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A Framework for Life-Cycle Cost Analyses and Environmental Life-Cycle Assessments for Fully Permeable Pavements

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Ting Wang
John T. Harvey
David Jones

Institute of Transportation Studies ◦ University of California, Davis
1605 Tilia Street ◦ Davis, California 95616
PHONE (530) 752-6548 ◦ FAX (530) 752-6572
www.its.ucdavis.edu

A FRAMEWORK FOR LIFE-CYCLE COST ANALYSES AND ENVIRONMENTAL LIFE-CYCLE ASSESSMENTS FOR FULLY PERMEABLE PAVEMENTS

TECHNICAL MEMORANDUM

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6. Author(s) T. Wang, J. Harvey, and D. Jones	**7. Caltrans Project Coordinator** Baskhar Joshi
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15. Abstract

This technical memorandum presents a summary of the methods and results from a life-cycle cost analysis, undertaken to understand the cost implications of constructing and maintaining fully permeable pavements. Input data for the models were obtained from the comprehensive laboratory investigation and computer performance modeling undertaken as part of the study, from California Department of Transportation databases, and from interviews with contractors. A framework for environmental life-cycle assessment for fully permeable pavements is also presented. A detailed life-cycle assessment could not be performed because of insufficient available data on the construction, long-term performance, maintenance, and salvage value of fully permeable pavements and currently used alternative best management practices (BMPs) for stormwater management. The results indicate that fully permeable pavements are potentially more cost-effective than currently available BMP technologies. These results will be used to prepare preliminary pavement designs for fully permeable pavement pilot studies in California and to identify under what conditions they are appropriate to use. The pavement designs will be presented in a separate report. A more comprehensive life-cycle assessment should be undertaken on completion of pilot studies.

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Stormwater Liaison,
Caltrans Division of Environmental Analysis, MS 27,
P.O. Box 942874,
Sacramento, CA 94274-0001,

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This document is not intended to be used as a guideline for the design, construction and maintenance of fully permeable pavements.

PROJECT OBJECTIVES

The objective of this project, titled "Laboratory Testing and Modeling for Structural Performance of Permeable Pavements under Heavy Traffic," is to develop preliminary designs for fully permeable pavements in California.

This objective will be met after completion of five tasks:

1. Evaluate the structural performance characteristics of all the materials potentially used in permeable pavement designs, namely porous asphalt, concrete, base, and subgrade materials.
2. Perform detailed performance modeling of these various designs based upon (1).
3. Develop recommended designs for subsequent accelerated pavement testing and field test sections on the UC Davis campus which are reasonably likely to perform satisfactorily, are constructible, and within reason, economical.
4. Based upon these designs, perform a preliminary life-cycle cost analysis (LCCA) and life-cycle analysis (LCA) of the various options.
5. Compile all the information gathered in this study into a comprehensive final report.

This technical memorandum summarizes Task 4.

The objectives did not include the preparation of guidelines for the design, construction and maintenance of fully permeable pavements, or any research into the influence of the design of fully permeable pavements on water quality.

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Chapter 1. Focus of the Tech Memo

The California Department of Transportation (Caltrans) initiated a laboratory and modeling investigation under Master Agreement 65A0108 to evaluate the structural performance of fully permeable pavements under heavy traffic. The main purpose of this technical memorandum is to present the experimental design and main findings for the life-cycle cost analysis (LCCA) and environmental life-cycle assessment (LCA) task of the study. The results of the LCCA and LCA will be used to help identify conditions under which fully permeable pavements are appropriate for use on Caltrans highways.

This technical memorandum is organized as follows:

1. Introduction to the study
2. Life-cycle cost analysis
3. Life-cycle assessment
4. Summary and future work

Chapter 2. Introduction

2.1 Background

Fully permeable pavements are defined for the purposes of this study as those in which all layers are intended to be permeable and the pavement structure serves as a reservoir to store water during storm periods in order to minimize the adverse effects of stormwater runoff. The California Department of Transportation (Caltrans) is interested in the development of fully permeable pavement designs for use in areas that carry heavy truck traffic as a potential stormwater management best management practice (BMP).

Since the late 1970s, a variety of fully permeable pavement projects have been constructed in a number of U.S. states for low traffic areas and light vehicles. Most of the information available in the literature is about successes, while few failures have been reported for these applications. Observations of several projects by the authors indicate that failures have occurred in localized areas due to clogging of the permeable surface, and to construction processes that have resulted in severe raveling (loss of particles from the surface) or cracking.

As noted, most applications of fully permeable pavements in North America have been for pavements that are not subjected to high-speed traffic or truck traffic, such as parking lots, which reflects road owner concerns about durability. Structural design methods have been empirical in nature, with little or no long-term monitoring data to support the empiricism. Purely empirical design methods require good comprehensive empirical data for all of the expected design conditions, which has limited the speed of technology development for fully permeable pavements because of the high cost of learning from inevitable failures. For this reason it is difficult for purely empirical design methods to consider different materials, climates, subgrades, and structural cross sections because of the need for a large factorial set of performance data that considers all of these design variable permutations. A review of design practice across the United States *(1)* shows the very limited scope of current applications for fully permeable pavements, even by the leading design firms specializing in this type of design. The limited scope of current applications is also reflected in the recently produced National Asphalt Pavement Association (NAPA) *(2)*, American Concrete Pavement Association *(3)*, and Interlocking Concrete Pavement Institute *(4)* manuals for design of porous asphalt, pervious concrete pavements, and permeable interlocking concrete pavements, respectively.

The mechanistic-empirical approach used in this project for the development of new fully permeable pavement designs will increase the speed of technology development. The mechanistic-empirical design development process consists of determining relevant material properties in the laboratory, and then using them in inexpensive and risk-free computer models to evaluate pavement performance, followed by empirical validation and calibration of failure mechanisms and performance of the most promising designs through accelerated pavement testing and field test sections.

There is limited published data on life-cycle cost analysis (LCCA) of fully permeable pavements that include actual costs and performance, and also little information regarding environmental life-cycle assessments (LCA) of fully permeable pavements. There have been several analyses of comparative initial costs for fully permeable pavements compared with conventional pavements, which indicate that the cost of constructing fully permeable pavements is greater than the cost of conventional pavements for residential streets; however some studies indicate that the total initial costs are similar or less because the fully permeable pavements do not require stormwater drainage systems. All of the studies in the literature are for slow-speed facilities with few trucks, and compare different fully permeable pavement systems with different conventional pavements for different applications (streets, parking lots, and other paved areas). None of the studies considered shoulder retrofit of a highway.

2.2 Objectives

2.2.1 Fully Permeable Pavement Development Program Objectives

The study discussed in this report is part of a larger development program being undertaken by the University of California Pavement Research Center (UCPRC) for Caltrans with the objective of developing guidelines, and inputs for specification language, for the use of fully permeable pavements as a potential BMP for controlling stormwater runoff from highways, maintenance yards, rest stops, and other pavements that Caltrans owns and manages.

This objective will be met after completion of laboratory testing to characterize the mechanical and hydrological properties of fully permeable pavement materials, structural and hydrological performance modeling to develop initial designs, life-cycle cost analyses and environmental life-cycle assessment studies, and full-scale testing in the field and/or using accelerated pavement testing (using the Caltrans Heavy Vehicle Simulator [HVS]) to validate the structural and hydrological designs, or if necessary to calibrate them to match the observed field performance. This step-wise development process of first performing laboratory testing and computer modeling, followed by full-scale validation with the HVS and field test sections is the typical process being used for development of other pavement technologies for Caltrans. Caltrans pavement designers have been involved in the process of reviewing the results of this development process, and the planning for this current project. As with any other new pavement technology, there is no commitment by Caltrans to implement it until the development process has reached a point at which the uncertainties have been sufficiently addressed to reduce the risk of pilot section failure on the state highway network to an acceptable level.

Successful completion of this project will provide Caltrans with structural design procedures, performance estimates, life-cycle cost analyses, and an environmental life-cycle assessment framework to compare fully permeable pavement BMPs with existing approved BMPs.

2.2.2 Objectives of this Project

The goal of the project covered in this current task order (RTA249), entitled *Laboratory Testing and Modeling for Structural Performance of Permeable Pavements under Heavy Traffic* is to develop preliminary fully permeable pavement designs that can be tested in pilot studies under typical California traffic and environmental conditions *(5)*. This goal will be achieved on completion of the following tasks:

1. Review the latest literature.
2. Prepare and test specimens in the laboratory for the structural properties necessary for undertaking a mechanistic-empirical design of fully permeable pavement structures. Develop new testing methods if required to evaluate non-traditional materials. Include the materials testing properties in the Mechanistic-Empirical Pavement Design materials database developed by the University of California Pavement Research Center (UCPRC) for Caltrans.
3. Prepare additional specimens for hydraulic performance testing in the laboratory as part of the companion task order (RTA247, *Laboratory Testing and Modeling for Hydraulic Performance of Permeable Pavements under Heavy Traffic*).
4. Estimate pavement performance for prototype designs using the laboratory test results in pavement performance models.
5. Perform a preliminary life-cycle cost analysis and environmental life-cycle assessment of the various options.
6. Based on the results of the computer model analysis, develop detailed structural designs for HVS and field test sections that include pavement dimensions and material specifications.

This report summarizes the work undertaken in Task 5.

More detailed life-cycle cost analysis (LCCA) and life-cycle assessment (LCA) will need to be performed after construction, evaluation, and performance validation of accelerated pavement test sections and field test sections to provide more realistic initial cost information and improved maintenance and rehabilitation cost estimates.

Chapter 3. Life-Cycle Cost Analysis

3.1 Introduction

In this project, life-cycle analysis is defined to include a cost analysis and an environmental assessment. For the cost analysis, a preliminary Life-Cycle Cost Analysis (LCCA) was undertaken to evaluate the net present value (NPV) economic costs of each project alternative. For the environmental assessment part, a preliminary Life-Cycle Assessment (LCA) was performed to understand the environmental impacts of each alternative (Chapter 4). As decision-assisting tools, LCCA and LCA both provide information for decision making, but not the decision itself. Conclusions from both these analyses need to be coordinated to support a final decision when choosing an appropriate best management practice for stormwater management.

LCCA allows the costs associated with each project alternative to be equitably compared against one another. To perform an LCCA, the future cost is converted to present value through a discount rate, thereby taking the time value of money into account. Since LCCA should be performed on alternatives which carry out the same function, it is assumed that fully permeable pavements and currently available treatment BMPs will have the same performance in accommodating stormwater runoff and in the treatment of pollutants from runoff.

Two fully permeable pavement scenarios are considered in this technical memorandum:

- **Shoulder retrofit for high speed highway scenario**: Comparison of conventional pavement shoulders on a two-lane highway and a six-lane highway (three lanes in each direction) with a conventional treatment BMP versus a fully permeable pavement shoulder. The example project length was one direction for one lane-mile (1,600 m) and the shoulder is 10 ft (3.0 m) wide.
- **Low-speed highway or parking lot/maintenance yard scenario**: Conventional pavement for low-speed traffic with a conventional treatment BMP versus fully permeable pavement. The example project has an area of 107,000 ft^2 (10,000 m^2).

These scenarios were considered for an example project in the Sacramento region to provide an example for LCCA for fully permeable pavement and comparison with LCCA for other BMPs.

3.2 Basic Elements of Life-Cycle Cost Analysis

The basic elements of life-cycle cost analysis include analysis period, discount rate, costs, and salvage value. Each element is briefly discussed in the following sections.

3.2.1 Analysis Period

The analysis period is a fundamental component of the life-cycle cost analysis process and is essentially a policy decision dependent on the agency, circumstances, and infrastructure involved. It should be long enough to include the maintenance, rehabilitation, and necessary reconstruction activities that are a consequence of the initial strategy selected, but the period should not fall outside what can be reliably predicted into the future from historical records. Furthermore, any costs anticipated far into the future that are discounted back to present worth will become negligible in terms of the other costs earlier on in the life-cycle. The analysis period is usually longer than the design life.

A general rule to determine the analysis period is approximately 1.5 times the design life of the strategy selected. The recommended analysis periods for comparing alternatives from the California *Life-Cycle Cost Analysis Procedures Manual* are listed in Table 3.1 *(6)*. These periods vary from 20 to 55 years, depending on the different pavement service life. Since this project needs to compare the fully permeable pavement and conventional treatment BMPs, the analysis period is constrained by the information of treatment BMPs. The design life for BMPs currently used in California is generally fixed at 20 years *(7,8)*. When it has reached this design life, the treatment BMP is demolished and a new treatment BMP is constructed. Therefore, to make an equitable comparison between fully permeable pavement (which would typically have a project life of more than 20 years) and currently used BMPs, an analysis period of 40 years was used in this study. It was assumed that a specific treatment BMP would be constructed twice during this period, and that the surface of the fully permeable pavement would be replaced every 10 to 20 years. The same 40-year analysis period was used for the comparison of all alternatives. For the purposes of this study, the costs of installing and maintaining treatment BMPs were annualized to simplify comparisons.

Table 3.1: Recommended Analysis Periods for Comparing Alternatives

Alternative Design Life	CAPM[1]	10-Year	15-20 Year	20-40 Year
	Analysis Period in Years			
CAPM[1]	20	20	20	-
10-Year	20	20	35	55
15 to 20-Year	20	35	35	55
20 to 40-Year	-	55	55	55

[1] Capital Asset Preventative Maintenance

3.2.2 Discount Rate

The discount rate takes the time value of money into account and is essentially the difference between inflation and the interest rate. The selection of an appropriate discount rate is critical since it essentially determines the portion of future cost (maintenance, rehabilitation, and reconstruction) relative to the cost of initial construction. If the discount rate is set too low, then the future cost will dominate the total cost. Conversely, if the discount rate is set too high, the initial construction cost will dominate the total cost. Caltrans typically uses four percent in its LCCA studies. In this project, zero percent and four percent discount rates were both used for calculation to assess the influence that this parameter has on the calculation outcome.

3.2.3 Salvage Value

Salvage value is used to make equitable comparisons between alternative pavement designs with different service lives. The salvage value of a pavement represents its economic value at the end of the analysis period. The Federal Highway Administration (FHWA) characterizes the salvage value as the cost of the last rehabilitation activity multiplied by the ratio of years until the end of the analysis period to the years until the next activity (e.g., rehabilitation or reconstruction) beyond the analysis period. This is essentially a straight line depreciation of the pavement asset *(9)*. Salvage values are typically small in comparison with the other costs associated with the life-cycle of a pavement. The Caltrans LCCA software used in this study also adopts a straight line depreciation to the end of the project's design life. In this study, the salvage value at the end of the analysis period was assumed to be zero because the analysis period is either four times or two times the design life.

3.2.4 Costs

The cost of a project usually includes agency cost and user cost. Agency costs include initial construction, maintenance and rehabilitation, salvage value at the end of the design period (discussed in the previous section), administration, traffic control, etc. User costs are basically the costs that the road user incurs, including vehicle operating costs, time delay cost, damage to freight when transporting goods on rough roads, etc. However, because of the high uncertainty in calculating user costs and given that user cost is unlikely to change significantly between the choices of BMP, only agency costs were analyzed in this project.

Mr. Bill Clarkson of Teichert Construction in Sacramento, California, volunteered to develop cost estimates for each of the example scenarios. Thickness designs were taken from the structural design calculations for open-graded hot-mix asphalt (HMA-O), open-graded portland cement concrete (PCC-O) and cast PCC pavements. The agency cost estimates from Teichert Construction include the following components:

- Mobilization of equipment

- Temporary K-Rail construction (only for shoulder retrofit)
- Roadway excavation
- Pavement material and construction. (These costs include conventional HMA, rubberized hot-mix asphalt [RHMA-O], PCC-O, granular base, PCC-O subbase, Class-2 aggregate base [only with conventional HMA surface], and relevant construction costs.)
- Other material and placement. (These costs include geofabrics [Mirafi NT100 Fabric, Mirafi 140NC Fabric], drainage systems [Multiflow 1200 Drainage Media, and Multiflow 12003 Outlet], membrane placement, and drainage placement).

The cost of scheduled maintenance and rehabilitation for conventional HMA was determined using the Caltrans *Life-Cycle Cost Analysis Procedures Manual (6)*. The annual maintenance schedule for fully permeable pavement was determined from a study performed by the United States Environmental Protection Agency (U.S. EPA) *(10)*, which suggests vacuum sweeping twice per year. The cost of vacuum sweeping is about \$400 to \$500 per year per half acre in total *(11)*. Therefore, an annual maintenance cost of \$0.02/ft^2 (\$0.22/m^2) was used for fully permeable pavement. Design lives of 10 years and 20 years were both used for calculation to assess the influence of this parameter on the calculation outcome, and to assist with designing cost-effective fully permeable pavement structures.

The construction cost and operation and maintenance (O&M) cost for unit volume of annual runoff treatment capacity for the treatment BMPs in this project were imported from the Caltrans' report *BMP Retrofit Pilot Program – Final Report (7)* and Caltrans' technical memorandum *BMP Operation and Maintenance Cost Analysis (8)*, both of which are based on individual BMP projects (including Wet Basin, Austin Sand Filter, etc) that were evaluated in Caltrans Districts 7 and 11. The total construction, operation, and maintenance cost were acquired by multiplying the unit cost (sourced from the above mentioned reports) by the annual runoff volume from a particular pavement section to obtain the total cost for the BMPs. The cost information from these reports is based on 1999 dollars, which was converted to 2007 dollars using a Consumer Price Index (CPI) conversion factor of 0.804 *(13)*. Table 3.2 shows an example runoff calculation for the Sacramento area, sourced from the results of the companion project *(12)* to this study which investigated hydraulic performance of fully permeable pavements.

It must be emphasized that the example cost comparisons included in this technical memorandum are based on current available relevant information for the Sacramento area, which is limited, and that these example comparisons are also likely to vary widely over time and between regions, and will depend on the specific constraints of a given project. These constraints will include but are not limited to the distance from available materials, traffic control requirements, site conditions, number of contractors interested in building these types of pavements, etc.

Table 3.2: Computation of Annual Runoff Volume for Different Scenarios in Sacramento Area

Input Parameter	Value
Annual rainfall for Sacramento	0.43 m/yr
Shoulder width	3.0 m
Lane width	3.7 m
Project length	1,600 m
Runoff coefficient[1]	1
Drained area: 2 lane road with shoulders (one direction)	10,780 m^2
Drained area: 6 lane road with shoulders (one direction)	20,434 m^2
Drained area: Maintenance yard/parking lot	10,000 m^2
Runoff Volume: 2 lane road with shoulders (one direction)	4,636 m^3/yr
Runoff Volume: 6 lane road with shoulder (one direction)	8,787 m^3/yr
Runoff Volume: Maintenance yard	4,300 m^3/yr

[1] Highway is highly impervious

3.3 LCCA Analysis Software

The Caltrans *RealCost* LCCA software *(6)* was used for calculating the pavement-related costs. Inputs include agency cost of each activity (including initial construction, maintenance, and rehabilitation, and reconstruction), design life, annual maintenance cost, discount rate, and analysis period. Output from the analysis is the Net Present Value (NPV), which is used to compare difference project alternatives.

3.4 LCCA Calculations

In this project, the standard engineering economics method was used to calculate the NPV. Each cash flow is discounted back to its present value, and the sum of these values is the NPV. The function for calculating present value is shown in Equation 3.1. The Caltrans *RealCost* LCCA software *(6)* was used to check the results.

$$NPV = \sum \frac{R_t}{(1+\alpha)^t} \tag{3.1}$$

Where: t is the time of cash flow, α is the discount rate, and R_t is the net cash flow.

3.4.1 Conventional HMA Pavement with BMP

Table 3.3 shows the BMP cost per cubic meter of water processed for a range of currently used BMPs. Pavement construction costs are not included as it is assumed that the BMPs are constructed adjacent to existing pavements. Construction and operation and maintenance cost data are only available for certain treatments and consequently only those treatment BMPs with both these costs were used for the life-cycle cost calculation. Table 3.4 shows the NPV for different BMPs for the first year of construction per cubic meter of water processed. In the 40-year analysis period, a treatment BMP will be constructed twice (i.e., in the first year and in the 21st year), based on a 20-year design life. These two construction events and all follow-up maintenance and operation are assumed the same in both design periods. In each 20-year period, the present value of the total cost was calculated for the first year of this period, and then these values were discounted to the first year of the 40-year analysis period to get final NPVs. These NPVs were then multiplied by the annual volume of runoff from the one-mile pavement section example in the Sacramento area (see Table 3.2) to obtain the total NPVs, also shown in Table 3.4 (last column). It is clear from Table 3.4 that there is a significant difference in the life-cycle costs of the different technologies over the design life of a pavement. Table 3.5 provides a summary of the highest and lowest NPVs for the three design scenarios over a 40-year analysis period. It should be noted that certain treatment BMPs may not be feasible in certain locations (e.g. there may not be sufficient space to construct a specific BMP technology), and local costs may differ from those used in these example comparisons.

3.4.2 Fully-Permeable Pavement

The three pavement design scenarios included in the structural analysis part of this project, namely open-graded asphalt, open-graded concrete, and jointed plain concrete with holes cast into it were each costed separately (

Table 3.6). The costs of removing any existing stormwater drainage infrastructure were not considered. The highest and lowest NPVs for each scenario were then extracted from the cost analysis for comparison with conventional asphalt pavement with a BMP, as shown in Table 3.7. The type of pavement used in the comparison tables in Section 3.4.1 (Table 3.3 through Table 3.5) were not stated because of the lack of historical cost data for the different kinds of pavement structure, and were intended to only provide a reasonable range for comparison with the conventional pavements with a currently available BMP technology. The costs in

Table 3.6 and Table 3.7 indicate that there is not a significant difference in the life-cycle costs of the three different surfacings, and that choice of surfacing may be driven by operational issues rather than cost issues.

3.5 Comparison of Life-Cycle Costs

A comparison of the life-cycle cost estimates of currently available BMPs installed adjacent to existing pavements (Table 3.4) with those of fully permeable pavements (

Table 3.6) indicate that the fully permeable pavement appears to be more cost effective than currently available BMPs in most instances for both the shoulder retrofit and maintenance yard/parking lot scenarios. Fully permeable shoulders draining single lanes were on the order of two-thirds the cost of the lowest cost currently available BMP; fully permeable shoulders draining three lanes were on the order of half the cost; while fully permeable maintenance yards/parking lots were of a similar cost when lowest costs were compared, assuming that the fully permeable system is replaced after 10 years in all instances. If highest costs are compared, fully permeable pavement systems are significantly more cost-effective than currently available BMP technologies. It must be emphasized again that these cost comparisons are intended as examples for order of magnitude comparison only, that costs will vary depending on a number of factors, and that the findings will need to be validated in full-scale field experiments. A project-specific LCCA should be performed for each project to ensure that appropriate technologies are compared.

Table 3.3: Currently Available BMP Cost per Cubic Meter of Water Treated

BMP Type	Average Construction Cost		Construction Cost per m^3 Water		Annual O and M Cost (2007$)	Annual O and M Cost per m^3 Water (2007$)
	1999$	2007$	1999$	2007$		
Wet Basin	448,412	557,726	1,731	2,153	21,206	40
Multi-chambered Treatment Train	275,616	342,806	1,875	2,332	7,147	14
Oil-Water Separator	128,305	159,583	1,970	2,450	No data	No Data
Delaware Sand Filter	230,145	286,250	1,912	2,378	2,497	5
Storm-Filter	305,355	379,795	1,572	1,955	No data	No Data
Austin Sand Filter - Conrete	242,799	301,989	1,447	1,800	2,553	5
Biofiltration Swale	57,818	71,913	752	935	4,124	8
Biofiltration Strip	63,037	78,404	748	930	671	1
Infiltration Trench	146,154	181,784	733	912	1,982	4
Extended Detention Basin	172,737	214,847	590	734	4,999	9
Infiltration Basin	155,110	192,923	369	459	3,728	7
Drain Inlet Insert	370	460	10	12	No data	No Data
Austin Sand Filter - Earthen	No data	No data	No data	543	3,129	6
Traction Sand Trap	No data	No data	No data	1,860	1,823	3
Gross Solids Removal Device	No data	No data	No data	760	4,963	9

Table 3.4: NPV of Currently Available BMPs per Cubic Meter of Water Treated (in 2007$)

BMP Type	Number of Construction Events in Analysis Period[1]	Analysis for Life of One Design Period (20-year design[1])			Analysis for 40-Year Period
		Initial Construction[2] ($)	Annual O and M Cost[2] ($)	NPV in the year of construction[2] ($)	Initial construction[2] ($)
Wet Basin	2	2,153	40	2,714	3,952
Multi-chambered Treatment Train	2	2,332	14	2,528	3,682
Delaware Sand Filter	2	2,378	5	2,444	3,560
Austin Sand Filter - Concrete	2	1,800	5	1,867	2,719
Biofiltration Swale	2	935	8	1,044	1,521
Biofiltration Strip	2	930	1	948	1,381
Infiltration Trench	2	912	4	964	1,404
Extended Detention Basin	2	734	9	866	1,261
Infiltration Basin	2	459	7	557	812
Austin Sand Filter - Earthen	2	543	6	625	911
Traction Sand Trap	2	1,860	3	1,899	2,766
Gross Solids Removal Device	2	760	9	892	1,299
Oil-Water Separator	2	2,450	No data	No data	No data
Storm-Filter	2	1,955	No data	No data	No data
Drain Inlet Insert	2	12	No data	No data	No data

[1] Assumed that BMPs are reconstructed after 20 years

[2] All costs are based on unit volume (m^3) of water treated annually

Table 3.5: Summary of Currently Available BMP NPV Costs for Total Runoff (Sacramento Example)

(Conventional HMA pavement with highest and lowest cost treatment BMP over 40-year analysis period)

Application	Traffic Index	Pavement (x $1,000)	High BMP (x $1,000)	Low BMP (x $1,000)	High Total (x $1,000)	Low Total (x $1,000)
BMP shoulder retrofit, 1 lane	N/A	Existing	18,321	3,764	-	-
BMP shoulder retrofit, 3 lanes	N/A	Existing	34,728	7,134	-	-
Maintenance yard or rest stop	7	1,110	16,995	3,491	18,105	4,601
	11	1,720	16,995	3,491	18,715	5,211

Notes
1. These cost values are Net Present Values (NPV) in life-cycle cost calculation.
2. The calculation of pavement is based on a 4% discount rate and recommended cost and schedules of M&R of pavements in the Caltrans LCCA manual.
3. BMP is assumed to have a 20-year design life.

Table 3.6: NPV of Fully Permeable Pavement for Total Runoff (Sacramento Example)[1]

Application	Traffic Index	Surface Type	Subbase Structure	Surface Thickness (mm)	Granular Base (mm)	Subbase (mm)	Initial Construction (x $1,000)	Remove & Replace (x $1,000)	Annual Maintenance (x $1,000)	10-year, 0% (x $1,000)	10-year, 4% (x $1,000)	20-year, 0% (x $1,000)	20-year, 4% (x $1,000)
Highway shoulder retrofit, 1 lane	7	RHMA-O	PCC-O	200	530	150	1,323	577	2	3,139	2,198	1,986	1,631
			No subbase	200	680	0	1,146	577	2	2,962	2,021	1,809	1,454
		PCC-O	PCC-O	250	530	150	1,496	801	2	3,986	2,694	2,383	1,906
			No subbase	250	680	0	1,319	801	2	3,809	2,518	2,207	1,729
		Cast PCC	PCC-O	420	530	150	2,500	0	2	2,586	2,544	2,586	2,544
			No subbase	420	680	0	2,323	0	2	2,409	2,367	2,409	2,367
	11	RHMA-O	PCC-O	260	530	150	1,417	683	2	3,552	2,445	2,186	1,773
			No subbase	305	680	0	1,310	763	2	3,685	2,453	2,159	1,702
		PCC-O	PCC-O	270	530	150	1,533	846	2	4,157	2,796	2,465	1,963
			No subbase	270	680	0	1,356	846	2	3,980	2,619	2,288	1,786
		Cast PCC	PCC-O	460	530	150	2,523	0	2	2,609	2,567	2,609	2,567
			No subbase	460	680	0	2,346	0	2	2,432	2,390	2,432	2,390
Highway shoulder retrofit, 3 lane	7	RHMA-O	PCC-O	200	1,000	150	1,519	577	2	3,335	2,394	2,182	1,827
			No subbase	200	1,150	0	1,338	577	2	3,153	2,212	2,000	1,645
		PCC-O	PCC-O	250	1,000	150	1,691	801	2	4,181	2,889	2,578	2,101
			No subbase	250	1,150	0	1,509	801	2	3,999	2,708	2,396	1,919
		Cast PCC	PCC-O	420	1,000	150	2,694	0	2	2,779	2,738	2,779	2,738
			No subbase	420	1,150	0	2,512	0	2	2,598	2,556	2,598	2,556
	11	RHMA-O	PCC-O	260	1,000	150	1,613	683	2	3,748	2,641	2,382	1,969
			No subbase	305	1,150	0	1,501	763	2	3,877	2,644	2,350	1,893
		PCC-O	PCC-O	270	1,000	150	1,728	846	2	4,352	2,991	2,660	2,158
			No subbase	270	1,150	0	1,546	846	2	4,170	2,809	2,478	1,976
		Cast PCC	PCC-O	460	1,000	150	2,717	0	2	2,803	2,761	2,803	2,761
			No subbase	460	1,150	0	2,535	0	2	2,621	2,579	2,621	2,579

Application	Traffic Index	Surface Type	Subbase Structure	Surface Thickness (mm)	Granular Base (mm)	Subbase (mm)	Initial Construction (x $1,000)	Remove & Replace (x $1,000)	Annual Maintenance (x $1,000)	10-year, 0% (x $1,000)	10-year, 4% (x $1,000)	20-year, 0% (x $1,000)	20-year, 4% (x $1,000)
Maintenance yard, rest stop, or parking lot	7	RHMA-O	PCC-O	200	530	150	1,593	635	4	3,664	2,593	2,394	1,968
			No subbase	200	680	0	1,277	635	4	3,348	2,277	2,077	1,652
		PCC-O	PCC-O	250	530	150	1,694	826	4	4,338	2,969	2,686	2,156
			No subbase	250	680	0	1,377	826	4	4,022	2,653	2,369	1,840
		Cast PCC	PCC-O	420	530	150	3,398	0	4	3,564	3,483	3,564	3,483
			No subbase	420	680	0	3,082	0	4	3,247	3,167	3,247	3,167
		HMA[2]	No subbase	120	370	0	609			1,721	1,110		
	11	RHMA-O	PCC-O	260	530	150	1,747	808	4	4,338	2,996	2,721	2,201
			No subbase	305	680	0	1,546	938	4	4,526	2,982	2,649	2,059
		PCC-O	PCC-O	270	530	150	1,742	1,194	4	5,488	3,546	3,101	2,371
			No subbase	270	680	0	1,425	1,194	4	5,171	3,229	2,784	2,055
		Cast PCC	PCC-O	460	530	150	3,435	0	4	3,600	3,520	3,600	3,520
			No subbase	460	680	0	3,119	0	4	3,284	3,204	3,284	3,204
		HMA[2]	No subbase	160	560	0	829			2332	1,720		

Notes
1. The cost values are Net Present Values (NPV) in life-cycle cost calculation.
2. The cost and schedule for maintenance and replacement is from the Caltrans LCCA manual, which are not listed here. They are not necessarily 10-year or 20-year based design life.
3. 10 years and 20 years are the surface layer replacement period.

Table 3.7: Summary Permeable Pavement NPV Costs for Total Runoff (Sacramento Example)

(Fully permeable pavement with highest and lowest cost over 40-Year Design)

Application	Traffic Index	Cost	10-Year Replacement (x $1,000)		20-Year Replacement (x $1,000)	
Highway shoulder retrofit, 1 lane	7	High	PCC-O	2,694	Cast PCC	2,544
		Low	RHMA-O	2,021	RHMA-O	1,454
	11	High	PCC-O	2,796	Cast PCC	2,567
		Low	Cast PCC	2,390	RHMA-O	1,702
Highway shoulder retrofit, 3 lane	7	High	PCC-O	2,889	Cast PCC	2,738
		Low	RHMA-O	2,212	RHMA-O	1,645
	11	High	PCC-O	2,991	Cast PCC	2,761
		Low	Cast PCC	2,579	RHMA-O	1,893
Maintenance yard or rest stop	7	High	Cast PCC	3,483	Cast PCC	3,483
		Low	RHMA-O	2,277	RHMA-O	1,652
	11	High	PCC-O	3,546	Cast PCC	3,520
		Low	RHMA-O	2,982	PCC-O	2,055

Notes
1. These cost values are Net Present Values (NPV) in life-cycle cost calculation.
2. The calculation of pavement is based on 4% discount rate
3. All cast PCC concrete in this table have a 40-year life. 10-year and 20-year replacement are only for RHMA-O and PCC-O.
4. Conventional HMA is not included.

Chapter 4. Framework for Life-Cycle Assessment

Life-cycle assessment (LCA) is an approach for assessing the life-cycle of a product from cradle to grave, and investigates and evaluates all the inputs and outputs from raw material production to the final end-of-life phase of the product. It provides a comprehensive and defendable means of evaluating the total environmental impacts of a product. LCA is a separate process from LCCA and uses different analysis approaches and inputs.

Although the International Organization for Standardization (ISO) has established a series of standards for conducting LCA, applying these general guidelines to long-life infrastructure such as pavements is constrained by the lack of current knowledge and the definition of system boundaries. Although several LCA studies have been undertaken on pavement projects, there is a general lack of consistency in the methodology followed and in how the system boundaries are defined. Other inconsistencies include poor identification of pavement life-cycle phases, unclear functional units, and poor interpretation of inventory. Consequently, the findings are debatable and, like other forms of environmental and cost analysis, can be influenced by the way that the input values are used and interpreted. Decisions made based on the outputs of such analyses can lead to unanticipated longer-term consequences. Therefore, this study strives to improve current knowledge and make recommendations towards dealing with some of the controversial inputs and system boundary definitions relevant to fully permeable pavements. Similar problems are encountered with assessing BMP devices and to date, no documented LCAs have been undertaken on treatment BMPs. Consequently, only a pavement-oriented LCA framework has been developed in this study. Furthermore, since many of these problems are still under discussion, no quantified results will be given here.

The life-cycle assessment discussed in this report follows the guidelines described in ISO 14044 – *Environmental Management – Life-cycle Assessment – Requirement and Guidelines (14)*. The basic stages of performing an LCA include goal and scope definition, life-cycle inventory, impact assessment, and interpretation (Figure 4.1). Since the interpretation stage is essentially an analysis procedure to draw conclusions, make recommendations, or assist decision-making, it is integrated into the description of all other stages.

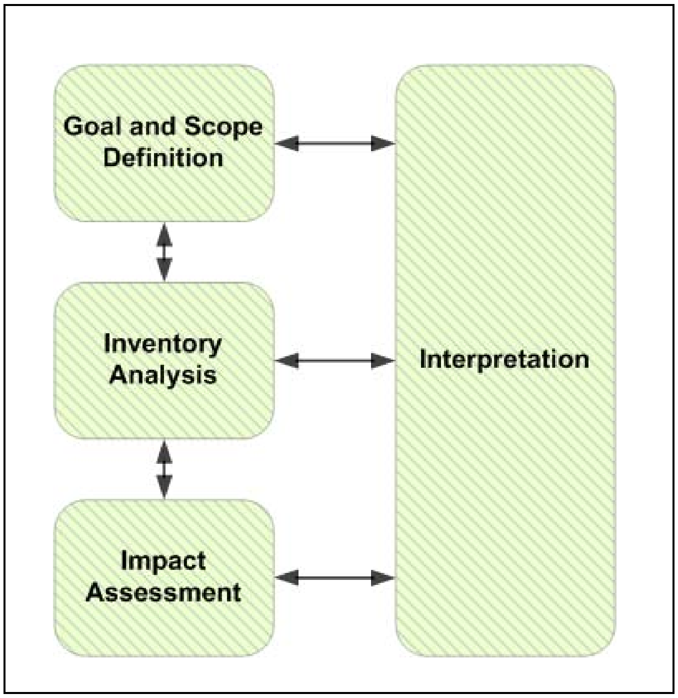

Figure 4.1: Stages for life-cycle assessment.

4.1 Goal and Scope Definition

4.1.1 Goal

Goal definition is the first stage in performing an LCA study. Defining the goal of a pavement LCA includes identifying its purpose and audience. For pavement LCA, this purpose could be characterizing a group of projects, where the result is to be used for policy or decision-making, or it could be identifying the benefit from a specific project. If the goal of the LCA is a framework that can be used across multiple projects, datasets reflecting average temporal and spatial information may need to be used. Conversely, in a project-specific LCA, site-specific and project-specific information should be used (when available) to develop local results. This type of resolution will be particularly important at the impact assessment stage.

4.1.2 Scope

Scope includes functional unit, analysis period, life-cycle phases and their system boundaries.

- **Functional Unit**. This is the reference unit representing a quantified performance of a product. It is the foundation of comparison between different construction methods. For pavements, it should address both the “reference unit” and “quantified performance” components. Defining a physical dimension is the general method used to represent the “reference unit” component. It includes length, width, and number of lanes for a highway system. The physical dimension needs to reflect the scale of a real-world project because certain activities can only be modeled at the scale of a practical project (e.g., mobilization of equipment or traffic analysis). A length of between 0.3 mi (0.5 km) and 60 mi (100 km) is a typical project dimension in highway construction.

- **Performance**. The performance of a pavement is combined with many parameters and thus it is difficult to develop a single indicator for performance. Functional design life, truck traffic, climate, subgrade, and criteria for functional performance should be included as parameters in any study to quantify performance.
  - **Analysis Period**. This refers to the time horizon used to inventory the inputs and outputs related with the functional unit. Since each initial construction will often have a different functional design life, and may be followed by a series of maintenance and rehabilitation activities, setting the analysis period correctly presents a challenge in quantifying the total effects in a life-cycle of a pavement. Some proposed methods to determine the analysis period include:
    - Using 1.5 times the longest functional design life among all alternatives. This method comes from the analysis period in LCCA. Adopting this method may result in greater compatibility between the LCCA and LCA results, and allow integrated analyses.
    - Selecting the minimal activity required for next major rehabilitation. This method serves to make a "fair" comparison between two rehabilitation activities with different design lives. Within the same period for each alternative, activities with a shorter design life will be penalized by a higher construction frequency.
    - Annualizing/amortizing construction events. This method also creates a "fair" comparison between alternatives by allocating one construction into the design life.
  - **System Boundaries.** The life-cycle phases of pavement include material production, construction, use, maintenance and rehabilitation, and end-of-life phase. A framework showing this process is presented in Figure 4.2.
    - Material production. In the material production phase, the inputs and outputs from the production process of all the materials (such as quarrying, or mixing, and the transport of materials) should be included. The allocation of impacts during asphalt production is, however, difficult since asphalt is a by-product of oil refining, and correctly allocating the energy consumption and pollutant emission to asphalt presents a challenge.
    - Construction, maintenance, and rehabilitation. Since maintenance and rehabilitation is essentially a construction process, it will have essentially the same system boundaries as the construction phase. In these phases, the inputs and outputs from transporting the materials and equipment and equipment usage are included. Important factors include the transport of water and water use during construction, which are often omitted in many studies. The additional fuel consumption and emission from vehicles affected by construction is also taken into consideration. Other energy use includes lighting during night construction and building the roadway lighting system.
    - Use. The factors considered in the use phase include increasing vehicle operating costs as the pavement deteriorates, heat island effect from solar reflection and evaporative cooling, non-greenhouse gas climate change effects, including radiated heat forcing from pavement surfaces, carbonation of cement (CO_2 absorption), and water pollution from leachate and runoff. The most significant part in this phase is thought to be the extra fuel use due to increased rolling resistance as the pavement deteriorates. However, there is currently no state-of-art model to simulate this problem and consequently it is difficult to quantify the effect.
    - End-of-life phase. In end-of-life phase, demolition and recycling are considered. For demolition, the emissions and fuel use during the hauling of demolished material are included. However, recycling imposes a critical problem regarding the allocation of net input/output between the system that generates the "waste" and the system that recycles the "waste." Currently there are a number of methods for doing this, but only two that are commonly used. One method assumes that each construction event is responsible for the

materials it uses. This implies that the construction event that uses virgin material is assigned all the environmental burdens for consuming that virgin material. Thus, all subsequent construction events that use recycled materials are only responsible for the recycling process and transport of the recycled materials. The other method allocates half the burden of producing and disposing of virgin materials to the first construction event and half to the final construction event, which uses recycled forms of the virgin material.

4.2 Life-Cycle Inventory

The *life-cycle inventory* stage involves data collection and modeling of the product based on the life-cycle phases and system boundaries identified in the previous stage. It includes all the inputs and outputs related to the product and its environment, within the boundary and based on the functional units defined in the first stage. However, currently a life-cycle inventory which meets the goal defined at the first stage (policy-level or project-level) is still under investigation. Some common categories of inventory include:

- **Energy Consumption.** Energy consumption should include all the energy used during the life-cycle, including feedstock energy and combusted energy. Feedstock energy is the embodied energy in a material which is usually utilized until combusted. Feedstock energy must be recorded because it can often be utilized when the material is burned for energy. In pavement, asphalt binder has very high feedstock energy; however, it is rarely burned for energy.
- **Greenhouse Gas Emissions.** This category quantifies the climate change effect in the impact assessment stage. Major greenhouse gas emissions, including CO_2, CH_4, and N_2O, need to be recorded. In addition, NO_X, particulates and other pollutants that are emerging as critical climate change factors should also be included as the scientific consensus develops on their effects/global warming potential.
- **Material Flows**, including fossil/non-renewable resource flows, and water flow.
- **Air Pollutants**, including NO_X, VOC (Volatile Organic Compounds), PM_{10}, $PM_{2.5}$, SO_2, CO, and lead.
- **Water Pollutants and Solid Waste Flows**, including toxics or hazardous waste.

4.3 Impact Assessment

The *impact assessment* stage provides comprehensive information to help assess the product's inventory results. The first step in this stage is to assign the appropriate inventory results to the selected impact categories, such as global warming, ozone depletion, etc. Then, the results that fall into the same category are characterized and calculated by a category indicator, such as Global Warming Potential (GWP), Ozone Depletion Potential (ODOP), etc. Usually a reference substance with a standard impact is set for each impact category, and all other substances are converted based on its impact over the reference level. For example, in global warming, CO_2 is set as the reference substance, and all other greenhouse gases will be converted to CO_2-equivalents based on their impact on global warming relative to CO_2. The final step is valuation, which integrates across impact categories using weights or other approaches enabling decision-makers to assimilate and consider the full range of relevant outcomes. However, because this step contains very high uncertainty and variability, and the second step is usually based on scientifically reliable research, many studies stop at the second step as a “mid-point” assessment. Some common impact categories include:

- **Climate Change.** The inventory of greenhouse gases should be tracked and reported in CO_2-equivalents or a similarly well-understood climate change indicator – preferably one that accounts for the timing of emissions. The source of method and time horizon used to calculate CO_2-equivalents must be reported in the analysis.
- **Resource Depletion.** This translates the inventory of material flows into categories of consumption, such as non-renewable use or abiotic resource use.
- **Other impact categories**, such as effects on human health, or environmental impact categories such as ozone depletion potential or acidification potential.

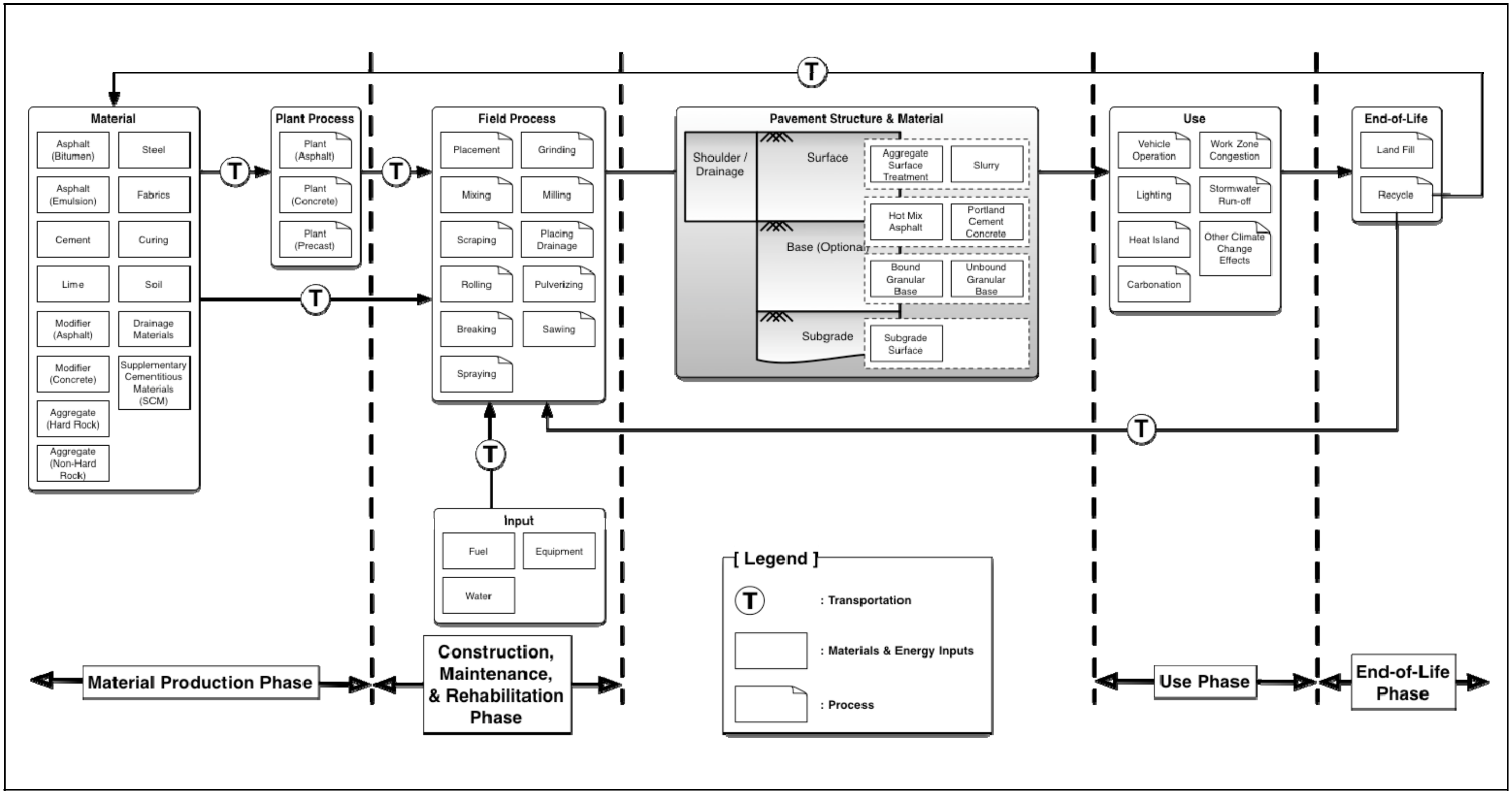

Figure 4.2: Proposed framework of pavement LCA.

Chapter 5. Summary and Future Work

This technical memorandum summarizes a framework for undertaking life-cycle cost analyses and environmental life-cycle assessments of fully permeable pavements. An example life-cycle cost analysis is provided to compare net present values of fully permeable pavements with those of existing best management practices for stormwater management. Detailed cost, environmental inventory, and actual life (as opposed to design life) data are not available for fully permeable pavements or for the other best management practices currently available for managing stormwater runoff on California highways. These data will only be available once full-scale field applications are systematically evaluated and documented. Consequently, only a simplified life-cycle cost analysis was undertaken based on available data and discussion with contractors and industry practitioners. An accurate environmental life-cycle assessment could not be undertaken.

A comparison of the life-cycle cost estimates of currently available BMPs installed adjacent to existing pavements with those of fully permeable pavements indicate that the fully permeable pavement appears to be more cost effective than currently available BMPs in most instances for both the shoulder retrofit and maintenance yard/parking lot scenarios. Fully permeable shoulders draining single lanes were in the order of two-thirds the cost of the lowest cost currently available BMP; fully permeable shoulders draining three lanes were in the order of half the cost; while fully permeable maintenance yards/parking lots were of a similar cost when lowest costs were compared, assuming that the fully permeable system is replaced after 10 years in all instances. If highest costs are compared, fully permeable pavement systems are significantly more cost-effective than currently available BMP technologies.

It should be noted that these cost comparisons are intended as examples for order of magnitude comparison only, that costs will vary depending on a number of factors, and that the findings will need to be validated in full-scale field experiments. Project-specific LCCAs should be performed for each project to ensure that appropriate technologies are compared and that applicable local input values (construction and maintenance costs and runoff volumes are used in the analysis).

Work still to be completed on this study includes the following:

- Final report.
- Preparation of structural designs for HVS and field test sections that include pavement dimensions and material specifications.

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