays.

Potential Negative Sustainability Attributes of Fog Seals/Rejuvenators

- Poorly constructed fog seals/rejuvenators can negatively impact surface friction and safety.
- Some non-emulsion-based rejuvenators contain volatiles that can negatively impact the local community.
- The application of asphalt binder over the entire surface results in moderate overall environmental impact, especially due to the relatively short performance period of the treatment (which, therefore, would require the application of multiple treatments over the life of the pavement).
- Fog seals/rejuvenators will typically darken the surface, and will likely decrease the pavement albedo.

Chip Seals

Figure 7-8. Chip seal construction.

Chip seals are typically used to seal the pavement, address minor, nonstructural surface distresses, and improve the friction of the wearing course. The construction of a chip seal (see figure 7-8) uses a non-polymerized, polymerized, or rubberized asphalt material as a binder, most commonly in emulsion form, but heated asphalt and cutbacks may also be used. The binder is applied to the pavement surface (typical application rates are between 0.35 and 0.50 gal/yd^2 [1.58 and 2.26 l/m^2]) followed by the application of aggregate chips (generally one stone thick; typical application rates are between 15 and 50 lb/yd^2 [27 kg/m^2]), and these are then rolled into the asphalt binder to achieve 50 to 70 percent embedment. Chip seals can be applied in single or multiple layers and in combination with other surface treatments (such as microsurfacing, which yields a "cape seal") to reduce concerns associated with loose aggregate chips and to improve ride quality. In many cases, chip seals can significantly extend pavement life at relatively low costs. Guidelines for constructing effective chip seal treatments are documented in an NCHRP synthesis document (Gransberg and James 2005).

Positive Sustainability Attributes of Chip Seals

- Chip seals renew the pavement surface, effectively sealing and addressing minor surface defects.
- Chip seals restore surface friction.
- When multiple courses are used, chip seals can improve ride quality and surface profile.
- Chip seals improve pavement aesthetics by creating the impression of a new pavement.
- The use of light-colored aggregates in chip seals can increase surface albedo.
- The construction of chip seals can be completed in a relatively short period of time, thus minimizing traffic disruptions and delays.
- Chip seals have a much lower initial cost than thin asphalt overlays.

Potential Negative Sustainability Attributes of Chip Seals

- Poorly constructed chip seals can result in vehicle damage due to loose chips and can result in wasted aggregate resources when excessively applied or poorly bound.
- Chip seals can exhibit a rough ride and high noise levels at high speeds, particularly if large size stone is used or if there is non-uniform stone loss due to poor application of the binder.
- The application of asphalt binder and aggregate over the entire pavement surface results in a moderate overall environmental impact, especially where traffic and climate

conditions result in a relatively short performance period of the treatment (requiring multiple applications over the life of the pavement).

Slurry Seals

Slurry seals (see figure 7-9) consist of a mixture of well-graded aggregate (fine sand and mineral filler) and asphalt emulsion that is spread over the surface of the pavement using a squeegee or a spreader box fixed to the back of the truck that is depositing the mixture. Slurry seals are generally used to seal the pavement surface, address low-severity cracking on the pavement surface, or improve the friction of the pavement surface. Slurry seals can also help reduce noise due to tire-pavement interaction to an extent (Peshkin et al. 2011). Slurries typically have a short service life on high speed routes due to abrasion loss.

Figure 7-9. Slurry seal application.

Positive Sustainability Attributes of Slurry Seals

- Slurry seals help keep water out of the pavement structure, potentially extending pavement life.
- Slurry seals can improve the surface friction of the pavement, thereby enhancing safety.
- Slurry seals improve pavement aesthetics by creating the impression of a new pavement.
- Slurry seal construction can be completed in a relatively short period of time, thus minimizing traffic disruptions and delays.

Potential Negative Sustainability Attributes of Slurry Seals

- The application of asphalt binder and aggregate over the entire pavement surface results in a moderate overall environmental impact, especially due to the relatively short performance period associated with slurry seals (requiring multiple applications over the life of the pavement).
- Improperly constructed slurry seals can adversely affect surface friction.
- Slurry seals are often dark in color and will likely decrease pavement albedo.

Microsurfacing

Typical microsurfacing consists of a mixture of crushed, well-graded aggregate, mineral filler, and polymer-modified emulsified asphalt spread over the entire pavement surface. This represents a broad category of different treatments, many of which are proprietary. The primary use of microsurfacing is to seal surface cracks, inhibit raveling and oxidation of the existing asphalt surface, address minor surface irregularities and rutting, and improve surface friction. Microsurfacing may be applied in a single or double course, depending upon project requirements. A double course usually involves a rut-fill application followed by another course to cover the entire pavement surface (Peshkin et al. 2011).

The cost, performance, and environmental impacts of microsurfacing depend on whether single, double, or multiple courses are used and the nature of the binder (i.e., binder type and level of polymerization). Many studies have specifically identified microsurfacing as a very sustainable treatment with relatively low life-cycle economic and environmental impacts (Chehovits and Galehouse 2010; Kazmierowski 2012; Uhlman 2012).

Positive Sustainability Attributes of Microsurfacing

- Microsurfacing renews and seals the pavement surface.
- Microsurfacing can restore surface friction and fills ruts, thereby improving safety.
- Microsurfacing improves pavement aesthetics by creating the impression of a new pavement.
- Although new material is used in microsurfacing projects, it is often of less quantity than that used in asphalt concrete paving options.
- Microsurfacing has a relatively long life when compared to other preservation treatments, reducing material consumption and construction impacts that are associated with frequent and repeated applications of other treatments.
- Microsurfacing construction can be completed in a relatively short period of time, thus minimizing traffic disruptions and delays.

Potential Negative Sustainability Attributes of Microsurfacing

- Some of the polymerized materials used in microsurfacing projects may have a relatively high environmental impact and this should be considered when determining life-cycle impacts.
- Microsurfacing is often dark in color and will likely decrease pavement albedo (although some microsurfacing techniques actually are designed to increase albedo).

Environmental Impact of Preservation Treatments

The environmental impacts of two pavement preservation treatment scenarios were evaluated by Uhlman (2012). The first scenario compared a polymer-modified emulsion microsurfacing to a 2-inch (51-mm) mill and replacement with a polymer-modified HMA overlay. The overall environmental impact of the microsurfacing was determined to be significantly lower because of specific aspects of the HMA alternative, namely its elevated production and application temperatures, the milling operation performed prior to HMA placement, and the increased fuel requirements. In a second scenario, various chip seal options (including a hot-applied chip seal incorporating ground tire rubber [GTR] and two different polymer-modified cold-applied emulsion chip seals with and without fibers) were compared. The chip seal made with GTR had the lowest impact for solid waste emissions due to the diversion of tires from landfill, yet it also exhibited the greatest environmental impact in all categories considered except toxicity potential. This was because of the extra requirements for precoating the aggregates, the higher manufacturing and application temperatures for the GTR chip seal, and the production and storage requirements for the GTR binder. Thus, although at face value the use of recycled products appears to be a "sustainable" practice, the results in this case indicate that the use of cold-applied polymer-modified emulsions provided lower environmental impacts over the life cycle. However, it is important to recognize that the findings from this study are not absolute, as different results might be obtained for projects constructed under different situations (e.g., traffic, climate, pavement condition, material sources, system boundaries for analysis).

Ultra-Thin and Thin Asphalt Concrete Overlays

This is a very broad category of overlays made with asphalt concrete in a central mixing plant and placed with a paver in thicknesses ranging from 0.625 to 0.75 inches (16 to 19 mm) for ultra-thin and 0.75 to 1.50 inches (19 to 38 mm) for thin overlays (see figure 7-10). Life-cycle cost, performance, and environmental impacts depend on traffic, binder type, bonding to the existing surface, the extent of cracking in the existing surface, and whether milling is performed prior to treatment placement.

Figure 7-10. Ultra-thin asphalt overlay.

Ultra-thin and thin overlays are effective in sealing the pavement, addressing minor surface cracking and rutting, and improving surface friction. They will generally be quieter and smoother than chip seals, but will have higher initial costs. The incorporation of polymer-modified binders may improve overall performance. These overlays may be constructed using dense-graded, open-graded, or gap-graded mixtures:

- **Dense-graded**—A well-graded, relatively impermeable mixture, for general application.
- **Open-graded**—An open-graded, permeable mixture containing crushed aggregate and a small fraction of manufactured sand. Open-graded mixtures are effective in addressing splash/spray issues and also in reducing noise due to tire-pavement interaction. Polymer and rubberized binders can extend pavement life in terms of cracking and raveling.
- **Gap-graded**—A gap-graded mixture with either rubberized gap-graded mixtures or stone matrix asphalt (SMA) containing polymerized binder and fibers. These mixtures are designed to maximize cracking and rutting resistance and durability through stone-on-stone contact and high binder film thicknesses. Rubberized gap-graded mixtures are specifically designed to be highly resistant to reflection cracking.

Positive Sustainability Attributes of Ultra-Thin and Thin Asphalt Concrete Overlays

- Ultra-thin and thin overlays address minor surface distress, restore surface friction, fill ruts, improve ride quality, and improve texture that results in improved safety. Open-graded overlays can reduce both splash/spray (thus improving safety in wet-weather conditions) and noise emissions.
- Ultra-thin and thin dense-graded overlays improve pavement aesthetics by providing a new pavement surface.
- Ultra-thin and thin dense-graded overlays exhibit a relatively long life if placed on a pavement that is not significantly cracked and if good bonding is achieved with the existing surface, which reduces material consumption and construction impacts due to repeated applications.

- Construction of ultra-thin and thin overlays can be completed in a relatively short time period, thus minimizing traffic disruptions and delays.
- Ultra-thin and thin overlays are generally quieter and smoother than chip seals.

Potential Negative Sustainability Attributes of Ultra-thin and Thin Overlays

- Ultra-thin and thin overlays require acquisition, processing, and transporting of material from central mixing facilities.
- Poor construction of ultra-thin and thin overlays, or their misapplication on badly deteriorated pavements, can result in early failures that negatively impact economic and environmental performance.
- Ultra-thin and thin overlays are initially dark in color and will likely decrease pavement albedo.
- In some cases, open-graded ultra-thin and thin overlays with conventional binders have exhibited notably shorter lives due to raveling.

Hot In-Place Recycling (HIR)

HIR is used to correct surface distresses limited to the top 2 inches (51 mm) of the existing asphalt surface by softening the binder using heat treatment, mechanically loosening it, and mixing it with recycling additives, rejuvenators, or virgin asphalt binder before placing and compacting the modified mixture. The National Highway Institute offers a training course (Course No. 131050) on asphalt pavement in-place recycling techniques where this topic is covered in further detail (see https://www.nhi.fhwa.dot.gov).

HIR includes three different techniques (Peshkin et al. 2011):

- **Surface recycling**—The wearing surface (typically 0.50 to 1.50 inches [13 to 38 mm]) is heated, loosened, and mixed with new asphalt binder and relaid and compacted. For low-volume roadways, a single-pass recycling operation is used where the recycled mixture is relaid and compacted and serves as the wearing surface. For high-volume roads, the recycled and relaid mixture serves as the base course on top of which an asphalt overlay or surface treatment may be placed.
- **Remixing**—The wearing surface is heated, loosened, and mixed with virgin aggregates and new asphalt binder and relaid and compacted for significant improvement and minor pavement strengthening. The recycled surface may serve as the wearing course (for low-volume roads) or as the base layer for a subsequent asphalt overlay or a surface treatment (for higher volume roads).
- **Repaving**—This technique essentially involves surface recycling followed by the placement of a thermally bonded asphalt overlay (see figure 7-11) in order to strengthen the pavement and restore the surface profile.

Figure 7-11. Hot in-place recycling with application of overlay (Kandhal and Mallick 1997).

Positive Sustainability Attributes of Hot In-Place Recycling

- HIR seals and restores the pavement surface.
- HIR addresses minor surface distress, restores surface friction, removes rutting, improves ride quality, and improves texture, all contributing to improved safety.
- HIR improves pavement aesthetics by providing a new pavement surface.
- If not resurfaced with an asphalt overlay, HIR requires very little use of virgin materials, thus reducing transportation of materials to the site.
- HIR exhibits a relatively long life, reducing material consumption and construction impacts.
- The construction of HIR can be completed in a relatively short time period, thus minimizing traffic disruptions and delays.
- HIR followed by an asphalt overlay can have a positive impact on tire-pavement noise emissions.

Potential Negative Sustainability Attributes of Hot In-Place Recycling

- The use of heat in the HIR process to soften the existing pavement surface and subsequently to combine with new material is energy and emission intensive.
- The HIR operation can generate fumes that can be objectionable in a community setting.
- The new surface produced by the HIR is initially dark in color and will likely have a lower albedo.
- A chip seal or asphalt overlay is often required as part of the HIR treatment, adding cost and environmental burden.
- The improper application of HIR can result in early failures that negatively impact economic and environmental performance.
- HIR followed by a chip seal can have a negative impact on tire-pavement noise emissions.

Cold In-Place Recycling (CIR)

CIR is primarily used to restore the profile/cross slope and address other minor surface distresses. CIR consists of cold milling, sizing the RAP, and mixing the RAP with asphalt emulsion, recycling additives, and new aggregate to produce a recycled cold mix; this cold mix is relaid and compacted to serve as the base course for a new surface (see figure 7-12). For low-volume roads, the surface resulting from the recycled cold mix is typically treated with a fog seal/rejuvenator to delay surface raveling. On higher volume roads, the recycled cold mix is treated with a more substantial treatment such as a chip seal or a thin asphalt overlay. The National Highway Institute offers a training course (Course No. 131050) on asphalt pavement in-place recycling techniques where this topic is covered in greater detail (see https://www.nhi.fhwa.dot.gov).

Figure 7-12. Cold in-place recycling (photo courtesy of D. Matthews).

Positive Sustainability Attributes of Cold In-Place Recycling

- CIR seals and restores the pavement surface.
- CIR addresses surface distress, removes rutting, and corrects minor profile deficiencies.
- Depending on the final surface, CIR can restore surface friction, improve ride quality, and improve surface texture, all contributing to improved safety.
- CIR improves pavement aesthetics by providing a new pavement surface.
- CIR uses existing materials in place, thus reducing the impacts of procuring and transporting new materials.
- CIR offers the potential for a relatively long life, thereby reducing material consumption and construction impacts due to repeated applications.
- CIR followed by an asphalt overlay can have a positive impact on tire-pavement noise levels.

Potential Negative Sustainability Attributes of Cold In-Place Recycling

- The sustainability of CIR is heavily dependent on the type of surface material applied on top of it.
- The new surface on a CIR project is often dark in color and will likely have a lower albedo.
- The construction of CIR projects is often performed in stages, which can result in traffic disruptions and delays.
- The improper application of CIR can result in early failures that negatively impact economic and environmental performance.
- CIR followed by a chip seal can have a negative impact on tire-pavement noise levels.

Ultra-Thin Bonded Wearing Course

This treatment is effective in addressing minor surface distresses and improving the frictional characteristics of the riding surface. It consists of a gap-graded or open-graded polymer- or rubber-modified asphalt layer (typically 0.4 to 0.8 inches [10 to 20 mm] thick) placed on a thick tack coat or membrane, and is commonly used as an alternative to chip seals, microsurfacing, or thin asphalt overlays.

Positive Sustainability Attributes of Ultra-Thin and Thin Bonded Wearing Course

- An ultra-thin bonded wearing course effectively seals the pavement surface.
- An ultra-thin bonded wearing course addresses minor surface distress, restores surface friction, improves ride quality, and improves texture, all contributing to improved safety.
- An ultra-thin bonded wearing course improves pavement aesthetics by providing a new pavement surface.
- An ultra-thin bonded wearing course can reduce noise generated through tire-pavement interaction.
- Ultra-thin bonded wearing courses can exhibit relatively long life, thereby reducing material consumption and construction impacts otherwise associated with repeated applications of other treatments.
- The construction of an ultra-thin bonded wearing course can be completed in a relatively short time period, thus minimizing traffic disruptions and delays.

Potential Negative Sustainability Attributes of Ultra-Thin Bonded Wearing Course

- An ultra-thin bonded wearing course requires the use of new material transported from a central mixing facility.
- The improper application of an ultra-thin bonded wearing course can result in early failures that negatively impact economic and environmental performance.
- An ultra-thin bonded wearing course is initially dark in color and will likely decrease pavement albedo.

Bonded Concrete Overlays

Bonded concrete overlays (sometimes referred to as thin or ultra-thin whitetopping) are placed on existing asphalt pavements to eliminate surface distresses and correct pavement deformations (rutting, corrugation, and shoving). This treatment is characterized by the placement of a thin (2- to 6-inch [51 to 152 mm] thick) concrete (sometimes fiber reinforced) layer onto a cold-milled asphalt pavement (Harrington and Fick 2014). The cold milling is necessary to establish a strong bond between the two materials. Typical slab dimensions range from about 2 to 6 ft (0.61 to 1.8 m) for thinner overlays to about 6 to 12 ft (1.8 to 3.6 m) for thicker (6-inch [152-mm]) slabs. Figure 7-13 shows the short panels associated with many thin overlays. A comprehensive document describing the use, application, and construction of bonded concrete overlays is available (Harrington and Fick 2014).

Figure 7-13. Short panels for bonded concrete overlay.

Positive Sustainability Attributes of Bonded Concrete Overlays

- A completely new concrete surface is bonded onto the existing asphalt pavement, effectively sealing it while addressing minor surface distress, rutting, and continued instability in the asphalt layer.
- The concrete surface can be shaped and textured as desired, restoring surface friction, eliminating profile deficiencies, and reducing tire-pavement noise.
- Bonded concrete overlays improve pavement aesthetics by providing a new pavement surface.
- The pavement can be easily colored or textured to enhance aesthetics.
- Bonded concrete overlays typically are initially light in color and will likely increase pavement albedo.
- Bonded concrete overlays exhibit relatively long life, reducing material consumption and construction impacts that would be otherwise caused by repeated applications of other treatments.

Potential Negative Sustainability Attributes of Bonded Concrete Overlays

- Bonded concrete overlays require the use of new material transported from a central mixing facility, so the environmental impact of those materials must be considered.

- The improper construction of bonded concrete overlays (primarily through poor joint layout, construction and sealing practices or poor bonding) can result in early failures that negatively impact economic and environmental performance.
- The construction of bonded concrete overlays may require a longer period of time, leading to the development of traffic disruptions and delays.

Energy Use and Emissions for Asphalt-Surfaced Pavement Treatments

Limited information is available on the life-cycle energy consumption and emissions generated by asphalt-surfaced pavement maintenance and preservation treatments. This is partly because the diversity of these treatments is such that they are not easily categorized for analysis. In addition, most of the early focus in investigating environmental impacts has been on new construction and major rehabilitation. It has not been until fairly recently that the life-cycle impacts of preservation have been investigated by the pavement community.

For example, table 7-4 presents energy consumption and GHG emissions data for some typical asphalt-surfaced pavement preservation treatments, along with assumptions related to the extension of service life (Chehovits and Galehouse 2010). Table 7-5, which is from the same study, presents similar data for typical new construction and major rehabilitation. In developing the values shown in tables 7-4 and 7-5, energy use and GHG emissions were calculated for each treatment on the basis of the unit area of the pavement surface being treated and using typical quantities of raw materials for each treatment (agency costs only, no user costs). Those values were then divided by the pavement life extensions for each treatment to produce annualized results to allow more meaningful comparisons of the energy use and GHG emissions associated with the different treatments. In this context, relative comparisons can be made between the different treatments.

What is evident from these data is that the energy consumption and GHG emissions per year are considerably lower for many of the preservation and maintenance treatments compared to new construction or major rehabilitation, although not universally so. For instance, thin HMA overlays and hot in-place recycling both exhibit energy and GHG emissions that are similar to those of new construction. This suggests that these alternatives are similar for the factors considered, but other environmental and social factors not included in the analysis (e.g., solid waste generation, noise, safety, particulate matter) could also impact the results. Furthermore, the boundary conditions for the analysis were quite limited, and did not include such items as traffic delays resulting from construction operations and improved vehicle fuel efficiencies associated with smoother pavements. Regardless of the limitations associated with the data, it clearly demonstrates the reduced energy consumption and GHG emissions associated with many preservation and maintenance treatments.

A study conducted in Ontario (Chan et al. 2011) on various asphalt pavement treatment alternatives found that microsurfacing had the lowest annualized energy consumption and emission levels when compared to the other treatment alternatives (see table 7-6). However, that study suffers from some simplifications in the analysis. For one, it assumes that all of the treatments exhibit similar benefits over their entire life. In addition, it does not consider the broader impact of creating additional traffic disruptions for short-lived treatments. Still, it illustrates that less material-intensive preservation treatments have positive environmental impacts than more material-intensive options, reinforcing the concept that the environmental impact of materials production and construction is generally well correlated with the thickness of the treatment.

Table 7-4. Energy consumption and GHG emissions data for some typical asphalt-surfaced pavement preservation treatments (Chehovits and Galehouse 2010).

Treatment	Details	Pavement Life Extension (Years)	Energy Use per Year BTU/yd²	Energy Use per Year MJ/M²	GHG Emissions per Year lb/yd²	GHG Emissions per Year kg/m²
Hot-Mix Asphalt	Thickness 1.5 in (3.8 cm)	5-10	4,660 – 9,320	5.9 – 11.8	0.9 – 1.8	0.5 – 1.0
Hot-Mix Asphalt	Thickness 2.0 in (5.0 cm)	5-10	6,080 – 12,160	7.7 – 15.4	1.2 – 2.4	0.7 – 1.3
Hot In-Place Recycling	Thickness 1.5 in (3.8 cm) 50/50 Recycle/New	5-10	3,870 – 7,740	4.9 – 9.8	0.7 – 1.4	0.4 – 0.80
Hot In-Place Recycling	Thickness 2.0 in (5 cm) 50/50 Recycle/New	5-10	5,130– 10,260	6.5 – 13.0	0.9 – 1.5	0.5 – 1.0
Chip Seal	Emulsion 0.44 g/yd² (2.0 L/m²) Aggregate 38 lb/yd² (21 kg/m²)	3-6	1,170 -2,340	1.5 – 3.0	0.15 – 0.3	0.08 – 0.10
Chip Seal	Emulsion 0.35 g/yd² (1.6 L/m²) Aggregate 28 lb/yd² (15 kg/m²)	2-5	1,026 – 2,565	1.3 – 3.3	0.14 – 0.35	0.08 – 0.20
Slurry Seal/ Micro-surfacing	Type III 12% Emulsion, 24 lb/yd² (13 kg/m²)	3-5	1,026 – 1,710	1.3 – 3.3	0.12 – 0.2	0.06 – 0.10
Slurry Seal/ Micro-surfacing	Type II 14% Emulsion, 16 lb/yd² (8.7 kg/m²)	2-4	968 – 1,935	1.2 – 2.4	0.10 – 0.2f0	0.05 – 0.10
Crack Seal	1 lin ft/yd² (0.37 m/m²), 0.25 lb/ft (0.37 kg/m²)	1-3	290 - 870	.05 – .14	0.05 – 0.14	0.03 – 0.08
Crack Fill	2 lin ft/yd² (0.74 m/m²), 0.50 lb/ft (0.74 kg/m²)	1-2	930 – 1,860	1.0 – 2.0	0.13 – 0.25	0.07 – 0.14
Fog Seal	0.05 gal/yd² (0.23 L/m²) 50/50 Diluted Emulsion	1	250	0.4	0.04	0.02
Fog Seal	0.10 gal/yd² (0.46 L/m²) 50/50 Diluted Emulsion	1	500	0.8	0.07	1.04
Fog Seal	0.15 gal/yd² (0.69 L/m²) 50/50 Diluted Emulsion	1	750	1.2	0.12	0.07

Table 7-5. Energy consumption and GHG emissions data for new construction and major rehabilitation activities (Chehovits and Galehouse 2010).

Treatment	Details	Pavement Life or Life Extension (Years)	Energy Use per Year BTU/yd²	Energy Use per Year MJ/M²	GHG Emissions per Year lb/yd²	GHG Emissions per Year kg/m²
New Construction	4 in (102 mm) HMA over 6 in (152 mm) Aggregate Base	20	7840	9.9	1.2	0.7
Major Rehab Hot-Mix Asphalt	4 in (102 mm) Overlay	15	7500	9.4	1.3	.08
Major Rehab Hot-Mix Asphalt	3 in (76 mm) Overlay	12	7050	8.9	1.3	0.7
Major Rehab Warm-Mix Asphalt	4 in (102 mm) Overlay	15	7210	9.2	1.3	.08
Major Rehab Warm-Mix Asphalt	3 in (76 mm) Overlay	17	6780	8.5	1.3	0.7

Table 7-6. Comparison between microsurfacing and other treatment alternatives for asphalt-surfaced pavement (Chan et al. 2011).

Treatments	Service Life	Energy	CO_2	NO_x	SO_x
Mill 1.95 in (50 mm) Pave 1.95 in (50 mm)	10 Yrs	65 million BTU (67,493 MJ)	3.9 ton (3.5 mt)	67.6 lbs (30.7 kg)	2110 lbs (958 kg)
Mill 1.95 in (50 mm) Pave 1.95 in (50 mm) WMA	10 Yrs	45 million BTU (47,782 MJ)	2.2 ton (2.0 mt)	35.5 lbs (16.1 kg)	1478 lbs (671 kg)
1.95 in (50 mm) HIR	10 Yrs	54 million BTU (56,694 MJ)	3.0 ton (2.7 mt)	52.6 lbs (23.9 kg)	1645 lbs (747 kg)
0.39 in (10 mm) Microsurfacing	7 Yrs	7.6 million BTU (8,064 MJ)	0.33 ton (0.3 mt)	14.1 lbs (6.4 kg)	619 lbs (281 kg)

Strategies for Improving Sustainability

The general strategies for improving sustainability discussed at the beginning of this chapter are applicable, namely that thinner cross sections, the use of local or in-place materials, maintaining high levels of smoothness, and increased construction quality all reduce environmental burden and contribute to more sustainable treatments. It is emphasized that significant differences may exist in the approaches that are used to reduce environmental impacts, depending on a number of project-specific characteristics (perhaps most notably the traffic volumes and associated burdens created in the use phase).

Future Opportunities

As interest in improving the sustainability of asphalt-surfaced pavement maintenance and preservations techniques continues to evolve and move forward, future opportunities exist in the following areas:

- Improved maintenance materials that require the use of less material or last longer. However, some of the materials now being developed and marketed are proprietary and the environmental impacts of the component materials used is not known.
- Improved approaches for optimizing treatment selection and timing through the use of more sophisticated pavement management systems and more proactive “leading” indicators of performance.
- Improved construction, particularly improvements in paving machines that place the tack coat just ahead of the laydown of the hot mix, and improved compaction from the use of warm mix.
- Other improvements identified in chapter 3 on materials.

Concrete-Surfaced Pavement Maintenance and Preservation Treatments

Introduction

Concrete-surfaced pavements are any pavement structures surfaced with concrete, including JPCP, CRCP, and older jointed reinforced concrete pavement (JRCP) designs. In general, these pavements consist of a concrete surface on one or more granular or bound layers, but concrete-surfaced pavement also includes various concrete overlays that can be placed on existing concrete pavements (unbonded and bonded concrete overlays) or on existing asphalt pavements (again, either bonded or unbonded). Although this represents a range of different pavement types, the maintenance and preservation activities are largely identical (although there are some variations in how the treatments are executed).

Table 7-7 presents an overall summary of various maintenance and preservation treatments applicable to concrete-surfaced pavements. First, it provides a brief description of the technique and then indicates its effect on a number of preventive and restorative benefits (“↑” indicates positive impact, “↓” indicates negative impact, and “↔” indicates both positive and negative impact). This is followed by a general assignment of the relative life expectancy and cost, and the relative environmental and social impacts.

As noted before in the discussions of the treatments for asphalt-surfaced pavements, these relative comparisons are inherently non-specific, which is due to the general lack of available information and the large number of variables that affect the performance, cost, life-cycle environmental impact, and social impact of each treatment. The relative comparisons will also vary depending on the traffic levels, climate region, and a host of other variables. In general, treatments that require more material or materials that have higher environmental impacts will have higher environmental impacts through construction. Those that last longer and have the greatest impact on preserving functional surface characteristics (e.g., ride quality, surface friction, and high albedo) will have reduced environmental impacts over the life cycle, especially in high-traffic applications where the economic and environmental impacts of vehicles are the greatest.

Table 7-7. Evaluation of sustainability impacts of treatments for concrete-surfaced pavements.

Treatment	Description	Preventive		Restorative				Performance and Cost		Relative Environmental Impact based on life cycle energy use and GHG emissions, materials (Low, Medium, High, Variable)	Societal Impact
		Seal Pavement	Prevent Intrusion of Incompressibles	Eliminate/ Control Faulting	Improve Texture for Friction	Improves Ride Quality and Surface Profile	Improve Texture for Noise	Relative Treatment Life (✓ to ✓✓✓✓)	Relative Cost ($ to $$$$)		
Joint Resealing/ Crack Sealing	Joint resealing consists of removing existing longitudinal/transverse joint sealants, preparing and installing new sealant material. Crack Sealing consists of cleaning, preparing and sealing longitudinal/transverse cracks	↑	↑		↓ Longitudinal overbanding can negatively impact friction		↔ Overbanding increases noise, filling can reduce noise	✓	$	Low	Reduced traffic delays; less pleasing aesthetics and potential roughness issues with crack sealing
Slab Stabilization/Slab Jacking	Slab stabilization involves the restoration of support to slabs by filling voids, thereby reducing deflections. Slab jacking involves raising slabs to their desired elevation by pressure inserting material beneath settled slabs			↑ In combination with other CPR treatments		↑ In combination with other CPR treatments		✓✓	$$$	Low to Medium Depends on amount of slab stabilization required	When combined with other treatments, results in long-term Improvement in ride quality
Diamond Grinding	Removal of thin concrete layer (0.12 to 0.25 in.) from pavement surface using special equipment.			↑	↑	↑ Significant improvements on faulted pavement	↑	✓✓✓	$$	Medium to High Depends on how much surface is being removed, hardness of the aggregate, level of smoothness obtained, and traffic level	Increases safety by improving friction, reduces noise from tire-pavement interaction
Diamond Grooving	Cutting narrow, discrete grooves (typically longitudinal) into pavement surface to increase friction and reduce noise				↑			✓✓✓	$$	Low	Improved wet weather safety and reduced noise. Some issues regarding negative impact on vehicle tracking (particularly motorcycles) have been cited
Partial-Depth Repairs	Localized removal and replacement of deteriorated concrete, most often in vicinity of joints) in the upper third of the slab using approved repair materials	↑ In combination with other CPR treatments	↑ In combination with other CPR treatments			↑		✓✓	$$$	Variable Depends on type of material used and amount of patching required	Rapid-setting repair materials used for partial-depth patching reduce traffic delays. Restoration of ride quality is significant for badly damaged pavement if slabs are ground. Aesthetics can be negatively affectively if repair material does not match existing pavement

Table 7-7. Evaluation of sustainability impacts of treatments for concrete-surfaced pavements (continued).

Treatment	Description	Preventive		Restorative				Performance and Cost		Relative Environmental Impact based on life cycle energy use and GHG emissions, materials (Low, Medium, High, Variable)	Societal Impact
		Seal Pavement	Prevent Intrusion of Incompressibles	Eliminate/ Control Faulting	Improve Texture for Friction	Improves Ride Quality and Surface Profile	Improve Texture for Noise	Relative Treatment Life (✓ to ✓✓✓✓)	Relative Cost ($ to $$$$)		
Full-Depth Repairs	Removal and replacement of deteriorated concrete through the full depth of the slab using approved repair materials; may be cast in-place of precast	↑ In combination with other CPR treatments	↑ In combination with other CPR treatments	↑ At affected joint(s)		↑		✓✓✓	$$$$	Medium to High Depends on amount of patching and type of material used; also depends on whether repairs are cast in-place or pre-cast	Pre-cast panels reduce traffic delays. Aesthetics can be negatively affectively if repair material does not match existing pavement
Dowel Bar Retrofit	Placement of dowel bars across joints or cracks in existing jointed concrete pavement			↑ In combination with other CPR treatments		↑ In combination with other CPR treatments		✓✓✓✓	$$$	Variable If globally applied, high initial negative impact but restoration of load transfer, in combination with diamond grinding, will make the smoothness last longer and have positive impact throughout the life cycle.	Improves ride quality by controlling faulting, which is eliminated when combined with diamond grinding. Aesthetics can be negatively affectively if repair material does not match existing pavement
Cross Stitching	Technique used to maintain load transfer across non-working longitudinal cracks that are in relatively good condition			↑					$$$	Low	Improves long-term performance by keeping longitudinal cracks tight. Eliminates the need for slab removal and replacement
Retrofitted Edge Drains	Technique used to collect water that has infiltrated into the pavement structure and discharges it to the ditches through regularly spaced outlet drains. Can have negative impact if creates "bathtub" through poor design or construction					↑		✓✓✓	$$$$	Variable Can have a large impact if poor drainage is primarily responsible for poor performance, but must be properly designed, constructed and maintained or can trap water in the pavement	Can improve long-term performance by reducing moisture induced distress
Ultra-Thin Wearing Course, typically open-graded with rubberized or polymerized binders	Used to improve the functional surface characteristics of the concrete pavement including enhancing friction and reducing noise. Consists of open or gap-graded aggregates and rubberized or polymer-modified asphalt layer (0.4 to 0.8 in. thick) well bonded to the concrete surface	↑	↑		↑	↑	↑	✓✓	$$$	Variable Depends on type of material used and life of treatment	Primarily used to enhance functional surface characteristics of the pavement, most notably noise reduction and improved friction
Bonded Concrete Overlay	Placement of a relatively thin (2 to 6 in.) concrete layer, with slab over an existing concrete-surfaced pavement	↑	↑		↑	↑		✓✓✓✓	$$$	Medium Virgin materials and concrete materials increase impact, thinner cross section reduces impact	Increases safety through improved friction and drainage; improved ride quality; improved aesthetics. Increase in albedo may positively impact the UHI effect

Note: Relative Environmental Impacts discussed in tale 7-3 provide rough comparisons; reliable estimates will be available only after new assessments are conducted.

Key: ↓ decreased
↑ increased
↔ no trend

Various resources are available that discuss concrete pavement preservation/maintenance strategies as well as each treatment type, including the types of pavement conditions addressed, how each treatment should be constructed, and their cost effectiveness. These include a web-based training series developed by the National Concrete Pavement Technology Center and offered by the National Highway Institute (NHI Course No. 131126) and a number of treatment-specific references available from the American Concrete Pavement Association, the FHWA, and others. As considerable information is readily available regarding the application, cost effectiveness, and construction of the various treatments, the following sections specifically address the sustainability aspects of each treatment, focusing on the environmental and social impacts.

Although any given concrete-surfaced pavement treatment can be applied alone (for example full-depth patching can be used to repair a localized slab failure), it is far more common to use several treatments together in an approach often referred to as concrete pavement restoration (CPR) to restore a structurally sound but distressed concrete pavement to a higher level of serviceability. Thus the sustainability impact of any one treatment is very difficult to assess, as ultimately the economic, environmental, and social impacts of the entire strategy should be assessed together. A recommended sequence for the placement of various treatments during a CPR project is illustrated in figure 7-14 (ACPA 2006). In the following discussion, each treatment is considered individually with the linkage to other treatments established in the narrative.

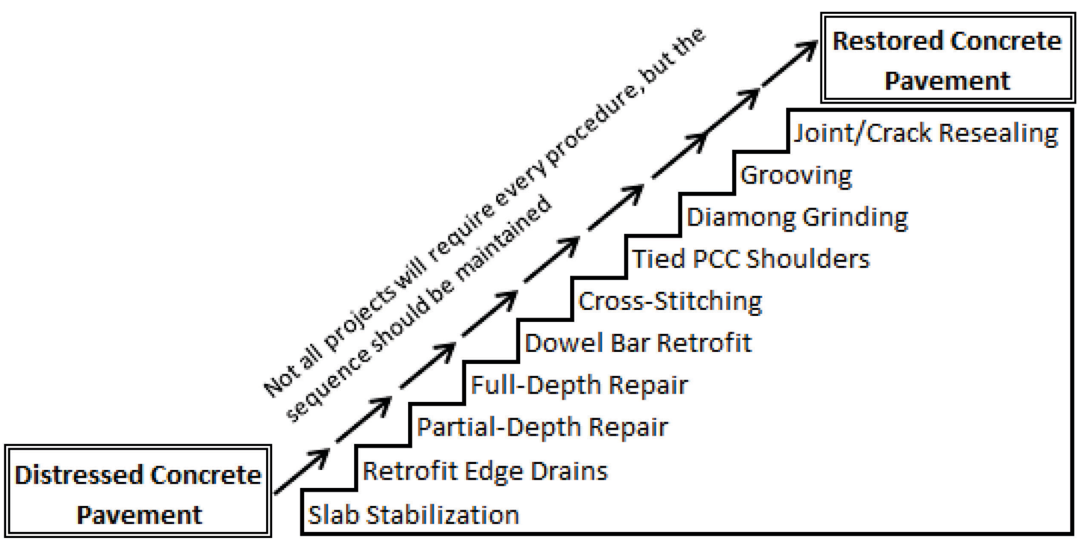

Figure 7-14. Typical sequence of concrete-surfaced pavement treatments as part of CPR (ACPA 2006).

Joint Resealing/Crack Sealing

Joint and crack sealing is a commonly performed pavement maintenance activity that serves two purposes: reduce the amount of moisture infiltration into the pavement structure, thereby reducing moisture-related distresses such as pumping, joint faulting, base and subbase erosion, and corner breaks; and prevent the intrusion of incompressibles to prevent pressure-related distresses such as spalling, blowups, buckling, and shattered slabs (Smith et al. 2014).

Joint resealing involves the removal of existing deteriorated sealant material (if present), preparation of the joint sidewalls, and installation of the new sealant material (see figure 7-15). Crack sealing is typically done only on longitudinal and transverse cracks and corner break cracks that are wider than 0.125 inch (3 mm) and involves routing, cleaning, and sealing cracks using a high-quality sealant material (Peshkin et al. 2011).

Joint resealing and crack sealing should be the last activities in the sequence of treatments performed on a given restoration project. Intended for pavements in relatively good condition, joint resealing can also be performed independently on a project with an original sealant that has failed or become ineffective.

Figure 7-15. Joint sealing.

Positive Sustainability Attributes of Joint Resealing and Crack Sealing

- Joint/crack sealing helps minimize the amount of moisture infiltrating the pavement, potentially extending the life.
- Joint/crack sealing uses relatively little material and, thus, does not have large material-related environmental impacts.
- Joint/crack sealing generates little construction waste.
- Joint/crack sealing operations use relatively little energy.
- Joint/crack sealing can be performed using a moving traffic control operation, thus minimizing traffic disruptions and delays.

Potential Negative Sustainability Attributes of Joint Resealing and Crack Sealing

- Joint/crack sealing can have a relatively short life when compared to that of the concrete pavement and thus must be repeated multiple times over the life cycle (with associated more frequent disruptions to traffic).
- Multiple joint resealing operations widen the joint reservoir and can negatively impact ride quality and increase tire-pavement noise emissions.
- Crack sealing can negatively impact pavement aesthetics over time.
- The sealant removal and cleaning portions of joint/crack sealing operations are typically noisy and can produce particulate that may be problematic in a community setting.

Slab Stabilization/Slab Jacking

Slab stabilization is a technique used to restore support beneath the concrete pavement by filling voids that developed under service, thereby reducing deflections (Smith et al. 2014). Slab stabilization should be performed in areas where loss of support is known to exist. For optimum performance, it is critical that this technique be used prior to the onset of damage caused by loss of support (ACPA 1994).

Slab jacking involves the injection of a cement grout or expansive polyurethane material beneath the slab to gradually elevate a settled slab back to its original profile. This technique is used to correct localized areas of settlement or depression, and not to address common transverse joint faulting (Smith et al. 2014).

Slab stabilization is rarely used alone, instead often being the first step in a restoration project. Slab jacking, on the other hand, can be applied independently of other treatments as its sole purpose is to elevate a slab that has settled due to underlying conditions (such as often occurs at bridge approach slabs or over culverts).

Positive Sustainability Attributes of Slab Stabilization/Slab Jacking

- Slab stabilization restores slab support, thereby reducing deflections and reducing the likelihood of corner breaking. However, in order for slab stabilization to be effective in the long term, the underlying causes of pumping and loss of support (such as poor drainage and poor load transfer) must be addressed.
- Slab stabilization and slab jacking use relatively little material and, thus, do not have large material-related environmental impacts.
- Slab stabilization and slab jacking generate little construction waste.
- The construction operations associated with slab stabilization and slab jacking use relatively little energy.
- Slab stabilization and slab jacking are expected to provide long-term positive impacts if the voids are filled and the root causes of the loss of support are addressed.

Potential Negative Sustainability Attributes of Slab Stabilization/Slab Jacking

- Slab stabilization must be appropriately applied to slabs in which loss of support has occurred. The inappropriate application of this treatment can result in waste and early pavement failure.
- Slab stabilization and slab jacking can be labor-intensive operations that may result in traffic disruptions and delays, but innovative construction practices and materials can be used to minimize that impact.
- Although material usage is low, the environmental impact of the materials (cement grout, polyurethane) must be evaluated.

Diamond Grinding/Grooving

Diamond Grinding involves the removal of a thin (0.12 to 0.25 inch [3 to 6 mm]) layer of material from the concrete surface using special grinding equipment equipped with gang-mounted, closely-spaced diamond saw blades. This technique has traditionally been used to address faulting and other surface irregularities (Peshkin et al. 2011). Diamond grinding contributes to improved sustainability by providing a smooth riding surface (which increases vehicle fuel efficiency) and also by providing a safe pavement surface (through increased surface friction) (Smith et al. 2014). Diamond grinding has also been used on new pavements and older pavements with no apparent distress simply to improve ride quality, provide frictional characteristics, and reduce tire-pavement noise emissions. Diamond grinding also creates an aesthetically pleasing surface that exposes the underlying aggregates (see figure 7-16).

Figure 7-16. Surface texture produced by diamond grinding (courtesy ACPA)

Positive Sustainability Attributes of Diamond Grinding

- Diamond grinding renews the pavement surface without the need for additional material other than the water used in the grinding operation and the wear of the diamond blades. This provides a significant sustainability advantage over treatments that rely on the application of new material.
- Diamond grinding produces a riding surface that is functionally (ride quality, surface friction, noise) as good, or better, than what was originally constructed. This significantly reduces user impacts as long as the high level of functionality is maintained.
- Diamond grinding generates little construction waste, although the disposal of the slurry that is produced during the operation must be addressed.
- Diamond grinding can be conducted under a moving traffic control operation, thus minimizing traffic disruptions and delays.
- Diamond grinding is expected to provide a long-term, positive impact if the pavement is structurally sound and the root causes of the roughness issues (i.e., faulting) are addressed.

Potential Negative Sustainability Attributes of Diamond Grinding

- The effectiveness of diamond grinding to restore surface friction is largely a function of the polishing susceptibility of the coarse aggregate. If the aggregate is susceptible to polishing, the positive effects of diamond grinding on surface friction will be short lived.
- Although material usage is low, the environmental impact of disposal of the slurry must be considered.

- If the coarse aggregates are dark in color, diamond grinding will result in a darker surface color, likely reducing the pavement albedo.
- Diamond grinding operations are typically noisy, which may be a potential issue in a community setting.

Diamond Grooving (see figure 7-17) involves cutting narrow, discrete grooves (longitudinal or transverse) to help improve safety by reducing hydroplaning potential, splash and spray, and wet-weather-related crashes. Transverse grooving, which is common on bridges, may have an adverse impact on tire-pavement noise, which is why longitudinal grooving is more commonly used on highways as it reduces tire-pavement noise while still reducing hydroplaning potential. A hybrid surface texture, called the Next Generation Concrete Surface, employs a combination of diamond grinding and diamond grooving and has demonstrated excellent restoration of the pavement functional characteristics (ride quality, friction, and noise reduction) (IGGA 2011).

Figure 7-17. Diamond grooving operation.

Positive Sustainability Attributes of Diamond Grooving

- Diamond grooving is specifically applied to reduce hydroplaning potential and the noise emissions associated with tire-pavement interaction. There is no need for additional material other than the water used in the grooving operation and the wear of the diamond blades. This provides a significant sustainability advantage over treatments that rely on the application of new material.
- Diamond grooving generates little construction waste, although the disposal of the slurry that is produced must be addressed.
- Diamond grooving can be conducted under a moving traffic control operation, thus minimizing traffic disruptions and delays.

Potential Negative Sustainability Attributes of Diamond Grooving

- Although material usage is low, the environmental impact of disposal of the slurry created by diamond grooving must be considered.
- Diamond grooving operations are typically noisy, which may be a potential issue in a community setting.

Partial-Depth Repairs

Figure 7-18. Partial-depth repair.

Partial-depth repairs (see figure 7-18) are used to address joint spalling and other surface distresses that are limited to the top third to top half of the slab through the use of approved repair materials. This treatment is effective in restoring the ride quality and structural integrity of localized areas while allowing joints to be effectively sealed. Improper repair finishing can result in poor ride quality, so diamond grinding is typically recommended to blend the repaired surface with the adjoining pavement (Smith et al. 2014).

Although they can be used alone to repair isolated damaged joints, partial-depth repairs are most typically conducted before full-depth repairs are completed and after slab stabilization is performed.

Positive Sustainability Attributes of Partial-Depth Repairs

- Partial-depth repairs use relatively little material and, thus, do not have large material-related environmental impacts.
- Partial-depth repairs generate a small amount of construction waste.
- Partial-depth repairs are expected to have long-term positive impacts if properly constructed in conjunction with other needed treatments.

Potential Negative Sustainability Attributes of Partial-Depth Repairs

- Partial-depth repairs must be appropriately applied to appropriate distresses and on slabs in which the limits of the damaged area are correctly identified and removed. The inappropriate application of partial-depth repairs can result in waste and early pavement failure.
- The construction of partial-depth repairs has historically been a labor-intensive, time-consuming operation with a high potential for traffic disruptions and delays; however, newer construction processes (including milling) and rapid-setting materials are being used to reduce these impacts.
- Partial-depth repairs can compromise pavement aesthetics if the repair material does not match the existing pavement material or if installed at a high density.
- The installation of partial-depth repairs is typically noisy and produces particulates, which may be problematic in a community setting.

Full-Depth Repairs


Figure 7-19. Full-depth repair.

Full-depth repairs (see figure 7-19) are effective in addressing structural distresses that extend through more than one-half of the slab thickness. Full-depth repairs extend through the entire thickness of the existing slab and involve the removal and replacement of full lane-width areas with cast-in-place or precast concrete. The additional joints created through full-depth repairs have the potential to decrease the ride quality. Hence, diamond grinding should be considered after full-depth repair installation to blend the repairs with the adjoining pavement and provide a smooth-riding surface (Smith et al. 2014). These repairs may not be a sustainable solution from an environmental and societal standpoint if they are performed over a large area of the project.

Positive Sustainability Attributes of Full-Depth Repairs

- Full-depth repairs are most often used to replace deteriorated joints or entire slabs, thereby restoring ride quality and pavement structural integrity.
- Full-depth repairs applied on a moderate scale have less environmental impact and lower costs than more extensive alternatives such as overlays or reconstruction.
- Full-depth repairs are expected to have a long-term positive impact on pavement longevity if properly constructed in conjunction with other needed treatments.

Potential Negative Sustainability Attributes of Full-Depth Repairs

- The installation of full-depth repairs is a labor-intensive operation that can result in significant traffic disruptions and delays. Various innovative construction practices and materials can be used to minimize this impact, but these are sometimes at a greater cost and a higher risk of early failure. Full-depth repair using precast concrete panels is an innovative option that can result in a reduction in environmental impact through reduced material-related impacts and expedited construction to minimize traffic delays.
- Full-depth repairs can compromise pavement aesthetics if the repair material does not match the existing pavement material or if installed at a high density.
- The installation of full-depth repairs is typically noisy and produces particulates, which may be an issue in a community setting.

Dowel Bar Retrofitting

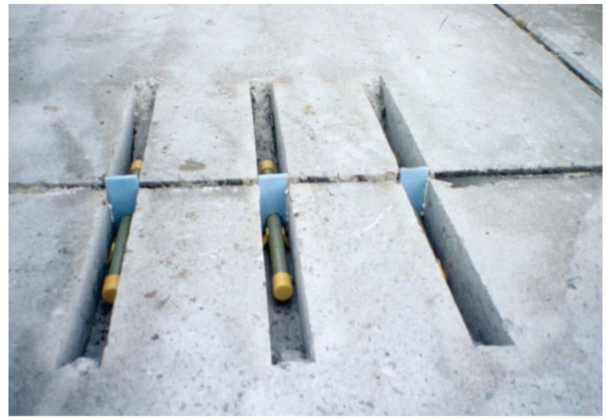

Figure 7-20. Placement of dowel bars in a dowel bar retrofitting operation.

Dowel bar retrofitting (also called load transfer restoration) involves the placement of dowel bars across joints or cracks with poor load transfer (see figure 7-20). The operation involves cutting slots, removing the existing concrete and preparing the slots, installing the dowels in the slot seated on a small chair, and backfilling the slot with repair grout. This technique helps reduce deflections by improving the load transfer across joints and cracks, thereby reducing the potential for the development of pumping, faulting, void formation, and corner breaks.

This treatment is often performed along with diamond grinding, which removes faulting and reduces noise levels. It is a common practice to use dowel bar retrofit to provide load transfer in jointed pavements that were originally constructed without dowels, or to provide improved transfer at mid-panel cracks.

Positive Sustainability Attributes of Dowel Bar Retrofitting

- Dowel bar retrofitting is used to provide/restore joint load transfer and reduce load-related stresses and deflections at joints and cracks, thereby helping to control the development of faulting and corner breaks.
- Dowel bar retrofitting uses relatively little material and thus does not have large material-related environmental impact. The use of dowels with a high recycled steel content provides further sustainability benefits.
- A relatively small amount of construction waste is generated by the dowel bar retrofitting operation.
- Dowel bar retrofit is expected to have a long-term positive impact if properly constructed in conjunction with other needed treatments.

Potential Negative Sustainability Attributes of Dowel Bar Retrofitting

- Dowel bar retrofitting must be appropriately applied to slabs; the inappropriate application or poor construction can result in early pavement failure at a high cost.
- Dowel bar retrofitting is a labor-intensive operation that can result in traffic disruptions and delays. The process can be expedited to some degree through the use of innovative construction practices and materials to minimize this impact, but at a greater cost and a higher risk of early failure.
- Dowel bar retrofitting can compromise pavement aesthetics if the repair material does not match the existing pavement material.
- The construction operations associated with dowel bar retrofitting are typically noisy and produce particulates, which may be problematic in a community setting.

Cross Stitching

Cross stitching is a technique used to maintain load transfer across non-working longitudinal cracks that are in relatively good condition (Smith et al. 2014). This treatment helps keep the cracks tight (or keeps them from opening further) by preventing vertical and horizontal movement, thereby maintaining adequate load transfer and reducing the rate of deterioration.

Positive Sustainability Attributes of Cross Stitching

- If done correctly, cross stitching provides a good long-term alternative to full-depth replacement of the affected slabs. This results in significant economic and environmental savings.
- Cross stitching uses relatively little material and thus has a small material-related environmental impact, made even less impactful if the steel has a high recycled content.
- Cross stitching generates little construction waste.

Potential Negative Sustainability Attributes of Cross Stitching

- Cross stitching must be appropriately applied to non-working cracks. Inappropriate application or poor construction can result in early pavement failure at a high cost.

Retrofitted Edge Drains

Retrofitted edge drains are sometimes used on concrete pavements that exhibit early indications of moisture-related distresses such as pumping and joint faulting. This technique involves the excavation of narrow trenches longitudinally at the outside edge of the pavement, the placement of a pipe or "fin" drain in the trench, and backfilling with drainable material to collect water that has infiltrated into the pavement structure and discharge it into the ditches through regularly spaced outlet drains (Smith et al. 2014). In some regions, retrofitted edge drains have been successful in slowing pavement degradation.

Retrofitting of edge drains is done near the beginning of the pavement restoration process, usually after slab stabilization has been completed.

Positive Sustainability Attributes of Retrofitted Edge Drains

- Retrofitted edge drains are intended to extend pavement life by removing excess moisture beneath the pavement.
- The installation of retrofitted edge drains can be completed in a relatively short time period and with relatively short work zones, thus minimizing traffic disruptions and delays.
- Retrofitted edge drains use no new paving materials, but do incorporate polyethylene or polyvinyl chloride piping materials whose environmental impacts must be assessed.

Potential Negative Sustainability Attributes Retrofitted Edge Drains

- Retrofitted edge drains must be appropriately installed, as the inappropriate application or poor construction can result in early pavement failure.
- The installation of retrofitted edge drains is a labor-intensive operation that can result in traffic disruptions and delays.
- Continued maintenance of the edge drain system is essential to its long-term effectiveness.

Ultra-Thin Wearing Course

This type of treatment on concrete pavement is used exclusively to improve the functional surface characteristics (friction and noise) of an existing pavement. These are very similar to the treatment of the same name discussed under asphalt-surfaced pavements, consisting of specially graded aggregates and a polymer-modified asphalt layer (0.4 to 0.8 inch [10 to 20 mm] thick) placed on a polymer-modified asphalt membrane. The life expectancy for ultra-thin wearing courses on jointed concrete pavements is shorter than when used on asphalt pavements due to the occurrence of joint reflection cracking in the wearing course (Tayabji, Smith, and Van Dam 2010). Ultra-thin wearing courses are applied to concrete pavements to achieve improved surface friction or to reduce noise emissions (or both).

Positive Sustainability Attributes of Ultra-Thin Bonded Wearing Course

- Ultra-thin wearing courses effectively seals the pavement, including joints and cracks.
- Ultra-thin wearing courses improve wet-weather safety by increasing texture and reducing splash and spray.
- Ultra-thin wearing courses improve pavement aesthetics by providing a new pavement surface.
- Ultra-thin wearing courses reduce noise generated through tire-pavement interaction.
- The construction of ultra-thin wearing courses can be completed in a relatively short time period, thus minimizing traffic disruptions and delays.

Potential Negative Sustainability Attributes of Ultra-Thin Bonded Wearing Course

- Ultra-thin wearing courses are dark in color and will likely decrease pavement albedo.
- Ultra-thin wearing courses require the use of new material transported from a central mixing facility.
- The life of ultra-thin wearing courses is relatively short when compared to the underlying concrete pavement, and thus will need to be reapplied multiple times during the pavement life.

Bonded Concrete Overlays

Figure 7-21. Bonded concrete overlay construction (courtesy ACPA).

Bonded concrete overlays (see figure 7-21) are characterized by the placement of a relatively thin (2 to 4 inch [51 to 102 mm] thick) concrete layer over an existing concrete pavement after isolated areas of deterioration on the existing pavement have been repaired and proper surface preparation practices have been followed to ensure adequate bonding. Bonded concrete overlays can be placed on existing concrete pavements to eliminate surface distresses and improve surface friction, ride quality, and noise emissions. A strong bond between the new overlay and existing pavement is required so that the resultant pavement behaves as a monolithic structure. Bonded concrete overlays require that the existing pavement be in (or be restored to) good or better structural condition. A comprehensive document on the use, application, and construction of concrete overlays is available from the National Concrete Pavement Technology Center (Harrington and Fick 2014).

Positive Sustainability Attributes of Bonded Concrete Overlays

- The concrete surface can be shaped and textured as desired, restoring surface friction, eliminating profile deficiencies, and reducing tire-pavement noise.
- Bonded concrete overlays improve pavement aesthetics by providing a new pavement surface.
- The pavement can be easily colored or textured to enhance aesthetics.
- Bonded concrete overlays are initially light in color and will likely increase pavement albedo.
- If properly designed and constructed, bonded concrete overlays exhibit relatively long life, reducing material consumption and construction impacts that would be otherwise caused by repeated applications of other treatments.

Potential Negative Sustainability Attributes of Bonded Concrete Overlays

- Bonded concrete overlays require the use of new material transported from a central mixing facility, so the environmental impact of those materials must be considered.
- Bonded concrete overlays can be difficult to construct, and improper construction (particularly the failure to achieve good bond between the overlay and the original pavement) can result in early failures that negatively impact economic and environmental performance.
- The construction of bonded concrete overlays may require a longer period of time, leading to the development of traffic disruptions and delays.

Energy Use and Emissions for Concrete-Surfaced Pavement Treatments

The information available regarding energy use and emissions for preservation and maintenance treatments placed on concrete-surfaced pavements is even more limited than that available for asphalt-surfaced pavements. Past studies of environmental impact have largely used LCI values for standard materials and computed hours of equipment use for a given treatment, assuming treatment life based on agency experience. Similar to asphalt-surfaced pavement treatments, the early focus has been on investigating the environmental impact of new construction and major rehabilitation. Only recently has the life-cycle value of preservation been investigated by the sector of the pavement community applying sustainability concepts.

One recent study (Wang et al. 2012) evaluated a limited number of concrete-surfaced pavement maintenance treatments and concluded that pavement maintenance can produce important net reductions in GHG emissions and energy use for high-volume routes. For segments with low-traffic volumes, the potential benefits take much longer to accrue, and payback may not occur before the end of the treatment life.

To elaborate, the study by Wang et al. (2012) examined the impacts of different material types for early-opening-to-traffic full-depth repairs (i.e., a high-cementitious mixture comprising AASHTO M 85 Type III cement with a high dose of accelerator, compared to a standard

Caltrans-specified calcium-sulfo-aluminate cement [CSA] mixture) as well as the benefits of diamond grinding. The construction efforts and performance periods for the two materials were considered identical; thus, the differences in energy consumption and GHG emissions were largely related to the material choices. As a result, the environmental impact of the more traditional Type III cement mixture was found to be significantly higher than that of the CSA mixture due to the following three factors:

- The Type III mixture had a cement content of 801 lbs/yd^3 (475 kg/m^3) versus 657 lbs/yd^3 (380 kg/m^3) for the CSA mixture.
- Although data on differences in embodied energy for the two cement types varies, the CSA cement is far less GHG intensive to produce than Type III cement as no calcination of limestone takes place.
- The Type III mixture used a very high dosage of accelerator (63 lbs/yd^3 [37 kg/m^3]). At that dosage rate, the accelerator had a significant environmental impact.

Figure 7-22 illustrates the impact of the material choice on the calculated energy consumption for the high-traffic-volume case study. As can be seen, although the cementitious binder had the single largest impact on the energy consumption, the accelerating admixture had a very significant impact as well. The same trend was observed for GHG emissions, but to a slightly lesser degree. Aggregates and mixing plant effects are minimal. This illustrates the importance of using mixture-specific information in any environmental analysis.

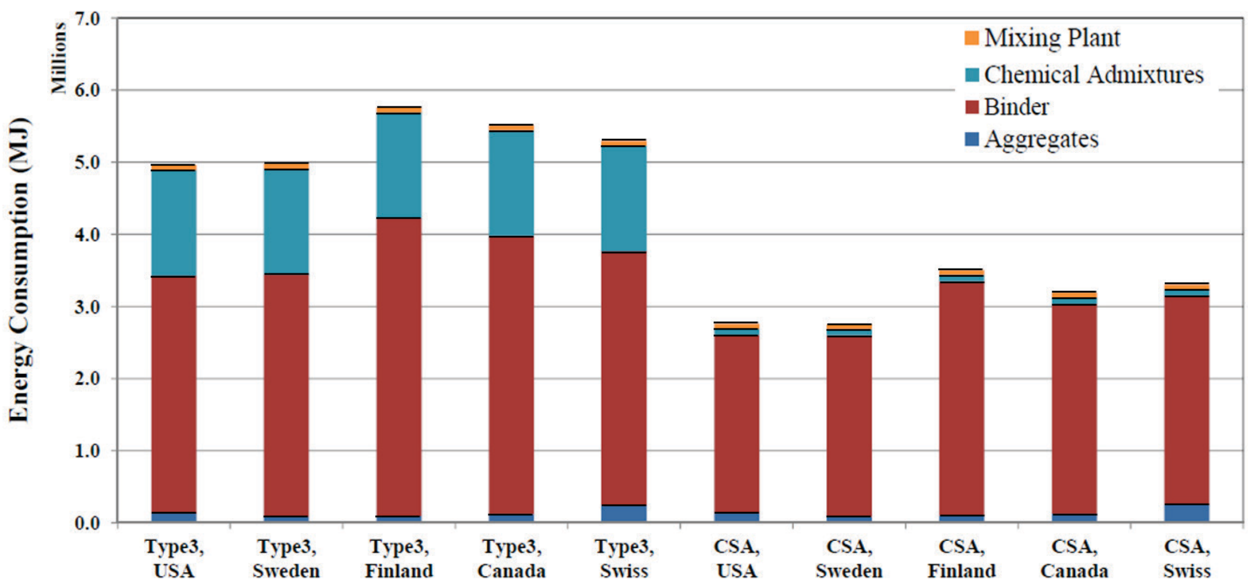

Figure 7-22. Details for the high-traffic case study of the material production phase showing the energy consumption for different LCI data sets (Wang et al. 2012).

In this same study, Wang et al. (2012) evaluated the use of diamond grinding to create three different levels of smoothness. It was concluded that the as-constructed pavement smoothness has an important effect on GHG emissions and energy use in the use phase and, therefore, on the total GHG emissions and energy use over the life cycle. It was also found that if the treatment does not result in a smooth pavement, then the environmental benefit is greatly reduced. Furthermore, although the emphasis on most work to date has been on materials and construction, the differences in net energy consumption, GHG emissions, and payback time between materials for a given treatment (i.e., repairs constructed using CSA cement or Type III portland cement) were small compared with the effects of smoothness over the life of the treatment. The authors noted that the impact of materials was probably reduced due to the limited number of slabs being replaced (3 percent) in the case studies.

Considerable work remains to be done in order to document and validate the effects of preservation and maintenance with regards to life-cycle environmental impacts. Nevertheless, this early work on concrete-surfaced pavements suggests that treatments that use less material and create smooth pavements that remain smooth for long periods of time will have distinct environmental benefits, particularly on more heavily traveled routes.

Strategies for Improving Sustainability

The general strategies for improving sustainability of preservation and maintenance treatments for concrete-surfaced pavements discussed at the beginning of this chapter are applicable. Thus, factors such as limited new material use, thinner cross sections, maintaining high levels of smoothness, and increased construction quality all reduce environmental burden and contribute to more sustainable treatments. As noted before, significant differences may exist in the approaches that are used to reduce environmental impacts, depending on a number of project-specific characteristics (perhaps most notably traffic volumes and associated burdens created in the use phase). As traffic volume increases, maintaining smooth surfaces becomes even more critical as the economic and environmental costs during the use phase begin to dominate the analysis. Although there is a clear distinction between agency costs and user costs with regards to economics, no such distinction exists when considering environmental impacts such as GHG and other emissions.

Future Opportunities

As interest in improving the sustainability of concrete-surfaced pavement maintenance and preservation techniques continues to evolve and move forward, future opportunities exist in the following areas:

- Improved materials that use less material and last longer. However, many of these innovative materials are (or will be) proprietary, so their environmental impacts are unknown or difficult to determine.
- Improved approaches for optimizing treatment selection and timing through the use of more sophisticated pavement management systems and more proactive "leading" indicators of performance.
- Improved construction, particularly improvements in equipment that can expedite some of the more labor-intensive and time-consuming activities.
- The use of precast solutions to reduce traffic disruptions and lane closures.

- Increased emphasis and refinement of renewable surfaces (e.g., diamond grinding).
- Alternative repair materials that can be opened to traffic more quickly without compromising future performance.
- Alternative load transfer devices that expedite construction yet have exceptional long-term performance.
- Increased sophistication of pavement evaluation equipment to determine suitability of various treatments.
- Other improvements as identified in chapter 3 for materials.

Concluding Remarks

This chapter reviews the effects of various maintenance and preservation treatments on the sustainability of pavement systems. There is a considerable lack of information on this topic, but clearly there are environmental and social impacts associated with the application of the broad range of preservation treatments on either asphalt-surfaced or concrete-surfaced pavements.

Although the cost effectiveness of these treatments has been investigated in recent years and they are widely accepted, the environmental and societal benefits still need to be explored. Specifically:

- Life-cycle inventories have not generally been done for pavement maintenance/ preservation treatments. Although preliminary work has demonstrated significant environmental value for some techniques, considerably more work needs to be done.
- Lower life-cycle costs are often highly correlated with lower environmental burden, with both being affected by:
  - Treatment selection.
  - Materials selection.
  - Timing of treatment.
- On higher-traffic routes, the higher economic cost of more frequent treatment may be offset by large reductions in environmental impact due to vehicle operation on smoother pavement.
- Treatment and materials selection.
  - Treatments with thinner cross sections having the same service life result in reduced environmental impacts.
  - The use of local materials reduces transportation costs, but must be balanced with the need to meet performance requirements.
  - Reducing traffic delays on high-volume routes must be balanced with the need to maintain high levels of smoothness.
  - New materials that enhance performance or lower energy consumption and emissions should be investigated.
  - The environmental footprint during the manufacture of some materials may be high. The development and implementation of Environmental Product Declarations (EPD) (discussed in chapter 10) will help provide useful information to decision makers.

- Construction quality.
  - Increased construction quality extends pavement life and reduces environmental burden.
  - The additional effort required to achieve additional quality is generally very low.
  - Pavements that are initially constructed smooth and that are maintained in a smooth condition over their life will result in reduced energy use and GHG emissions.

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