Sustainable Pavement Maintenance Practices

DETAILS

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SUSTAINABLE PAVEMENT MAINTENANCE PRACTICES

This digest contains excerpts from a study conducted for NCHRP Project 20-05, "Synthesis of Information Related to Highway Problems." The study was conducted by Susan L. Tighe, University of Waterloo, Waterloo, Ontario, Canada, and Douglas D. Gransberg, Iowa State University, Ames, Iowa. Jo Allen Gause is the Senior Program Officer for this study.

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SUMMARY

Today's transportation agencies, faced with the difficulty of meeting pavement maintenance and performance goals with limited budgets, are further challenged to ensure that their efforts contribute to their organizations' desire for environmental sustainability. In 1987, the Bruntdland Commission provided the following global definition for sustainability: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs." Sustainable transportation according to the FHWA is defined as ". . . providing exceptional mobility and access in a manner that meets development needs without compromising the quality of life of future generations. A sustainable transportation system is safe, healthy, affordable, renewable, operates fairly, and limits emissions and the use of new and nonrenewable resources."

This synthesis reports on the state of the practice in sustainable pavement maintenance and preservation. It is concerned and directed at quantifying and understanding how pavement maintenance and preservation practices minimize environmental impacts. The FHWA differentiates between pavement preservation and pavement maintenance and uses this to allocate federal funds accordingly. Although Canadian agencies recognize and practice the concepts of pavement preservation, there is no regulatory differentiation between it and maintenance as compared with the United States. Pavement preservation promotes environmental sustainability by conserving energy, virgin materials, and reducing greenhouse gases by keeping good roads good. Therefore, the foundation of a sustainable pavement maintenance program is to commit personnel and resources to pavement preservation.

Currently, public agencies in the United States and Canada have done little to extend the knowledge gained from research and practice in sustainable highway project delivery beyond construction completion and into the pavement preservation and maintenance phase of a road's life cycle. Therefore, there are many opportunities for future research and enormous potential for agencies to accrue benefits in this area of practice. These potential benefits are diverse and of strategic importance as they encompass improvements to virgin material usage, alternative material usage, pavement in-service monitoring and management, noise, air quality, water quality, and energy usage. Treatments identified in this report are primarily related to preservation and maintenance. However, these are not exclusive to preservation and maintenance and can be used in pavement rehabilitation.

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The synthesis provides the summary results of a comprehensive literature review, a survey of U.S. state and Canadian provincial highway agencies, and presentation of eight case studies of agencies that are implementing environmental sustainability programs that involve pavement preservation and maintenance practices. Although the highlighted case studies primarily focus on environmental sustainability and how it relates to pavement design and pavement construction, they provide an excellent basis for future application to pavement preservation and maintenance treatment. The survey was issued to state and provincial maintenance engineers in the United States and Canada. A total of 49 responses were received, 42 from U.S. state departments of transportation (DOTs) and 7 from Canadian provincial ministries of transportation, yielding response rates of 84% and 70%, respectively. The eight case studies of sustainable pavement programs included four U.S. DOTs (Arizona, New York, Oregon, and Washington State), the Ministry of Transportation in Ontario (MTO), the city of Philadelphia, a Pennsylvania state-level program for sustainable dirt and gravel road maintenance, and the New Zealand Transport Agency. Each case study demonstrates promotion of environmental performance utilized by the agency that also provides technical and economic benefits.

The major conclusions identified in this report are summarized as follows:

- Environmental sustainability research that is related specifically to post-construction operations is an emerging field.
- Thin asphalt overlays are the most prevalent preventive maintenance treatment for asphalt and composite pavements.
- Diamond grinding and joint sealing are the most commonly used treatments for concrete pavements.
- Regrading and regraveling are the most prevalent treatments for graveled roads, whereas chip seals are the preferred treatment for surface-treated roads.
- Quantification of sustainability with pavement preservation and maintenance programs is not commonly practiced in the United States and Canada.
- Various construction and design sustainability initiatives are available in the literature; however, an assessment tool to properly quantify environmental sustainability in the pavement preservation and maintenance context is both missing and required.
- The case studies demonstrate that environmental sustainability can be incorporated into pavement preservation and maintenance practices.

One purpose of this synthesis study was to identify gaps in the knowledge of sustainable pavement preservation and maintenance treatments and suggest possible research to address these gaps. Following is a summary of the seven major research needs presented in the report:

- There is a need for pavement preservation and maintenance-specific research to furnish agency pavement maintenance engineers with the fundamental data on the relative environmental sustainability of common treatments.
- There is a need to develop pavement preservation and maintenance-specific life-cycle assessment and cost analysis methods that include values for factors such as carbon sequestration, resource renewability, and other salient elements of environmental sustainability to furnish a rational approach to treatment selection.
- Research is needed to develop training and information to be disseminated throughout the United States and Canada that quantifies the importance of preservation and maintenance treatments in the environmental sustainability impact factor areas discussed in this report.
- There is a need to complete research in adapting recycled and alternate materials for use in pavement preservation and maintenance treatments.
- There is a need for research to identify and develop appropriate noise standards for pavement preservation and maintenance operations and life-cycle assessment.
- There is a specific need for research to quantify the contribution that crack sealing makes to the environmental sustainability of all types of pavement surfaces to demonstrate its importance in sustainable pavement preservation and maintenance.
- There is a need to research policies, technology, materials, specifications, standards, equipment, capacity-building, recycling/waste reduction, emissions reduction (air pollution), and life-cycle cost analysis. In this regard, it is necessary to incorporate sustainable pavement maintenance elements into on-going and future pavement maintenance research.

INTRODUCTION

Increasing societal awareness of the environmental effects of constructing, operating, and maintaining the highway infrastructure has led to new demands on transportation agencies to conduct their business in a more environmentally friendly, or sustainable, fashion. One key approach is for agencies to implement a pavement preservation program; restoring pavements that are still in good condition and extending their service life. The FHWA considers pavement preservation as a proactive approach to maintaining highways. Pavement preservation and maintenance treatments usually provide the least expensive pavement management strategy available on a life-cycle cost basis (FHWA 2005).

This synthesis is directed at benchmarking the current state of the practice in usage and quantification of pavement preservation and maintenance practices in terms of environmental performance. "Sustainability" in the synthesis refers to promoting environmentally friendly practices that also provide technical and economic benefits. The seven sustainability impact factor areas evaluated are virgin material usage, alternative material usage, program for pavement in-service monitoring and management, noise, air quality/emissions, water quality, and energy usage and their relationship to typical pavement preservation and maintenance practices. Information in the synthesis examines all pavement types including asphalt, concrete, composite, surface-treated and gravel roads, and pavements.

Synthesis Objective

The objective of this synthesis is to identify and synthesize current sustainable pavement preservation and maintenance practices. The focus is on determining what the current state of practice is in this area and also to identify needs for future research. The synthesis identified those agencies that are demonstrating efforts to quantify environmental performance and stewardship in maintenance and preservation and related areas.

To assess the way that environmental sustainability relates to pavement maintenance, the methodology of this synthesis was to prepare a literature review, conduct a survey of practitioners and evaluate their responses, and assemble case studies from several exemplary programs.

Background

Pavement infrastructure is critical to the quality of life and prosperity of society. As the pavement structure deteriorates over time, proper pavement preservation and maintenance is necessary to achieve a high-performing, safe, and cost-effective pavement network for the users. In a society where currently resources and funding are limited, it is more important than ever that transportation agencies seek ways to use these resources to maximize benefits as part of daily operations. At the same time, attention to the notion of environmental sustainability has become more important to society. In general, environmental sustainability has been defined by the Bruntdland Commission as "[meeting] the needs of the present without compromising the ability of future generations to meet their own needs" (Bruntdland Commission 1987). Recently, the FHWA defined sustainable transportation as "providing exceptional mobility and access in a manner that meets development needs without compromising the quality of life of future generations. A sustainable transportation system is safe, healthy, affordable, renewable, operates fairly, and limits emissions and the use of new and nonrenewable resources" (Harmon 2010). The basis of environmental sustainability consists of the three elements shown in Figure 1: economy, society, and environment. Sustainable pavement preservation and maintenance are a subset of sustainable transportation where the impacts of the treatments on the economy, environment, and social equity are defined and evaluated. It can also be evaluated according to the technical and economic effectiveness and the associated impacts on the natural environment (Jeon and Amekudzi 2005). It can be noted that a study of state departments of transportation (DOTs) indicated

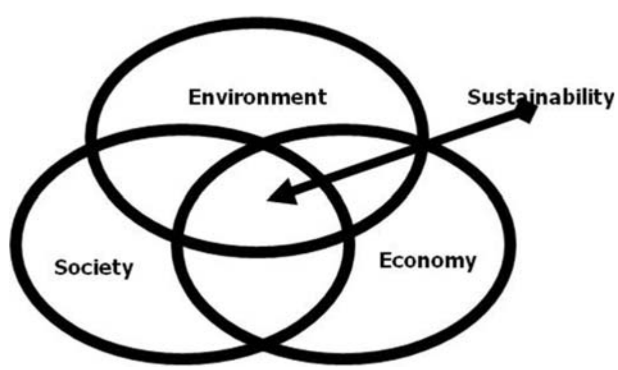

Figure 1 Fundamental sustainability model (CH2M Hill 2009).

that although environmental sustainability is not explicitly mentioned in the mission and vision statements of most agencies, many do include the three elements (Amekudzi and Jean 2007; Ramani et al. 2009).

The concept of environmental sustainability and how it can be employed in various practice areas is gaining wide support from the general public, governments, and professionals (Chan and Tighe 2010; Muench 2010). The need of quantifying sustainable practices is also challenging and requires a holistic approach. The initiatives by LEED™ (USGBC 2010), Greenroads (Muench 2010), GreenLITES (NYSDOT 2009), and GreenPave (MTO 2010) certification programs are leading examples of programs that promote and quantify sustainable practices (Chan and Tighe 2010). In addition, there are several other initiatives such as PaLATE (Horvath 2009), EIO-LCA (EIOLCA 2010), and some industry initiatives that will be described later in the report. However, although it is notable that many of the environmental sustainability initiatives consider preservation and maintenance treatments and their contributions to long life pavements, there is limited explicit assessment of those treatments in terms of environmental performance.

As noted in FHWA's newsletter, *Strategic, Safe and Sustainable: Today's Vision for Pavements,* environmental sustainability is of critical importance (Stephanos 2009). It was noted in that article, in the new decade of environmental awareness, that maximizing recycled materials in pavement construction and rehabilitation is a priority and this is further advanced through the FHWA participation in Green Highways Partnership, which is an attempt to align various state specifications for using recycled materials. Other initiatives include using warm mix that generates fewer emissions and conducting research on expanding the types and amount of fly ash that can be used in concrete paving. Although these initiatives tend to focus primarily on usage in pavement construction and rehabilitation treatments, they are also an important part of pavement preservation and maintenance treatments.

Additionally, recent research in France and New Zealand (Ball et al. 2008) mirrors a U.S. movement from solvent-based binders toward water-based emulsion binders for use in pavement preservation and maintenance treatments as a result of concern for the environment. Emulsions are "more . . . environmentally friendly that . . . cut back asphalts" (James 2006). A New Zealand study confirmed this assertion when it found: "Current indications are that chip sealing emulsions typically would be classified as safe . . . " (Ball et al. 2008). Thus, adding an environmental sustainability factor to the pavement preservation and maintenance decision-making process is both timely and appropriate.

Key Definitions

The synthesis will use a number of definitions. It is important for the reader to understand the specific definition of each of the terms to gain a full understanding of the meaning of this study. The most notable key definitions for this work include pavement maintenance versus pavement preservation. For this study, the current FHWA definitions for pavement preservation and maintenance terminology have been used. These definitions provide the basis of assessment for this synthesis.

Pavement preservation is "a program employing a network level, long-term strategy that enhances pavement performance by using an integrated, cost-effective set of practices that extend pavement life, improve safety, and meet motorist expectations" (FHWA 2005). Pavement preservation is comprised of the following activities:

- *Preventive maintenance* is "a planned strategy of cost-effective treatments to an existing roadway system and its appurtenances that preserves the system, retards future deterioration, and maintains or improves the functional condition of the system (without significantly increasing the structural capacity)" (FHWA 2005).
- *Routine maintenance* "consists of work that is planned and performed on a routine basis to maintain and preserve the condition of the highway system or to respond to specific conditions and events that restore the highway system to an adequate level of service" (FHWA 2005).
- *Minor pavement rehabilitation* consists of "structural enhancements made to the existing sections to eliminate age-related, top-down surface cracking that develops in flexible pavements due to environmental exposure. Because of the non-structural nature of minor rehabilitation techniques, these types of rehabilitation techniques are placed in the category of pavement preservation" (FHWA 2005).

Sustainability Impact Factor Areas

Measuring environmental sustainability is an emerging field in the transportation industry, and even more so with respect to the pavement maintenance treatment selection process. The literature is rife with newly coined terms to describe a given treatment's impact on the environment (Takamura et al. 2001; James 2006; Ball et al. 2008; Chaignon and Mueller 2009; Lane 2010; Muench 2010). "The terms 'Green,' 'Sustainable Development,' 'Environmental Impact,' 'Energy Efficiency,' 'Global Warming,' 'Greenhouse Gases,' and 'Eco-efficiency,' are becoming more widely recognized . . . " (Chehovitz and Galehouse 2010).

Unfortunately, each article or manual focuses its evaluation of environmental impact on a different set of impacts. For example, Takamura et al. (2001) coined the term "eco-efficiency" to describe the comparative analysis of six parameters: virgin material consumption, energy consumption, land use, emissions, toxicity, and risk potential. Pittenger's research (2010) included virgin material consumption, life-cycle cost, and a factor from the Greenroads certification program (Muench 2010); whereas Chehovitz and Galehouse (2010) confined their analysis to greenhouse gas emissions and energy consumption. Thus, it is difficult to adopt a single, universally recognized term to identify the process of evaluating competing pavement preservation and maintenance treatment options on the basis of relative environmental sustainability.

The AASHTO Center for Environmental Excellence (CEE) provides a basis for identifying and promoting environmental excellence in the efficient delivery of transportation services (Kober 2009). The CEE evaluates sustainability parameters by identifying focus areas. Consequently, seven sustainability impact factor areas identified by the CEE will be considered in this synthesis. Each one of the areas and how they relate to pavement preservation and maintenance treatments is described herein. It should be noted that other life-cycle assessment tools such as the ISO 14040 Standard are available and many of these do cite other environmental sustainability impact factors (ISO 2006). However, for the purpose of this synthesis, the seven aforementioned factors have been examined and are described here.

1. Virgin material usage examines reducing the need to use nonrenewable resources. Pavement materials can be expensive and some resources may be limited; therefore, it is important to make good use of available materials. The primary focus of this area is to consider the reduced need for virgin material usage and demand of virgin materials for treatments. Many maintenance treatments involve in-place recycling, which enables re-use of the materials already committed to roadways. Prolonging the time between major rehabilitation and reconstruction through proper pavement treatment selection is an effective way to reduce virgin material usage.
2. Alternative material usage examines the opportunity to recycle materials and to use other materials in the pavement structure during preservation and maintenance. This could mean incorporating reclaimed asphalt pavement, recycled concrete aggregate, recycled asphalt shingles, recycled rubber tire, glass, or any other materials that might be appropriate. Proper processing of these materials can result in equivalent performance to virgin aggregate (Infraguide 2005). Careful blending and crushing of recycled materials is required to achieve consistent gradation and performance of the material (Infraguide 2005).
3. Programs for Pavement In-Service Monitoring and Management assists agencies in finding the right treatment for the right pavement at the right time. Robust information systems help determine existing and forecasted pavement conditions so that decisions can be accurately made and funds programmed for network improvements. Pavement in-service monitoring and management would consider the life-cycle and associated serviceability of the treatment.
4. Noise is defined as the unwanted or excessive sound associated with pavement construction and improvements. Studies show that the most pervasive sources of noise in the environment relate to transportation. Therefore, noise is examined as an environmental sustainability factor area whereby pavement preservation and maintenance treatments are evaluated on their noise impacts (CEE 2010a).
5. Air quality/emissions examines six principal air pollutants, namely carbon monoxide, lead, nitrogen dioxide, ozone, particulate matter, and sulfur dioxide (CEE 2010b). The intent is to assess each pavement preservation and maintenance treatment in terms of these pollutants. This would involve both calculations for the

air quality/emissions for the equipment and materials. Also considered would be the associated impact the treatments have on the travelling public in terms of emissions associated with traffic delays resulting from the treatment placement. Part of the calculation of this factor would be the preventive maintenance treatment's service life.

6. Water quality evaluates the effects of transportation-related impacts associated with alternative maintenance strategies and materials. Regulatory requirements relate to the operation and maintenance of municipal storm sewer systems, storm water discharge associated with construction activities, and effluent standards related to the total maximum daily effluent discharge standards. Treatments and programs should be evaluated for their individual and collective effect on these resources (CEE 2010c).
7. Energy usage relates to the quantification of cumulative energy usage of the pavement preservation and maintenance treatment throughout the life cycle. Energy usage is important in its correlation to emissions of greenhouse gases and their relationship to climate change.

Study Approach

The approach used to complete the synthesis essentially relied on three independent sources of information. The first was a comprehensive review of the literature. An effort was made to obtain not only the most current information but also historical information, so that any changes over time could also be properly described and documented. The second source of information included the survey responses of U.S. and Canadian maintenance engineers employed by the state or provincial highway agencies. Finally, case studies based on both the surveys and literature were included. Collectively, this information was used to identify current gaps in the state of the practice and identify how these gaps can be addressed in future research.

Protocol to Develop Conclusions and Recommendations for Future Research

The major factor in developing a conclusion was the intersection of trends found in the literature, survey, and case study documentation. All three tools were used to develop the conclusions and suggestions presented in this synthesis.

Organization of the Report

The information collected in this study is presented as follows:

- Summary of Literature Review and Survey and Results
- Quantifying Environmental Sustainability in Pavement Preservation and Maintenance
- Case Studies
- Conclusions and Future Research Needs.

SUMMARY OF LITERATURE REVIEW AND SURVEY AND RESULTS

Introduction

This report employed the following major study instruments:

- A comprehensive literature review.
- A survey of U.S. state DOTs and Canadian provincial transportation agencies.
- Case study analyses of selected U.S., Canadian, and one New Zealand sustainable pavement preservation and maintenance programs.
- The structure and content of each of the instruments were integrated to identify trends in the data.

The literature found in sustainable transportation is largely about design, construction, and material selection. Very little information was found that was specific to sustainable pavement preservation and maintenance quantification. Most of the studies involved the comparison of specific pavement preservation and maintenance treatments, such as chip sealing or microsurfacing, to hot mix or portland cement concrete overlays or rehabilitation. Although this information is valuable, there is no single source of environmental sustainability data on the suite of commonly used pavement preservation and maintenance treatments. The Recycled Materials Resource Center's (RMRC) website (http://www.rmrc.unh.edu/) appears to have the most current and complete collection of highway environmental sustainability research. A search of that archive revealed that the majority of the research has been in the area of material science and hazard analysis. RMRC Project No. 23 notes that: "We have not found publications on the environmental effects of the different maintenance activities" (Horvath 2004). This demonstrates that environmental sustainability research that is related specifically to post-construction operations is an emerging field. Thus, the first conclusion reached in this synthesis is that there is an immediate need for maintenance-specific research to provide agency pavement maintenance engineers with the fundamental data on the relative environmental sustainability of common treatments and preservation programs.

A survey was issued to the state and provincial maintenance engineers in the United States and Canada (see web-only Appendixes A and B for details). A general survey on sustainable pavement preservation and maintenance practices provided 49 responses from 42 U.S. state DOTs and 7 Canadian provincial ministries of transportation shown in Figure 2. This corresponds to an individual response rate of 84% for the United States and 70% for Canada. The survey also received responses from three U.S. counties; however, the number of responses from nonstate-level agencies was small and they are not included in the analysis. This analysis separated the U.S. and Canadian responses to account for the difference in the construction contracting regulatory environment that exists in both countries. Additionally, information from the international agencies is added as appropriate throughout the synthesis.

The case studies were identified after a review of the available literature and responses to the survey, along with input and recommendations of candidates familiar to the synthesis panel. Although there is limited available data and the field is relatively new, case studies were found that highlight each of the environmental factors

Opportunities to Implement Sustainability in Maintenance

The literature is rich with information on sustainable practices that can and have been applied to highway design and construction, although not to maintenance. Each study represents an opportunity for maintenance engineers to potentially adopt aspects of the sustainable practices in maintenance and preservation. In other cases, the identified sustainable practices will likely need to be adapted or altered before their use in pavement preservation and maintenance applications. Table 1 consolidates the information found in the literature and extends each study's result to possible pavement preservation and maintenance applications. In most cases, the possible application was mentioned in the cited report or paper, and the mention took the form of a recommendation for additional research to validate the concept. The report by Denevillers (2010) detailed actual field testing of

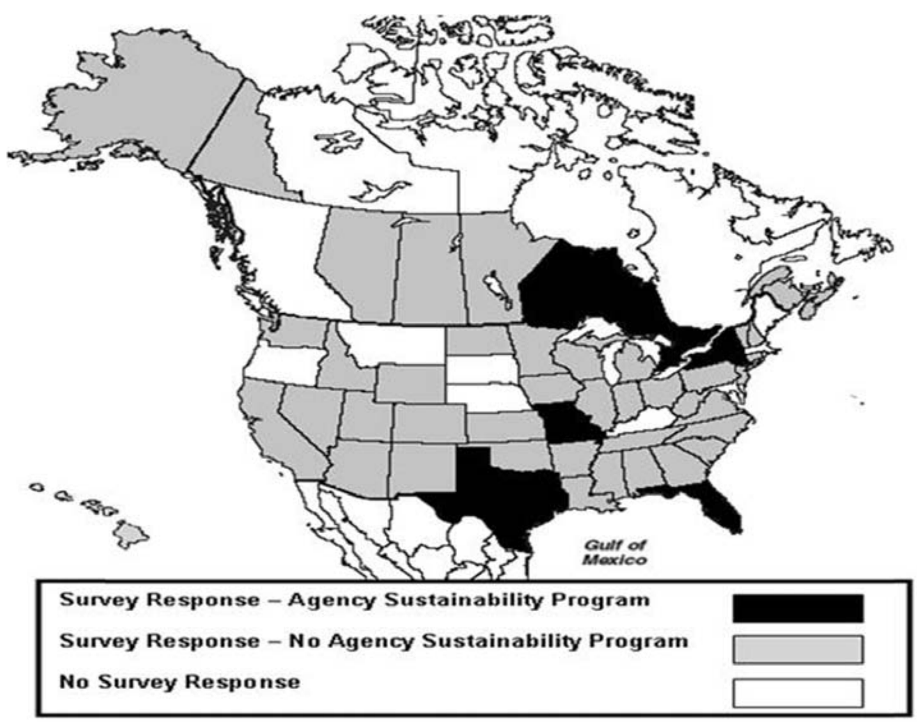

Figure 2 Survey responses.

Table 1 Alternative, recycled, and renewable highway design and construction literature review results

Material/ Technique	Literature Cited	Possible Preservation Uses	Possible Maintenance Uses	Remarks
Bio-fluxing Agent	Denevillers (2010)	• Prime coat • Chip seals • Microsurfacing	• Overlay tack coat • Cold mix • Warm mix	Trade name is Vegeflux®
Bio-binder	Denevillers (2010)	• Chip seals • Microsurfacing	• Cold in-place recycling • Chip seals • Road marking	Trade name is Vegecol®
Recycled Concrete Aggregate (RCA)	Gardner and Greenwood (2008)	• Whitetopping	• 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 maintenance mixes • Microsurfacing	Widely used in a variety of products
Bottom Ash	Carpenter and Gardner (2007)	• Microsurfacing mineral filler	• Subase under gravel surface	
Flue Gas Desulpherization Gypsum	Benson and Edil (2009)	• Microsurfacing mineral filler • Slurry seal mineral filler	• Concrete maintenance mixes	
Kiln Dust	MnDOT (2005)	• Prime coat • Microsurfacing	• Prime coat • Microsurfacing	
Baghouse Fines	ISSA (2010)	• Microsurfacing mineral filler • Slurry seal mineral filler	• Untried	
Crushed Slag	Chappat and Bilal (2003)	• Chip seal aggregate	• Special binder road mix	
Ultra-High Pressure Water Cutter	Pidwerbesky and Waters (2007)	• Restore macro-texture 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	Transport Canada (2003)	• Restore micro-texture 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 overlays	• Chip seals • Thin overlays	Also found to reduce road noise

HMA = hot-mix asphalts; PCC = portland concrete cement.

vegetable-based carbon emulsions. One of the principles of environmental sustainability is to minimize the use of nonrenewable resources. For example, the use of a renewable bio-fluxing agent as a prime coat was successfully demonstrated in Morocco, and also tested and used in chip seals on Route 960 in Saumur, France. The same is true for the bio-binder, which has been successfully applied in Canada and seven European countries. Although it is not in the table, it can be noted that it has successfully been used in road marking paints in France and England. It can be noted that many of these treatments can be evaluated in the broader environmental sustainability context as details in the literature were limited.

Table 1 illustrates that whereas fundamental research has been done on enhancing highway environmental sustainability through the use of recycled materials, alternate materials, and green construction technologies, the information necessary to extend these promising opportunities to pavement preservation and maintenance must still be developed through future research and field testing. Additionally, the economic analyses contained in those reports are very rudimentary. A recent study found that the standard FHWA-approved life-cycle cost analysis method for new construction is not easily applied to pavement preservation projects (Pittenger 2010). As a result, rigorous research would be needed to apply a life-cycle cost analysis algorithm that goes beyond merely looking at treatment construction costs and provides a rigorous methodology to assign a value to such things as carbon sequestration and resource renewability.

Sustainability Within Agency Maintenance Programs

In recent years, transportation agencies have been placing increasing importance on maintenance efforts; as funding becomes scarcer, it becomes critical to take care of the infrastructure they already have. Therefore, influencing the environmental sustainability of pavement maintenance efforts within DOTs will have a meaningful impact. Table 2 summarizes the survey responses regarding the relative magnitude of pavement preservation and maintenance programs in the United States and Canada. In those agencies on the low end of the funding spectrum, the need for an aggressive pavement preservation program is critical to getting as much value out of each maintenance dollar as possible (Galehouse et al. 2003; NHI 2007). Pavement preservation promotes environmental sustainability because it seeks to minimize the amount of natural resources consumed over a pavement's life cycle (FHWA 2005). Focusing on pavement preservation rather than reactive maintenance and repair furnishes a broad foundation on which to build an agency's pavement maintenance environmental sustainability program.

The survey contained a number of questions designed to draw a relationship between agency pavement preservation and maintenance programs and environmental sustainability (Table 3). The conclusion from these data is clear. Most agencies do not consciously consider either environmental performance or environmental sustainability when planning and conducting pavement preservation and maintenance activities. A comment on the Louisiana DOT's response accurately describes current state of the practice: "We are concerned about environmental sustainability but have no active program in pavement maintenance." The agencies that did indicate that some kind of pavement environmental sustainability program existed in their organizations were Ontario, Florida, Missouri, New York, and Texas. New York and Ontario are detailed in the case studies in addition to providing some information from a few other agencies. Note that some of these were not directly related

Table 2 Summary of annual maintenance budgets from survey respondents

	Approximate Annual Maintenance Budget		
Range	**Low**	**Average**	**High**
Canada	$2.8 million	$99.0 million	$276.4 million
$US per lane-mile	$1,127	$26,064	$51,054
% of 2009 Program	1.9%	15.9%	26.7%
U.S.	$15.0 million	$278.5 million	$1.7 billion
$US per lane-mile	$1,650	$15,669	$79,589
% of 2009 Program	1.4%	14.9%	33.4%

Table 3 Summary responses to environmental and sustainability programmatic questions

	Does your agency use environmental performance to select maintenance and/or preservation program practices?		Do you have an agency-wide "sustainability" program that includes pavement maintenance activities?		Does your agency have sustainable maintenance specifications?		Does your agency use PMS software to monitor environmental performance	
	No	Yes	No	Yes	No	Yes	No	Yes
Canada	7	0	5	2	7	0	7	0
U.S.	40	2	38	4	41	1	36	6
Total	47	2	43	6	48	1	43	6
Percentage	96%	4%	88%	12%	98%	2%	88%	12%

PMS = Pavement Management System.

to maintenance but rather to construction or planning of pavements. A closer look at some of those programs shows that the agency-wide program is focused on sustainable design and construction with little specific guidance being given to environmental sustainability within pavement preservation and maintenance. This leads to the identification of a need for future efforts to develop the programmatic guidelines and specifications needed to implement sustainable pavement preservation and maintenance programs.

Summary

Although agencies are becoming more aware of the significance of the concept of environmental sustainability, this does not translate to direct measures for use within their maintenance programs. More than 80% of responding agencies indicated that their agency did not use environmental performance, nor did they have agency-wide environmental sustainability or sustainable maintenance specifications.

Conclusions

The following conclusion was reached in this chapter:

- *Environmental sustainability research that is related specifically to post-construction operations is an emerging field.*

Future Research Needs

The following research needs were identified in this chapter:

- *There is a need for pavement preservation and maintenance-specific research to furnish agency pavement maintenance engineers with the fundamental data on the relative environmental sustainability of common treatments.*
- *There is a need to develop a pavement preservation and maintenance-specific life-cycle assessment and cost analysis method that includes values for factors such as carbon sequestration, resource renewability, and other salient elements of environmental sustainability to furnish a rational approach to treatment selection.*

QUANTIFYING ENVIRONMENTAL SUSTAINABILITY IN PAVEMENT PRESERVATION AND MAINTENANCE

Introduction

This chapter presents the seven environmental sustainability impact factor areas and the extent to which the survey responses used them in their construction and maintenance decisions. Environmental stewardship considers the use of renewable resources at below their rates of regeneration and nonrenewable resources below rates of development of substitutes as noted by the first two environmental sustainability impact factor areas. In addition, the need to provide a clean environment from both an air quality and water quality perspective could be included in an environmental monitoring plan, as well as including pollution prevention, climate protection, habitat preservation and aesthetics (Ramani et al. 2009).

Recycling, reusing, and reclaiming of existing materials is crucial to advance sustainable development (Carpenter and Gardner 2007). Construction materials can be expensive and now some resources are in limited supply, making it important to make good use of available materials. One of the concerns with the use of recycled material is potential uncertainty regarding the actual composition of a recycled material when compared with the virgin material it would replace. As a result, some agencies have withheld permission to use recycled materials, whereas others have limited the amount of recycled material that can be incorporated into the pavement structure (Melton and Morgan 1996; Smith and Romine 2009). Several successful uses of recycled asphalt pavement and recycled concrete aggregate are available in the literature and it can be noted that in addition to providing technical benefits, they improve the performance of the pavement (Beatty et al. 2002; Alkins et al. 2008; Tighe et al. 2008; Smith and Tighe 2009; Scholz 2010). Further, both hot and cold in-place recycling are used by agencies for maintenance and rehabilitation of pavements, minimizing the amount of new materials for the work and reducing energy requirements for transporting materials to the job site. Table 4 shows that roughly 70% of the responding agencies permit the use of recycled materials in their pavement preservation and maintenance programs.

Alternative materials also hold the promise of being able to enhance environmental sustainability in pavement preservation and maintenance. Research has shown that materials such as recycled asphalt shingles, recycled rubber tire, recycled glass, and reclaimed carbon from copier toner can be successfully incorporated into new pavements (Chan and Tighe 2010). The incorporation of innovative materials can also potentially enhance pavement performance and reduce the demand for virgin materials (Horvath 2004). Thus, the survey sought to find the level of alternative material usage in agency pavement preservation and maintenance programs in Canada and the United States. Table 5 shows that alternative materials have a lower level of use than recycled materials, probably awaiting further research into their long-term performance in maintenance applications. Table 5 reflects the relatively widespread use of fly ash in concrete, as well as asphalt shingles and recycled rubber tires in hot-mix asphalt pavements. However, the use of other alternative materials remains relatively uncommon. These results suggest that future research into applications and performance of alternative materials could be of value.

Minimizing or eliminating noise pollution is another element of a sustainable design and construction program, and it follows that standards imposed on construction may also be applicable to maintenance operations. Table 6 shows the results of that portion of the survey. Only about 21% of the respondents believed that noise pollution is an important/very important issue in their agencies. Only 7% were aware of noise standards for their agencies' pavement maintenance operations, whereas more than one-third of the survey respondents did not have any noise standards for maintenance operations. Relevant future research could help establish appropriate noise standards for construction and maintenance operations, and provide a tool for using noise considerations as part of treatment selection. As noted by the high number of respondents choosing the "no opinion" or "don't know" categories, it could be suggested that education and training be provided in this environmental sustainability impact factor area for maintenance personnel.

For the environmental sustainability factor of *water quality,* there is a similar unfamiliarity among the survey respondents about how agency policies are applied to maintenance activities. Based on this evaluation, there are no current measures available that

Table 4 Summary of recycled and alternative materials authorization

	Are Recycled Materials Allowed in Your Current Program?		Are Alternative Materials Allowed in Your Current Program?	
	No	Yes	No	Yes
Canada	0	7	2	5
U.S.	14	28	18	24
Total	14	35	20	29
Percentage	28.6	71.4	40.8	59.2

TABLE 5 Summary of recycled and alternative material usage by pavement type

Recycled/Alternative Material	Gravel		Surface Treated		Asphalt	
	Canada	U.S.	Canada	U.S.	Canada	U.S.
Fly Ash	0	0	0	1	1	0
Shingles	0	1	0	1	2	13
Tire Rubber	0	1	0	1	2	13
Glass	0	2	0	0	0	3
Foundry Sand	0	0	0	0	0	1
Carbon	0	0	0	0	0	1

Recycled/Alternative Material	Concrete		Composite			
	Canada	U.S.	Canada	U.S.	Total	Percentage
Fly Ash	4	21	0	1	28	57.1
Shingles	0	0	0	0	17	34.7
Tire Rubber	0	0	0	0	17	34.7
Glass	0	1	0	0	6	12.2
Foundry Sand	0	2	0	0	3	6.1
Carbon	0	0	0	0	1	2.0

quantify the effects of pavement maintenance and preservation on water quality. The data indicate that the pavement preservation and maintenance treatment's impact on water quality is considered less than half the time, probably because less than half the responding agencies indicated that they have agency water quality guidelines. That roughly one-third of all respondents did not know if their agency considered water quality or had water quality guidelines indicates that coupling programmatic environmental sustainability with pavement preservation and maintenance programs has not yet happened in North America. Again, this would reinforce the need to develop measures in this area for quantification.

The news with regard to *air quality* is better. A little over 60% of the agencies reported that they monitor air quality in the course of their pavement maintenance operations. However, only 25% of

Table 6 Summary of noise pollution measures

	How important is noise distribution during pavement maintenance operations in your agency?						Agency Noise Standards in Effect				
	Very Important	Important	Neutral	Not Important	Not Even Considered	No Opinion	Construction Noise	Maintenance Noise	Traffic Noise	No Noise Standard	Don't Know
Canada	0	1	3	0	2	1	2	1	0	4	0
U.S.	4	4	12	0	4	11	7	2	3	11	15
Total	4	5	15	0	6	12	9	3	3	15	15
Percentage	9.5	11.9	35.7	0.0	14.3	28.6	21.4	7.1	7.1	35.7	35.7

the agencies consider energy usage when selecting pavement preservation and maintenance treatments. Both of these are areas where the use of preventive maintenance treatments in a pavement preservation program can have a noticeable effect. Many of the treatments are emulsion-based, with comparatively low emissions. Similarly, providing quantitative measures for differences among energy use among the various treatments would be a valuable tool in treatment selection.

Summary

This chapter examines the current state of the practice related to the environmental sustainability impact factor areas and their application to pavement preservation programs and maintenance treatments. The recycled and alternative materials authorization is the most prevalent. Although it is not explicitly stated, the role of pavement in-service monitoring and pavement management is also common. If implemented properly, a sustainable pavement management program emerges, because the pavement monitoring system triggers pavement preservation activities, which in turn extend the service life of the pavement and reduce the impact to the environment in all categories. In short, keeping good roads good is the most effective way to sustain the service life of a road without consuming significant amounts of energy, virgin materials, and nonrenewable resources, which automatically reduces air, water, and noise pollution. A recent study of the Georgia DOT network-level pavement management system (Wang et al. 2010) demonstrated that such a system also makes economic sense. The report found that a robust in-service pavement monitoring system "will help decision makers address the question of paying for roadway preservation now at a lower cost or later at a much higher cost" (Wang et al. 2010). Further examination and quantification of this impact could be examined in future work as the direct policies and practices to pavement preservation and maintenance treatments could be explicitly reviewed for these environmental sustainability impact factor areas. In terms of noise pollution, water quality, and air quality there is clearly an opportunity to incorporate these environmental sustainability impact factor areas into preservation and maintenance operations.

The following conclusion was reached in this chapter:

- *Although most agencies have environmental analysis incorporated into their design and construction operations, many maintenance practitioners are not familiar with how they could or should be applied to maintenance and preservation decisions.*

CASE STUDIES

As part of this report, eight case studies were selected to demonstrate how agencies might apply environmental sustainability factors to their maintenance programs. Information for the case studies was obtained from technical publications. Each case study was selected to demonstrate a specific aspect of practice related to environmental sustainability. The case studies were drawn from the literature. Several sustainable transportation case studies are available through the AASHTO Center for Environmental Excellence (CEE 2010d). Each case study provides a basis for understanding the context of how pavement preservation and maintenance can be evaluated. However, again, there is limited explicit information on how in practice agencies are carrying quantifying sustainable preservation and maintenance treatments. In any case, this section has involved identifying some examples of environmental stewardship. Each case study is presented in a similar manner.

Case Study Descriptions

The case studies were drawn from agencies across the United States and in Canada, encompassing a range of climates and reflecting a variety of program types (Table 7).

Case Study 1: Arizona Department of Transportation

The Arizona DOT (ADOT) developed a comprehensive environmental stewardship program (Kober 2004). The program involved an overarching environmental performance evaluation and development of a plan for implementing it within ADOT. It includes leadership and stewardship; planning, management, and compliance; environmental elements of core business policies and procedures; recycling and waste reduction; water management; and various other areas. Table 8 briefly summarizes how the ADOT program relates to the seven environmental sustainability impact factor areas. Specific elements

Table 7 Case study program summary

Case Study	Agency/Location	Reason for Inclusion
Environmental Stewardship Program	Arizona DOT, Phoenix, Arizona, U.S.	Comprehensive system-wide framework for a DOT
Transportation Sustainability Plan	Oregon DOT, Salem, Oregon, U.S.	Evaluation of air quality and water quality at a system level
Sustainable Highway Materials	Washington State DOT, Olympia, Washington, U.S.	Evaluation using a practical and straight-forward approach to assessing sustainability impact factor areas
GreenPave	Ministry of Transportation Ontario Toronto, Ontario, Canada	Evaluation using a practical and straight-forward approach to assessing sustainability impact factor areas
Dirt and Gravel Maintenance Program	Pennsylvania State Conservation Commission, Pennsylvania, U.S.	Comprehensive assessment of dirt and gravel road maintenance
Greenworks Program	City of Philadelphia, Pennsylvania, U.S.	Comprehensive city overview of sustainability impact factor areas
GreenLITES Program	New York State DOT Albany, New York, U.S.	Utilizes a spreadsheet-based self-assessment of design that could be adapted to the design/selection of pavement preservation and maintenance treatments
Sustainable Land Transport	New Zealand Transport Agency Wellington, New Zealand	Provides specific guidance for low-volume roads.

Table 8 ADOT environmental stewardship business

Sustainability Impact Factor Area	Description/Relevance to Pavement Preservation and Maintenance
Virgin Material Usage/Alternative Material Usage	• Throughout the document concerted emphasis on limiting virgin material usage and alternative material usage • No direct quantification on pavement preservation and maintenance
Program for Pavement In-Service Monitoring and Management	• Usage of updated manuals and management practices encourage environmental stewardship • No direct quantification on pavement preservation and maintenance
Noise	• Direction to mitigate traffic noise
Air Quality/Emissions	• Emphasis is placed on reducing impacts to the air through proper maintenance of equipment and appropriate operations • No direct quantification on pavement preservation and maintenance
Water Quality	• Development of protocols to reduce sediment into streams and ensure proper storm water management • No direct quantification on pavement preservation and maintenance
Energy Usage	• Addresses a holistic approach to saving energy including indirect savings by simplifying maintenance paperwork, minimizing travel through web conferencing, etc. • Advocates using energy audits to quantify pavement preservation and maintenance energy consumption

of the ADOT program involved highway maintenance manual updates; usage of a maintenance management system; environmental evaluation on routine maintenance areas; and development of best management practices for paved and unpaved surfaces including paving equipment cleaning, paving staging areas, and material stockpiling, erosion, and sediment pollution control and disposal of equipment.

The ADOT program reinforces the commitment to environmental stewardship throughout the organization and provides a system-level analysis for the agency to gauge its success. In this case study, six of the identified seven environmental sustainability impact factor areas apply. The quantification of sustainable preservation and maintenance techniques within the environmental sustainability impact factor areas context could be accomplished if the program is modified to permit the collection and assembly of environmental sustainability performance evaluation (Kober 2004). This ADOT documentation could serve as a strong basis for development for practical guidelines.

Case Study 2: Oregon Department of Transportation

The state of Oregon recently started a transportation environmental sustainability plan to develop Oregon's polices with economic, social, and environmental stewardship. This philosophy is being reflected in both their short-term and long-term goals. As part of this, the Oregon DOT (ODOT) has developed a Maintenance Environmental Management System, which is directed at "minimizing the environmental impacts of maintenance of the transportation system throughout Oregon while providing an effective transportation system that supports economic activities" (ODOT 2004). One of the specific outcomes is to "reduce adverse impacts of transportation on air quality and water quality."

Overall, the system provides a holistic evaluation on how ODOT performs its road and bridge maintenance practices. As noted here, it has relevance to preservation and maintenance treatments although it does not specifically quantify anything beyond recycling of pavements. Table 9 provides a summary of some of the key features and how they relate to the environmental sustainability impact factor areas identified in this synthesis.

The ODOT environmental sustainability plan initially focuses on practices at the maintenance yards to ensure that operations do not adversely impact air quality and water quality. Additionally, it furnishes specific recycling targets for 193 bridges that are programmed to be replaced as part of a multi-billion

Table 9 ODOT emergency management system case study facts

Sustainability Impact Factor Area	Description/Relevance to Pavement Preservation and Maintenance
Virgin Material/Alternative Material Usage	• Sets forth an "Environmental Management System" for bridge demolition that focuses on maximizing recycling • Recycling target set to quantify the amount of recycling in 193 bridge projects. Pavements associated with these bridges are included in the goal
Air Quality/Emissions	• Focus on reducing pollutants in the air • Pollutants identified as ozone, particulate matter, nitrogen oxides, carbon monoxide, sulfur dioxide, toxins, and carbon dioxide • Lower particulate matter related to gravel roads by paving them • Encourage multimodal transportation, thus having impacts on pavement preservation and maintenance treatments • No direct quantification of pavement treatments and associated air quality
Water Quality	• ODOT implementing best management practices to transportation infrastructure to improve water quality with special attention to avoid contamination of water • Development of integrated vegetation management program to protect environment • No direct quantification to pavement treatments and associated water quality
Energy Usage	• Directs consideration of fuel consumption in decision making

Source: ODOT (2004).

dollar infrastructure renewal program. Within the plan there is an opportunity to evaluate preservation and maintenance techniques, although details of exactly how that can be accomplished are not available. Given the available information provided, ODOT is reaching its targets as outlined. Another important aspect of this case study is that this initiative is successful given it is strongly supported both financially and morally by the governor and the director of ODOT. This is a critical component to follow through and support.

Case Study 3: Washington State Department of Transportation

The Washington State DOT (WSDOT) promotes sustainable highway materials through the reuse and recycling of materials; use of warm-mix asphalt; reducing the need to replace infrastructure by proper design, construction, and maintenance; use of pavement management (the Washington State Pavement Management System) to incur the lowest life-cycle cost proactive usage of recycled asphalt pavement and recycled concrete aggregate pavements, hot in-place recycling, cold in-place recycling, asphalt shingles, alternative hydraulic cements, and restoration of construction sites with plants and shrubs. Table 10 summarizes the initiatives and relevance to the environmental sustainability impact factor areas.

WSDOT is very proactive in the promotion of sustainable pavement design, construction, and rehabilitation. As noted in the table summary, three of the identified seven environmental sustainability impact factor areas are taken into consideration in the WSDOT plan. It is already producing good stewardship in several of the environmental sustainability impact factor areas and identifies pavement preservation and maintenance as important to achieving long-life pavements. Through the further development of specific guidelines related to the environmental sustainability impact factor areas for pavement preservation and maintenance, this agency would be well positioned to implement them. They have a good basis to expand this practice area further.

Case Study 4: GreenPave: Ministry of Transportation of Ontario

The new GreenPave tool builds on more than 20 years of research, development, and implementation of green initiative at the Ministry of Transportation of Ontario (MTO). MTO has recently developed a green rating system for pavements. The program focuses on assessing the greenness of flexible and rigid pavement designs and their construction (MTO 2010). Subsequent maintenance is not considered in the analysis. GreenPave is loosely based on LEED™ certification, but it was also influenced by Greenroads, GreenLITES, and the Transportation Association of Canada (TAC) Guide for Green Roads (TAC 2010). Table 11 summarizes the key features and how they relate to the environmental sustainability impact factor areas.

The GreenPave tool is a direct effort to quantify overall environmental sustainability within MTO's

Table 10 WSDOT sustainable pavements

Sustainability Impact Factor Areas	Description/Relevance to Pavement Preservation and Maintenance Treatments
Virgin Material Usage/Alternative Material Usage	• Encourages recycling of RAP and RCA, usage of HIR, CIR, usage of hydraulic cements that are recycled, and use of asphalt shingles • Most of these would relate to design and construction of new or rehabilitated pavements. However, similar applications to maintenance could be incorporated
Program for Pavement in Service Monitoring and Management	• Attempts to optimize sustainable designs through active PMS and monitoring • Already examines proper preservation and maintenance so development of guidelines to promote sustainable maintenance would be possible
Air Quality/Emissions	• Using warm asphalt on a trial basis that recognizes lower emissions • Directed at design, construction, and rehabilitation, but could be modified for use in preservation and maintenance

RAP = recycled asphalt pavement; RCA = recycled concrete aggregate; HIR = hot in-place recycling; CIR = cold in-place recycling; PMS = pavement management system.

Table 11 MTO Greenpave case study factors

Sustainability Impact Factor Areas	Description/Relevance to Pavement Preservation and Maintenance Treatments
Virgin Material Usage and Alternative Material Usage	• This is directed at optimizing usage/reusage of recycled materials and to minimize material transportation distances • A total of 14 points is assigned to this category • Directed at design, construction, and rehabilitation, but possibly could be modified for use with pavement preservation and maintenance treatments
Program for Pavement In-Service Monitoring and Management	• Attempts to optimize sustainable designs to include long-life pavements, permeable pavement, noise mitigating pavements, and pavements that minimize the heat island effect • Total of nine points is assigned to this category • Directed at design, construction, and rehabilitation, but possibly could be modified for use with pavement preservation and maintenance treatments
Noise	• Directs the use of means to minimize road noise
Air Quality/Emissions	• Minimizes energy consumption and GHG emissions • Total of nine points is assigned to this category • Directed at design, construction, and rehabilitation, but possibly could be modified for use with pavement preservation and maintenance treatments
Energy Usage	• Directs consideration of fuel consumption in decision making
Other: Innovation and Design Process	• Recognizes innovation and exemplary efforts to foster sustainable pavement designs • Total of four points is assigned to this category • Directed at design, construction, and rehabilitation, but possibly could be modified for use with pavement preservation and maintenance treatments

Source: MTO (2010).
GHG = greenhouse gas.

long-standing Green Pavement Initiatives (GPI) program (Lane 2010). GPI has been in place since 1988 and credits itself for recycling more than 1.2 million tonnes of aggregate as well as the following reductions in greenhouse gases:

- 88,400 tonnes of carbon dioxide,
- 720 tonnes of nitrous oxide, and
- 15,400 tonnes of sulphur dioxide (Lane 2010).

This case study applies to five of the seven environmental sustainability factors, along with an additional evaluation category of innovation and design process. The MTO GreenPave program would result in the rating of projects whereby bronze (7–10 points), silver (11–14 points), gold (15–19 points), and trillium (20+ points) levels would be recognized in a similar manner as LEED™. There is also a proposal to calculate a green discounted life-cycle cost and set targets province wide to obtain a specified number of green pavement designs per year. Finally, a Green Paver of the year award may also be considered. This program does provide a good framework that could be extended for development of sustainable pavement preservation and maintenance points and ratings. Overall, this initiative is gaining momentum as it is strongly supported by senior MTO management and is being developed in partnership with industry through consultation with the Ontario Hot Mix Producers Association and the Ready Mixed Concrete Association of Ontario.

Case Study 5: Pennsylvania's Conservation Commission

The Pennsylvania State Conservation Commission (PSCC) has a Dirt and Gravel Maintenance Program. It provides training and funding to local road-owning entities, usually townships, to mitigate sediment pollution to streams originating from dirt and gravel roads (PSCC 2010). The sediment from roads, farms, construction sites, logging, and various other sources is the largest contributor of pollutants to the state's waters. Pennsylvania has the largest network of rivers and streams in the United States, with the exception of Alaska, so their protection is of critical

Table 12 Pennsylvania State Conservation Commission

Sustainability Impact Factor Area	Description/Relevance to Pavement Preservation and Maintenance
Water Quality	• Focus on reducing roadway sediment runoff into rivers and streams • Primary source of sediment from dirt and gravel roads • Program provides funding to conservation districts and focuses on sensitive maintenance of unpaved roads • Provides funding to control the amount of sediment from dirt and gravel roads and focuses on good pavement preservation and maintenance practices

Source: PSCC (2010).

importance. Although gravel road maintenance often involves getting water quickly off the road, this results in tons of sediment that enters into the state streams. The presence of the sediment can cause great harm to the ecosystem, including disruption of natural stream order and flow, damage to fish species through direct abrasion to body and gills, loss of fish spawning areas, sediment killing small organisms in the streambed, and a filling of dams and reservoirs (PSCC 2010). Table 12 summarizes the Pennsylvania's State Dirt and Gravel Maintenance Program and its relevance to the environmental sustainability impact factor areas.

The program works with public and private entities through a task force to assist with local projects and decision making, education and training, simplified grant applications and publicprivate partnerships. It creates standards and requirements for the construction and environmental protection of dirt and gravel roads (PSCC 2010). This program received the 2000 Governor's Award for Environmental Excellence.

Case Study 6: City of Philadelphia—Greenworks Philadelphia

The Greenworks program is a local action plan for climate change and emphasizes clean air, better management of stormwater, and increasing in-service condition of city streets and roads (Nutter 2009). The plan's "Target 13—Increase the State of Good Repair in Resilient Infrastructure" creates a direct relationship to sustainable pavement preservation and maintenance treatments. The Greenworks plan requires the city of Philadelphia to establish a pavement in-service monitoring and management system to permit its Department of Streets to better identify and address pavement maintenance issues. It also sets forth targets to encourage recycling of pavement materials. The plan is quite ambitious and will require substantial city resources ($35 million per year) to execute (Nutter 2009). Table 13 summarizes the key features and how they relate to the environmental sustainability impact factor areas.

Table 13 City of Philadelphia

Sustainability Impact Factor Area	Description/Relevance to Pavement Preservation and Maintenance Treatments
Virgin Material Usage and Alternative Material Usage	• Encourages recycling in road work; mentions hot-in place recycling and recycled asphalt pavement • Framework could provide incentive for application to pavement preservation and maintenance treatments
Program for Pavement In-Service Monitoring and Management	• Requires establishment of pavement monitoring system
Air Quality/Emissions	• Attempts to reduce carbon dioxide, methane, and nitrous oxide • Focuses primarily on types of vehicles; there could be an opportunity to use the framework to achieve goals
Water Quality	• Increased rainfall and associated runoff will affect the ability to process storm water and subsequently impact water quality • Could be applied to pavement area

Source: Nutter (2009).

Greenworks is a multidimensional program that has several key target areas, including four of the environmental sustainability impact factor areas. Although there is a direct mention of sustainable pavement preservation and maintenance, the development of guidelines related to the environmental sustainability impact factor areas would fit well within the Greenworks program.

Case Study 7: New York State Department of Transportation GreenLITES

GreenLITES is a "project design certification program" for projects that will be delivered as typical New York State DOT (NYSDOT) construction projects (NYSDOT 2009). It is very comprehensive and may be the most pointed of the DOT programs because it references pavement preservation and maintenance treatments, such as diamond grinding, crack sealing, and liquid asphalt treatments. Additionally, there is a provision in category 27F, Innovative and/or Unlisted Activities, to accord credit "to pavement related practices that significantly build upon *GreenLITES* categories and objectives or that incorporate significant innovations in transportation environmental sustainability that have not been previously used in NYSDOT operations" (NYSDOT 2009). This provision, although generic, could be used to gain credit for pavement preservation and maintenance practices that are not specifically included in the approved list of green activities. For example, the use of shotblasting to restore microtexture and macrotexture on concrete pavement and asphalt pavement is very sustainable, as it does not consume any virgin material and recycles both the shot and potentially the collected residue (Gransberg 2009). Adding shotblasting to the pavement preservation and maintenance programs could result in additional GreenLITES credit under 27F. In short, the pavements portion of this program could be used as an initial template for creating an agency program to encourage and measure environmental sustainability inside its current pavement preservation and maintenance program. Table 14 summarizes the environmental sustainability impact factor areas and their relevance to the NYSDOT GreenLITES program.

GreenLITES provides a rational methodology that is based on previous work in the area of measuring environmental sustainability of infrastructure design and construction, such as LEED™ and

Table 14 NYSDOT Greenlites

Sustainability Impact Factor Area	Description/Relevance to Pavement Preservation and Maintenance
Virgin Material Usage and Alternative Material Usage	• Emphasis on limiting virgin material usage and alternative material usage is stressed in the program • Quantification on pavement preservation and maintenance done through credits earned, use of recycled tire rubber, and recycled asphalt pavement
Noise	• Specific reference to inclusion of measures for reducing pavement noise • Quantification on pavement preservation and maintenance done through credits earned for diamond grinding
Air Quality/Emissions	• Emphasis is placed on reducing impacts to the air through proper maintenance of equipment and appropriate operations • Quantification on pavement preservation and maintenance done through credits earned
Water Quality	• Development of protocols to reduce sediment into streams and ensure proper storm water management • Quantification on pavement preservation and maintenance done through credits earned
Energy Usage	• Credit for reducing electricity and petroleum consumption • Quantification on pavement preservation and maintenance done through credits earned for documented analysis of design that reduces carbon footprint
Other: Innovation	• System encourages engineers to extend the scope of the program to previously unlisted techniques that comply with the spirit of the program • Quantification on pavement preservation and maintenance done through credits earned in Innovative and/or Unlisted Category

GreenRoads™ using a credit system to quantify the degree of environmental sustainability. It includes five of the seven environmental sustainability impact factor areas. The 2009 operations program can easily be expanded to include pavement preservation and maintenance operations. To do so will entail additional work to develop the comparative environmental foot-printing data necessary to differentiate between the suite of pavement preservation and maintenance treatments. Consequently, the spreadsheet-based rating system could be leveraged into a very powerful tool to enhance environmental sustainability in North America.

Case Study 8: New Zealand Transport Agency—Sustainable Land Transport

New Zealand has a record of aggressive pavement preservation and a maintenance program based on its performance-specified maintenance contracting (PSMC) system (Manion and Tighe 2008). The nation's highway system typically consists of "a sprayed chip seal over unbound granular base and sub-base layers" (Pidwerbesky and Waters 1997). The New Zealand Transport Agency (NZTA) provides for district-level pavement maintenance planning in six of the seven environmental sustainability factors. The program is outsourced and the PSMCs are controlled through a sophisticated set of more than 200 key performance indicators (KPIs). Most KPIs are established using direct measurements of physical properties such as macrotexture and skid resistance. As a result of this feature, this system is slightly different from traditional pavement management systems in North America.

The change in pavement maintenance culture has supported the development of green pavement maintenance technologies such as the Ultra-High Pressure Water Cutter that restores pavement macrotexture without consuming any virgin materials. Another innovation is a form of microsurfacing that is used in areas with low volumes of traffic, but with high shear stresses such as mountain curves on grades where chip seals fail and hot mix is not justified. The treatment was deliberately designed to minimize the total amount of virgin material consumed in its production (Pidwerbesky and Waters 1997). NZTA must maintain 40,000 km of gravel-surfaced roads. A sustainable maintenance technique is the use of the New Zealand Otta seals (note these are different from those used in the United States) to improve air quality during dry periods and reduce erosion and enhance water quality during wet periods (Waters 2009). The New Zealand Otta seal provides a use for recycled motor oil and asphalt plant reject aggregate and, if properly applied, has a service life of 2 to 3 years in New Zealand.

The combination of the maintenance culture shift, the incentive/disincentive scheme that is part of the PSMC, and the national commitment to environmental responsibility has led to a very robust pavement preservation and maintenance program that emphasizes preservation over repair (Waters 2004). Additionally, the prescribed pavement design method is based on life-cycle cost analysis. This results in an effective standard where average annual daily traffic must exceed approximately 25,000 vehicles per day to meet a warrant for hot-mix asphalt or portland cement concrete pavement (TNZ 2005). Table 15 lists the NZTA program details.

As noted in the summary table, NZTA has the most robust pavement preservation and maintenance environmental sustainability program reviewed in this synthesis. Not only does it cover the full range of environmental sustainability impact factor areas categories, but it is coupled with a life-cycle cost-based pavement design method and a performance-based maintenance contracting system that create an unbending predisposition to environmental sustainability in pavement maintenance.

Results from Case Studies

Overall, the information gathered through the three study instruments indicates that there are some good environmental sustainability plans and protocols in place. Although most are focused on design and construction, in a majority of cases the principles on which they are based can directly be applied to pavement preservation and maintenance programs. The identified environmental sustainability impact factor areas are relevant to the current preservation and maintenance practices and, although there were no case studies or tools found in the literature that cover all seven factors, they are mentioned at varying levels. In addition, many of the available tools are not necessarily specific to pavement infrastructure. However, the frameworks and protocols serve as a foundation upon which they can be adapted to pavements.

Table 16 is a synopsis of the eight case studies and how their programs cover the seven environmental sustainability impact factor areas categories.

Table 15 NZTA sustainable land transport

Sustainability Impact Factor Area	Description/Relevance to Pavement Preservation and Maintenance
Virgin Material Usage/Alternative Material Usage	• Emphasis on limiting virgin material usage and alternative material usage is stressed in the program • No direct quantification of pavement treatments and associated material usage
Program for Pavement In-Service Monitoring and Management	• Contracting structure creates a continuous monitoring of pavement condition • Quantification is part and parcel of the contract monthly payment mechanism
Noise	• Cites standards for measures for reducing pavement noise • No direct quantification of pavement treatments and associated noise reduction
Air Quality/Emissions	• Emphasis is on minimizing congestion in work zones and thus it reduces emissions • Strict standards for air quality during all phases of pavement construction and maintenance • No direct quantification of pavement treatments and associated air quality
Water Quality	• Includes volume and area limits on soil disturbance to reduce sediment into streams and ensure proper storm water management • Quantification of pavement treatments impact associated water quality via testing protocols
Energy Usage	• Whole life approach to minimizing petroleum consumption • No direct quantification of pavement treatments and associated energy usage reductions
Other: Life-Cycle Cost Based Pavement Design	• Mandated design method is based on life-cycle cost calculations and AADT. Hot mix is only warranted for roads with AADT > 25,000. PCCP warrants are only for high-volume urban motorways • Method inherently reduces the amount of energy and virgin material required for the national highway system

AADT = average annual daily traffic; PCCP = portland cement concrete pavement.

Table 16 Summary of case study agency sustainability programs

Case Study Agency	Virgin Material Usage	Alternative Material Usage	Pavement In-Service Monitoring and Management	Noise	Air Quality/ Emissions	Water Quality	Energy Usage
ADOT	√	√	√	√	√	√	√
NYSDOT	√	√		√	√	√	√
ODOT	√	√			√	√	√
WSDOT	√	√	√		√		
MTO	√	√	√	√	√		√
NZTA	√	√	√	√	√	√	√
PSCC						√	
Phila.	√	√	√		√	√	
Totals	7	7	5	4	7	6	5

In most cases, the fundamental elements of a comprehensive environmental sustainability program are part of design and construction activities and could potentially be adjusted for application in pavement preservation and maintenance operations. Table 16 suggests that the relationship between pavement monitoring of maintenance and preservation treatments and their direct relationship to environmental sustainability is not currently fully developed. The mantra of the pavement preservation movement is "put the right treatment, on the right road, at the right time" (Galehouse et al. 2003). Overall, a robust pavement in-service monitoring and management system is the foundation upon which the decisions that ultimately impact the environment are made. The conclusion argues that integration of environmental sustainability metrics into agency pavement management information systems is necessary to maximize the ultimate environmental sustainability of the pavement preservation and maintenance program.

Summary

This chapter summarized the case study findings and how the lessons learned could be leveraged into future research. Overall, the current state of the practice is characterized by a systems approach in that most of the information found was developed for design and construction. This is no criticism of the case study agencies. It is however validation of the conclusions reached from the survey and literature review that most agencies are not connecting environmental sustainability and pavement preservation and maintenance. Consequently, if the environmental sustainability impact factor areas were to be applied to pavement preservation and maintenance treatments, additional detailed guidelines and protocols would need to be developed.

Conclusions

The synthesis of the eight case studies led to the following conclusions:

- *The case studies showed that environmental sustainability can be incorporated into pavement preservation and maintenance practices.*
- *Environmental sustainability metrics could be developed and integrated into pavement preservation and maintenance treatment programming.*

CONCLUSIONS AND FUTURE RESEARCH NEEDS

This synthesis has identified and quantified seven environmental sustainability impact factor areas: virgin material usage, alternative material usage, a program for pavement in-service monitoring and management, noise, air quality/emissions, water quality, and energy usage, which are of strategic importance to pavement preservation and maintenance. A survey was conducted to evaluate how environmental sustainability was being incorporated into pavement preservation and maintenance. The results of the survey were coupled with information found in the literature and eight case studies to identify trends, form conclusions, and locate gaps in the body of knowledge that require future research.

Conclusions

The following conclusions were reached in this study:

1. Environmental sustainability research that is related specifically to post-construction operations is an emerging field.
2. Thin asphalt overlays are the most prevalent treatment for asphalt and composite pavements.
3. Diamond grinding and joint sealing are the most commonly used treatments for concrete pavements.
4. Regrading and regraveling are the most prevalent treatments for graveled roads, whereas chip seals are the preferred treatment for surface-treated roads.
5. Quantification of environmental sustainability with pavement preservation and maintenance programs is not commonly practiced in the United States and Canada.
6. Various construction and design environmental sustainability initiatives are available in the literature. However, an assessment tool to properly quantify environmental sustainability in the pavement preservation and maintenance context is required.
7. The case studies showed that environmental sustainability can be incorporated into pavement preservation and maintenance practices.

Future Research Needs

The following future research needs have been identified in this synthesis to assist practitioners in the quantification of environmental sustainability for incorporation into pavement preservation and maintenance in the United States and Canada:

1. There is a need for pavement preservation and maintenance-specific research to furnish agency pavement maintenance engineers with the fundamental quantitative data on the relative environmental sustainability of common treatments.
2. There is a need to develop a pavement preservation and maintenance-specific life-cycle assessment and cost analysis method that includes values for factors such as carbon sequestration, resource renewability, and other salient elements of environmental sustainability to furnish a rational approach to treatment selection.
3. Research is needed to develop the fundamental information needed to prepare training to be disseminated throughout the two countries that quantifies the importance of preservation and maintenance treatments in the environmental sustainability impact factor areas.
4. There is a need to complete research in adapting recycled and alternate materials for use in pavement preservation and maintenance treatments.
5. There is a need for future research to identify and develop appropriate noise standards for pavement preservation and maintenance operations and life-cycle assessment.
6. There is a specific need for research to quantify the contribution that crack sealing makes to environmental sustainability of all types of pavement surfaces.
7. There is a need to research policies, technology, materials, specifications, standards, equipment, capacity building, recycling/waste reduction, emissions reduction (air pollution), and life-cycle cost analysis. In this regard, it is necessary to incorporate sustainable pavement maintenance elements into on-going and future pavement maintenance research.

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GLOSSARY OF ACRONYMS AND TERMS

Asphalt level-up—A surface course composed of a compacted mixture of mineral aggregate and asphaltic material constructed on the previously completed existing wearing surface, or in the case of a bridge, on the prepared slab. Its purpose is to raise the final elevation of an existing pavement to match an adjacent pavement.

Chip seal—A pavement surface treatment that combines a layer of asphalt with a layer of fine aggregate.

Cold patches—Pothole and other pavement defect repair made with cold-mix asphalt.

Corrective maintenance—Maintenance performed once a deficiency occurs in the pavement; that is, loss of friction, moderate to severe rutting, extensive cracking or raveling.

Crack seal—Product used to fill individual pavement cracks to prevent entry of water or other noncompressible substances such as sand, dirt, rocks, and weeds.

Diamond grinding—The process of removing a thin layer of existing concrete pavement surface by grinding it with a machine that has a series of closely spaced rotating diamond saw blades.

Dowel bar retrofit—A method of reinforcing cracks in highway pavement by inserting steel dowel bars in slots cut across the cracks.

Dust palliative—A highly diluted petroleum emulsion sprayed on an unpaved surface to control direct particulate matter emissions (commonly called "road dust") from unpaved roads and other surfaces with vehicle and machinery traffic.

Fog seal—A light application of a diluted, slow-setting asphalt emulsion to the surface of an aged pavement surface.

Gravel blading—The process of spreading small amounts of gravel on localized areas of unpaved roads to fill holes, restore ride quality, and reestablish the transverse geometry (commonly called the "crown") to facilitate drainage.

Hot patches—Pothole and other pavement defect repair made with hot-mix asphalt

Joint seal—Joint seals, seal expansion, and contraction joints in concrete.

Microsurfacing—A polymer-modified cold-mix paving system that can remedy a broad range of problems on today's streets, highways, and air fields. This is a mixture of dense-graded aggregate, asphalt emulsion, water, and mineral filler.

Mud jacking—Process of pumping a water, dirt, and cement mixture under concrete slabs in order to lift it.

Otta seal—A low-cost type of road surface, usually a 16–30-mm-thick mixture of bitumen emulsion and well-graded crushed rock.

Otta seal (New Zealand)—Low-cost type of road surface, usually a 16–30-mm-thick mixture of recycled motor oil (commonly called "Norwegian road oil") and well-graded crushed rock.

Pavement preservation—The sum of all activities undertaken to provide and maintain serviceable roadways. This includes corrective maintenance and preventive maintenance, as well as minor rehabilitation projects.

Pavement preventive maintenance—Planned strategy of cost-effective treatments to an existing roadway system and its appurtenances that preserves the system, retards future deterioration, and maintains or improves the functional condition of the system (without increasing the structural capacity).

Pavement rehabilitation—Work undertaken to extend the service life of an existing pavement. This includes the restoration, placing an overlay, and/or other work required to return an existing roadway to a condition of structural and functional adequacy.

Regrade/regravel—A process similar to "gravel grading" defined earlier, but including the entire length of a given road project.

Shot blasting—A process that restores the microtexture and macrotexture of both asphalt and concrete pavement surfaces by abrading it with steel shot. The process includes a magnetic system that collects and recycles the expended shot and a vacuum system that collects the residue for disposal.

Slurry seal—Mixture of emulsified asphalt, water, well-graded fine aggregate, and mineral filler that has a creamy, fluid-like appearance when applied.

Spread millings—The use of recycled asphalt pavement millings to maintain gravel roads. The millings are used in place of virgin aggregate.

Thin overlay—A layer of new pavement that is laid on the existing surface for purposes of restoring surface characteristics with no intention of enhancing the structural capacity of the underlying pavement. These are usually less than 1.5 in. (3.75 cm) thick.

Thin portland cement concrete overlay—A thin overlay consisting of portland cement concrete (commonly called "white-topping").

Thin hot mix asphalt overlay—A thin overlay consisting of hot mix asphaltic concrete (commonly called "black-topping").

APPENDICES A AND B

Appendices A and B as submitted by the consultant are not published herein. These appendices are available as part of the web version of this document at: http://www.trb.org/Publications/Pubs NCHRPResearchResultsDigests.aspx, see Research Results Digest 365.

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