LIFE CYCLE COSTS FOR LIME IN HOT MIX ASPHALT

VOLUME I – SUMMARY REPORT

by

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FOREWARD

This is Volume I of a three-volume report:

- Volume I – Final Report: describes the study, summarizes findings, and provides conclusions and recommendations.
- Volume II – Appendices A-D: contains all of the supporting data for the study.
- Volume III – LCCA Software User's Guide: is a user's guide for the Windows-based software program developed specifically for this study.

The summary report (Volume I) and appendices (Volume II) will be of interest to State highway agency personnel and hot-mix asphalt paving contractors responsible for conducting and/or reviewing pavement design life cycle cost analyses. The software user's guide (Volume III) will be of interest to those practitioners that wish to use the LCCA software.

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ABSTRACT

Life cycle cost analysis (LCCA) is recognized by public agencies as an effective tool to assist in the selection of highway construction, maintenance, and rehabilitation treatments. Accordingly, the Federal Highway Administration (FHWA) has developed an LCCA methodology that will likely become the standard in the industry. The methodology can be used to evaluate the life cycle costs (LCC) of paving materials with additives/modifiers, such as hydrated lime.

This report uses information from past highway projects to:

- identify the benefits and costs of adding lime;
- compile past performance data into an LCCA model; and
- compare the LCCs for asphalts with and without lime.

Estimated lives used in the LCCA model are based on interviews and on engineering judgment. Practitioners can use project-specific data with the LCCA software to generate project-specific estimates of life cycle costs.

This report presents the LCCA results for interstate and state highway projects. The findings show that lime is the most cost effective design for all of the applications studied. Life cycle cost savings from lime are, on average, \$2 to \$3 per square yard; or, \$13,000 to \$21,000/lane mile (13% to 15% of project life cycle costs). These results are based on the widely accepted use of lime as an additive that reduces stripping.

ACKNOWLEDGMENTS

The authors are grateful for the assistance of the following agencies and contractors that provided the information to perform life cycle cost comparisons:

Agencies

- Arizona
- California
- Colorado
- FHWA (WFLHD[*])
- Georgia
- Mississippi
- Oregon
- Nevada
- South Carolina
- Texas
- Utah

Contractors

- APAC
- FNF Construction
- Granite Construction
- Kiewit Pacific
- Lafarge
- C.W. Matthews Contracting
- Morse Brothers
- Staker Construction
- Dean Word Company
- Young Contractors

The information provided and used in the analyses was verified by those surveyed.

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy presented herein. The contents do not necessarily reflect the official views of the agencies and contractors that provided information in support of the study. Users of the LCCA model need to apply their judgment when using the results of this report or the software described in Volume III.

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[*] Western Federal Lands Highway Division of the Federal Highway Administration

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1.0 INTRODUCTION

1.1 Background

Lime in hot mix asphalt (HMA) has been used in highway applications since the 1970s for a variety of reasons (Hicks, 1991). The most common reason for adding lime is to inhibit the effects of moisture damage. However, studies have also shown that the addition of lime generates other benefits such as acting as an active filler, anti-oxidant, and additive that reacts with clay fines in HMA (Little and Epps, 2001). Thus, lime is an additive that can increase pavement life and/or performance through a number of mechanisms.

Decisions on when and where to use lime in HMA must be based on cost and expected performance. The Federal Highway Administration (FHWA) and several state highway agencies are advocating the use of Life Cycle Cost Analysis (LCCA) to help determine the most appropriate rehabilitation and maintenance strategies for a given situation (FHWA, 1995). This report presents results of a study sponsored by the National Lime Association (NLA) to develop an LCCA tool to help highway designers evaluate the cost effectiveness of lime for a number of different applications.

1.2 Objectives

The specific objectives of this report are to:

- Provide an overview of the use of lime in HMA;
- Describe the life cycle cost analysis approach used in this study;
- Present examples of the LCCA for selected applications; and
- Provide guidelines for cost effective uses of lime.

The analyses are based on maintenance and rehabilitation scenarios used in a number of states on interstates and state highways.

1.3 Study Approach

This study includes the following elements:

1) Literature Review. We first collected information to identify the benefits and costs of adding lime to HMA. We also identified the distress types that are minimized by adding lime. The results appear in Chapter 2.
2) Select LCCA Procedure. The FHWA method, which includes both deterministic and probabilistic approaches, was selected for use in this study. The method is described in Chapter 3.
3) Collect Project Information from State Transportation Departments. This task consisted of: 1) collecting information on maintenance and rehabilitation strategies as well as expected lives for the various strategies, by highway category, 2) agency cost data for construction, maintenance, and rehabilitation activities, and 3) user costs associated with delay. This was accomplished through a survey of users (see Volume II, Appendix A) to identify the maintenance and rehabilitation strategies used, as well as cost and user delay information (see Volume II, Appendix B).
4) Conduct LCCA Analysis. The LCCA model uses the data collected and verified by the various agencies. Chapter 4 presents a summary of the results. The scenarios evaluated are presented in Volume II, Appendix C and the detailed results of the analyses appear in Volume II, Appendix D.

The user's guide for the LCCA software is in Volume III.

2.0 USE OF LIME IN HMA

In the late 1970s a number of premature HMA pavement failures occurred in the western and southeastern parts of the United States. Stripping was identified as a major problem, but its rather sudden appearance has never been fully explained. Possible causes include the following:

- changes in properties of asphalt cements as a result of the oil embargo in early- to mid-1970s;
- increases in the traffic levels – both volume and weight;
- changes in HMA construction equipment, e.g., the advent of drum mixers and the use of dust collectors; and
- new aggregate sources resulting in changes in aggregate characteristics.

An NCHRP study completed in 1991 (Hicks, 1991) presented a comprehensive review of moisture damage problems in the U.S. Many of the agencies surveyed reported moisture-related distress in the form of rutting in the wheel paths, bleeding in selected areas of the pavement, early raveling, and/or pot holing.

Because lime had been used by some agencies prior to the 1970s, several states (including Georgia, Nevada, Oregon, South Carolina, Texas, and Utah) began to use lime to solve their moisture susceptibility problems. Lime has continued to be a widely used anti-strip agent and is used extensively by at least 15 states in the U.S. (Little and Epps, 2001).

This chapter identifies the major benefits of adding lime to HMA, the cost of adding lime, and some of the challenges. A discussion of methods used to add lime appears in an appendix at the end of this volume.

2.1 Benefits

The primary reason for adding lime to HMA is to reduce moisture sensitivity and/or stripping. Lime is by far the most widely used anti-strip agent. Other products used include chemicals (e.g., liquid amines and diamines) and liquid polymers (e.g., latexes). Paving contractors often prefer liquid anti-strip additives because of their ease of use, the lack of dust, and/or avoiding the need to add water to the aggregates. However, many of the lab and field studies conducted on the effectiveness of lime in HMA show that it is a superior product in terms of eliminating moisture sensitivity problems in asphalt pavements (Hicks, 1991; Little and Epps, 2001).

Not only does the addition of lime provide anti-stripping benefits, but it also has been shown to:

1) act as a mineral filler to stiffen the binder and reduce rutting;
2) improve resistance to fracture growth (i.e., improves fracture toughness) at low temperatures;
3) favorably alter oxidation kinetics and reduce their deleterious effects; and
4) alter the plastic properties of clay fines to improve moisture stability and durability.

Each of these additional benefits is discussed in more detail in the report by Little and Epps (2001).

Table 2.1 summarizes the reasons agencies contacted in this study use lime in HMA. As expected, all consider lime as an anti-stripping agent. Several states are aware of lime's other benefits in improving HMA performance.

Table 2.1. Reasons for Using Lime

Agency	Resist Stripping	Improve Aging Resistance	Stiffen Binder	Improve Fracture Toughness	Alter Properties of Fines
Arizona	1	3	2	3	2
California – Dist 2	1	2	3	1	1
Colorado	1	3	3	3	1 (when appropriate)
Georgia	1	3	3	3	3
Mississippi	1	1	2	—	3
Nevada	1	3	3	2	1
Oregon	1	2	3	3	3
South Carolina	1	2	2	2	2
Texas	1	3	2	3	2
Utah	1	2	2	2	2

Level of importance:
1 = very important
2 = moderately important
3 = less important

2.2 Cost of Adding Lime

The cost of lime added to the HMA is dependent on the methods used and the amount of lime added. Typical costs appear in Table 2.2.

Table 2.2. Typical Costs for Adding Lime – Contractors

Agency	Contractor	Method Used	% Lime Used	Added Cost $/Ton-Mix
Arizona	FNF	Non-Marinated	1.0	1.00
	Kiewit-Pacific	Non-Marinated	1.0	1.00-1.50
California	FNF	Marinated	0.7-1.2	3.75-4.25
	Granite	Marinated	0.7-1.2	4.00-4.50
	Kiewit-Pacific	Marinated	0.7-1.2	4.00
Colorado	Lafarge	Non-Marinated	1.0	1.00-1.25
Georgia	APAC	Non-Marinated	1.0	1.25-1.50
Mississippi	APAC	Non-Marinated	1.0	1.25-1.50
Nevada	FNF	Non-Marinated	1.5	1.00-1.50
		Marinated	1.5	3.75-4.25
	Granite	Non-Marinated	1.5	1.25-1.50
		Marinated	1.5	2.75-4.50
Oregon	Kiewit-Pacific	Non-Marinated	1.0	1.25-1.50
	Morse Brothers	Non-Marinated	1.0	1.25-1.50
South Carolina	APAC	Non-Marinated	1.0	1.25-1.50
Texas	APAC	Non-Marinated	1.0-1.5	1.00-1.50
	F.M. Young	Non-Marinated	1.0-1.5	1.00-1.50
Utah	Granite	Non-Marinated	1.0-1.5	1.25-1.50
	Staker	Non-Marinated	1.0-1.5	1.25-1.50

3.0 LIFE CYCLE COST ANALYSIS (LCCA) PROCEDURE

This chapter presents the driving forces for LCCA and describes the procedure used in this study. The procedure is based on the approach developed by the Federal Highway Administration documented in Publication No. FHWA-SA-98-079, "Life-Cycle Cost Analysis in Pavement Design," (Walls and Smith, 1998), hereafter referred to as the *FHWA Interim Technical Bulletin*.

3.1 Driving Forces

Agencies have historically used some form of LCCA to assist in the evaluation of alternative pavement design strategies. For example, the 1986 AASHTO *Guide for the Design of Pavement Structures* encouraged the use of LCCA and described a process to evaluate the cost effectiveness of alternative designs (AASHTO, 1986).

However, until the National Highway System (NHS) Designation Act of 1995, which specifically required agencies to conduct LCCA on NHS projects costing $25 million or more, the process was used routinely only by a few agencies (Walls and Smith, 1998). The implementing guidance for this legislation did not recommend specific LCCA procedures, but rather specified the use of good practice. The FHWA position on the use of LCCA is defined in its Final Policy Statement published in the September 18, 1996, *Federal Register* (Walls and Smith, 1998). More generally, FHWA policy indicates that LCCA is a decision support tool. As a result, FHWA encourages the use of LCCA in analyzing all investment decisions.

Although the Transportation Equity Act for the 21st Century (TEA-21) has removed the requirement for agencies to conduct LCCA on high cost projects, it is still the intent of FHWA to encourage the use of LCCA for NHS projects. As a result, FHWA has developed a training course titled “Probabilistic LCCA in Pavement Design” (Demonstration Project No. 115) to train agencies in the importance and use of sound procedures to aid in the selection of alternate designs or rehabilitation strategies (Walls and Smith, 1998).

3.2 LCCA Process

LCCA should be conducted as early in the project development cycle as possible. In addition, the level of detail in the analysis should be consistent with the level of investment. Basically, the process involves the steps shown in Figure 3.1 and described in further detail below.

Establish Alternative Maintenance and Rehabilitation Strategies

The primary purpose of a LCCA is to quantify the long-term economic implications of initial pavement design decisions. Various rehabilitation and maintenance strategies can be employed over the analysis period (Figure 3.2). This first step is to identify alternative strategies over the analysis period, typically 35-40 years. This LCCA model includes maintenance and rehabilitation strategies employed by selected states that use lime in asphalt pavements, which were obtained through personal interviews or telephone calls.

Determine Expected Life of Maintenance and Rehabilitation Strategies

The next step is to obtain estimates of expected lives for the various maintenance and rehabilitation strategies. This information was also obtained through interviews with state agency personnel. Typical lives for maintenance and rehabilitation treatments are given below:

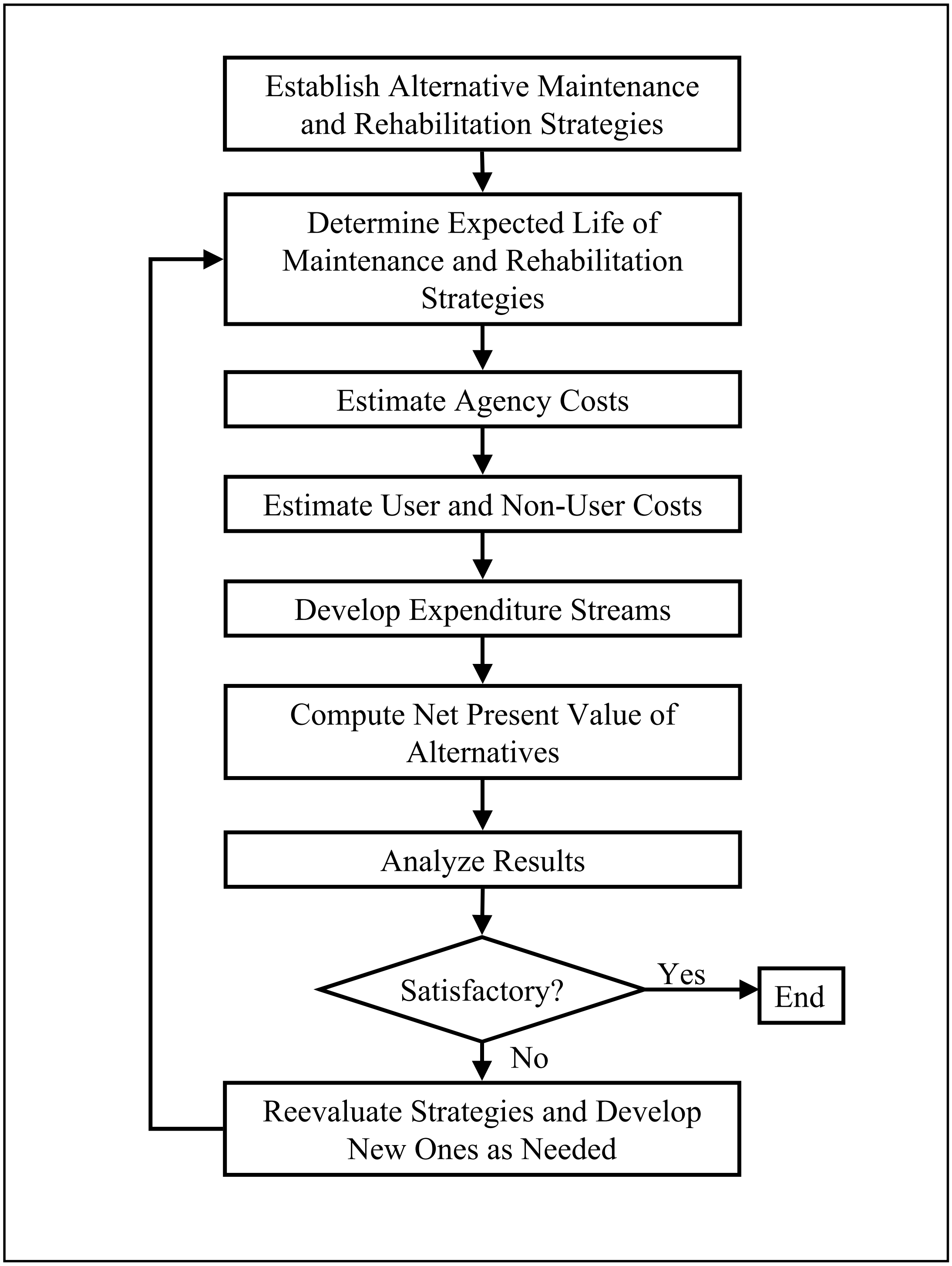
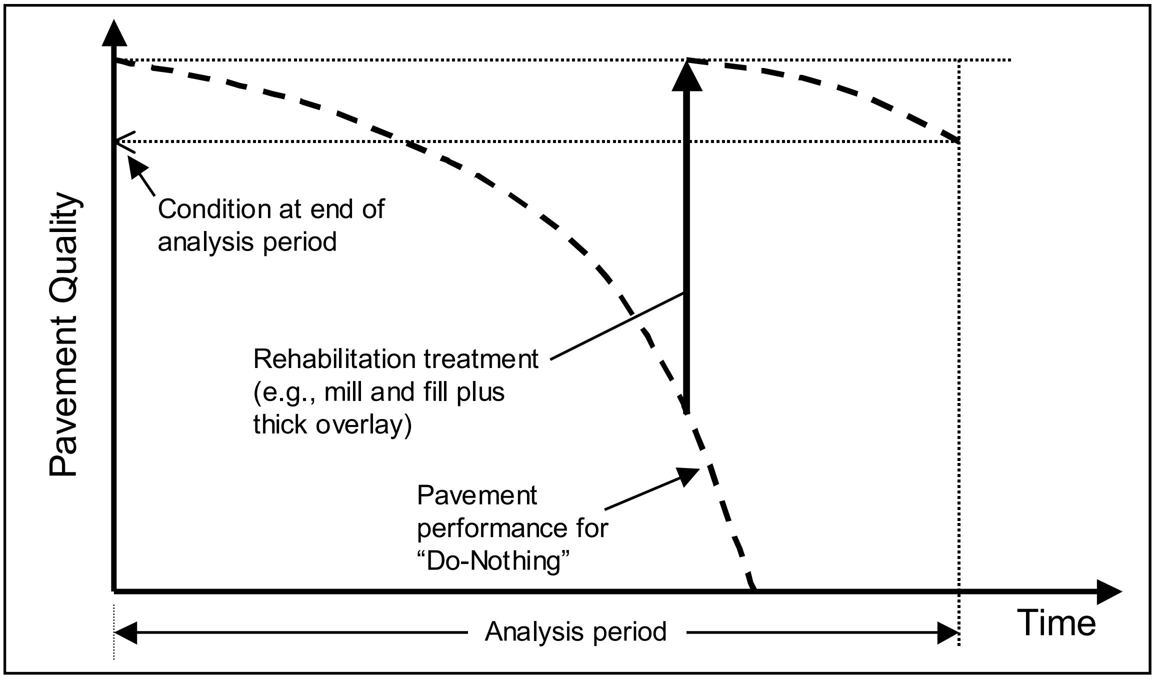
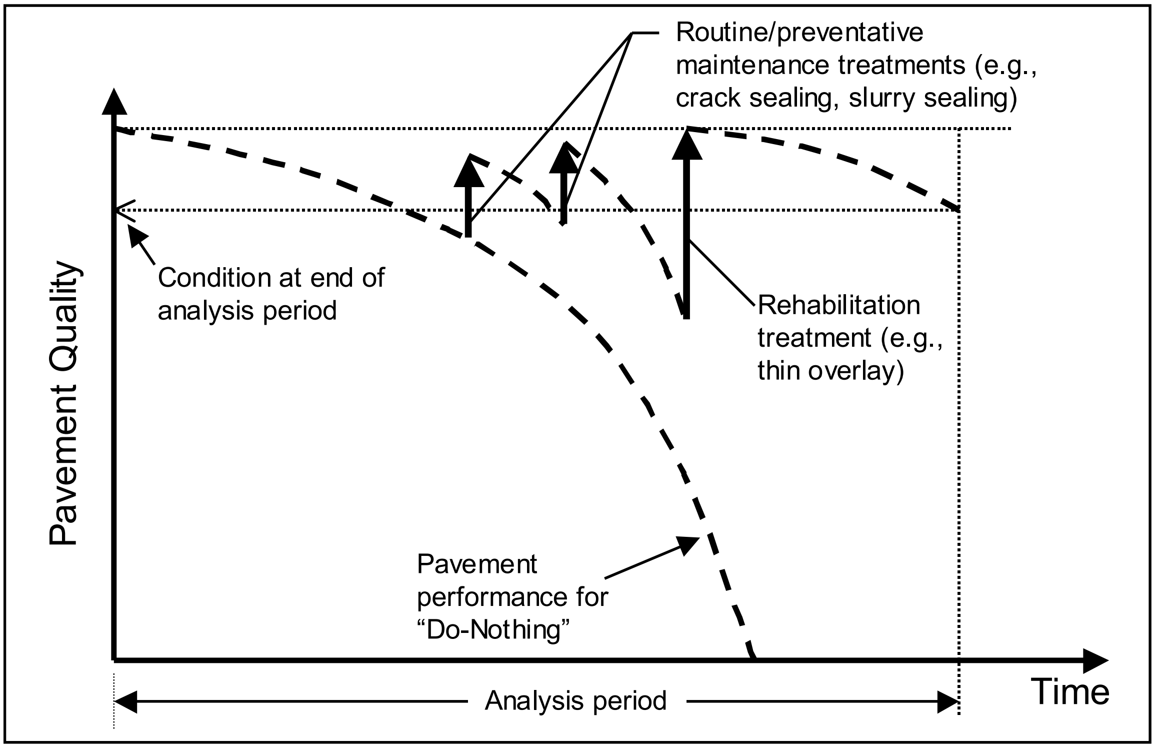


Figure 3.1. LCCA Process



a) Alternative A (single major rehabilitation treatment)



b) Alternative B (multiple treatments)

Figure 3.2. Alternative Strategies for Maintenance and Rehabilitation Activities.

Strategy	Treatment	Expected Life, Years
Maintenance	Fog Seal	2-4
	Crack Seal	2-5
	Chip Seal	3-7
	Slurry Seal	3-7
	Microsurfacing	5-9
	Thin HMA – < 1.5 inch	7-10
Rehabilitation	2 inch Overlay	10-15
	Mill and Fill plus 2 inch Overlay	15-20

Each agency surveyed provided specific information on the lives of their treatments, which are given in Volume II, Appendix B.

Estimate Agency Costs

Agency costs include all costs incurred directly by the agency over the analysis period. These costs typically include expenditures for engineering, contract administration, construction, including construction supervision, and all future maintenance (routine and preventive), resurfacing, and rehabilitation. Estimates for these costs were obtained through interviews of state agency personnel. Typical values for costs of various maintenance and rehabilitation treatments are given below:

Strategy	Treatment	Cost ($\$/yd^2$)
Maintenance	Fog Seal	0.30-0.45
	Crack Seal	0.40-0.60
	Chip Seal	0.80-1.00
	Slurry Seal	0.80-1.00
	Microsurfacing	1.10-1.30
	Thin HMA (1 inch)	1.75-2.00

Strategy	Treatment	Cost ($\$/yd^2$)
Rehabilitation	2 inch Mill	1.50-2.00
	4 inch Mill	3.00-3.50
	2 inch Overlay	3.50-4.25
	2 inch Mill and Fill plus 2 inch Overlay	5.00-6.25

Reported values for each agency surveyed are given in Volume II, Appendix B.

Salvage value (credit for remaining life) represents the value of an investment alternative at the end of the analysis period. One method that can be used to account for salvage value prorates the cost of the final rehabilitation activity based on the portion of life consumed relative to the expected life of the rehabilitation treatment as shown below:

$$SV = \left(1 - \frac{L_A}{L_E} \right) C \qquad \text{(Eq. 3.1)}$$

where:

SV = salvage value, $

L_E = the expected life of the rehabilitation alternative, years

L_A = portion of expected life consumed, years

C = cost of the rehabilitation strategy, $.

Estimate User and Non-User Costs

In simple terms, user costs are those incurred by the highway user over the analysis period. They include vehicle operating costs (VOC), user delay costs, and accident costs. It is recommended that user costs be included whenever the initial construction activity involves a rehabilitation treatment (e.g., overlay on an existing pavement) or a reconstruction of an existing pavement because these types of activity require a work zone and therefore road users incur delay costs. However, if the initial construction activity involves constructing a new pavement (i.e., where one did not exist before), user costs for the initial construction activity can be excluded.

For most pavements in the National Highway System (NHS), the VOC are considered to be similar for the different alternatives. However, slight differences in VOC rates caused by differences in roughness could result in significant differences in VOC over the life of the pavement. For purposes of this project, VOC rates will be assumed to be equal for alternative strategies.

Accident and non-user costs may also vary with type of maintenance and rehabilitation strategy. However, for purposes of this project, these costs were assumed to be equal for alternative strategies.

With regard to user delay costs, two approaches were identified as candidates for inclusion in the methodology. The first approach, based on capacity flow analysis, is used to estimate the user delay costs associated with establishing a work zone. The second approach uses lane rental fees to account for user delay costs indirectly. These two approaches are discussed briefly in the following paragraphs:

> Work Zone User Costs. The *FHWA Interim Technical Bulletin* provides a step-by-step procedure for estimating user delay costs associated with a work zone. The principal advantage of this approach is that user delay costs are estimated through a rigorous methodology. The principal disadvantage of this approach is that it is computationally complex and would require numerous user inputs, such as the directional

hourly distribution of average daily traffic (ADT) on the highway under consideration, unit costs for speed change delays, idling costs, and speed of traffic in queues developed upstream of work zone.

Lane Rental Fees. An alternative approach to account for user delay costs, albeit indirectly, is to use lane rental fees. Typical values for lane rental fees based on traffic volume (Rohlf, 1994; Herbsman and Ellis, 1995; Herbsman and Glagola, 1998) are given below:

Type of Highway	Average Daily Traffic	$/Lane-Mile/Day
Low Volume	< 5,000	1,000
Moderate Volume	5,000-15,000	5,000
High Volume	> 15,000	≥10,000

In this approach, estimating user delay costs is a simple matter of estimating the duration of the maintenance or rehabilitation activity (i.e., number of days a work zone is in place) and multiplying this duration by the daily lane rental fee. The principal advantage of this approach is that it is simple to implement in LCCA. The principal disadvantage is that it is only a surrogate for estimating user delay costs.

For this project, it was decided to base user delay costs on the latter approach (i.e., lane rental fees).

Develop Expenditure Streams

Expenditure streams are graphical or tabular representations of expenditures over time. They are generally developed for each maintenance and rehabilitation strategy to visualize the extent and timing of expenditures. Figure 3.3 is an example of an expenditure stream in graphical format. Normally, costs are depicted as upward arrows and benefits are depicted as

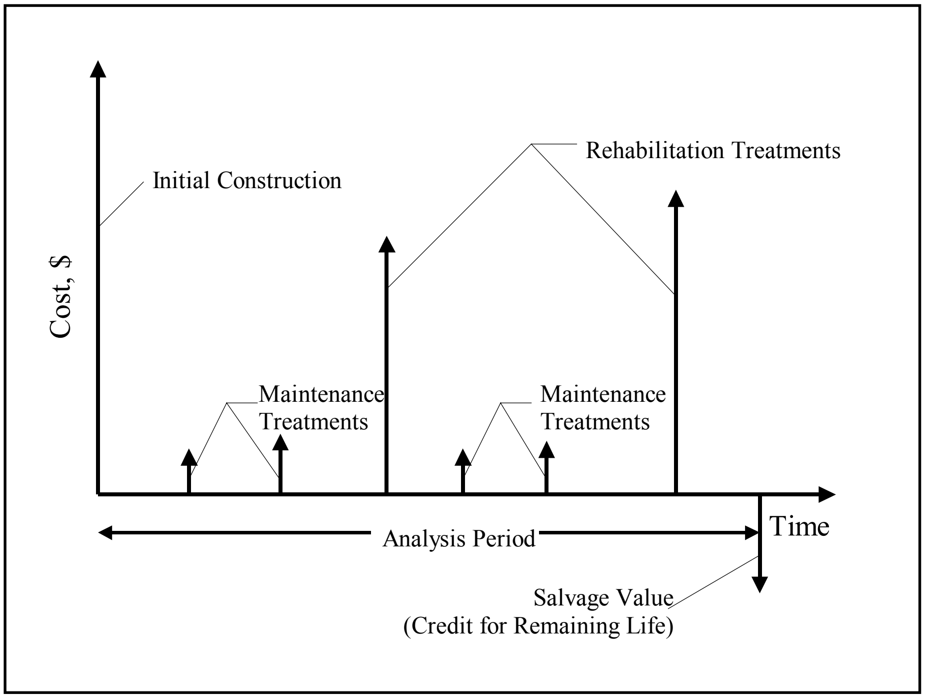


Figure 3.3. Typical Expenditure Stream for a Pavement Design Alternative.

downward arrows (or negative costs). The only benefit, or negative cost, would be the cost associated with the salvage value (credit for remaining life) of the pavement alternative at the end of the analysis period.

Compute Net Present Value (NPV)

LCCA is a form of economic analysis used to evaluate the cost efficiency of various investment options. Once all costs and their timing have been established, the future costs must be discounted to the base year and added to the initial cost to determine net present value (NPV). NPV is calculated as follows:

$$\text{NPV} = \text{Initial cost} + \sum_{k=1}^{n} (\text{future costs})_k \left[\frac{1}{(1+i)^{n_k}} \right] \qquad \text{(Eq. 3.2)}$$

where:

i = discount rate, typically 3 to 5%
n = year of expenditure
k = maintenance or rehabilitation strategy plus user cost and salvage value (credit for remaining life)

Both agency and user costs were incorporated in the methodology used in this study. Analyses were conducted using both a deterministic and a probabilistic approach. Deterministic analyses use only the mean (average) values of the inputs, and thus do not consider variability. This is appropriate whenever the variability of the inputs is small, or not known. Probabilistic analyses, on the other hand, consider the variability of the inputs through Monte Carlo simulations. However, this form of analysis requires knowledge (or estimation) of the variability (in terms of standard deviation) of the inputs.

Analyze Results

Once completed, all LCCA results should be subjected to a sensitivity analysis to determine the influence of major input variables. Many times the sensitivity analysis will focus on best case/worst case scenarios in an attempt to bracket outcomes. For example, if a conventional asphalt pavement lasts 10 years, how long must an asphalt pavement with lime last for it to be cost effective?

Following the sensitivity analysis, the results of the analyses should be evaluated for reasonableness. Questions to be considered include:

1) Are the expected lives and maintenance and rehabilitation costs appropriate?
2) Have all pertinent costs been considered?
3) Has uncertainty been adequately treated?

4) Are there other alternatives that should be considered?

5) Are there significant cost differences in the alternatives?

Reevaluate Strategies

Based on the analysis of the results, it may be necessary to modify scenarios or refine input data. For example, it may be necessary to reevaluate expected performance of a given rehabilitation alternative. Modifications should be reasonable, objective, reevaluated in a sensitivity analysis, and well documented.

4.0 LCCA EXAMPLES

The life cycle cost analysis (LCCA) calculations presented herein were completed using a Windows-based program developed specifically for this project. The program (described in Volume III) allows LCCA using both a deterministic and probabilistic approach. The latter incorporates a Monte Carlo simulation process – as encouraged by FHWA (Walls and Smith, 1998). This chapter describes the scenarios investigated, common features, and assumptions.

4.1 Scenario Overview

Several features were common to each analysis:

1) A 40-year analysis period was selected based on FHWA recommendations (Walls and Smith, 1998).
2) Each major rehabilitation activity triggered a lane rental cost.
3) Routine (preventive) maintenance was applied between major rehabilitation activities depending on the agency. Lane rental fees were not applied to maintenance activities.
4) Salvage values (credits for remaining life) were calculated as a prorated percentage of the expected life of the final rehabilitation activity.
5) All costs were converted to net present worth values to compare alternatives.

Several assumptions and simplifications were necessary:

1) Maintenance was applied as indicated by the agency. Once triggered, periodic maintenance costs continued until the next major rehabilitation activity.
2) User delay costs were approximated using the lane rental costs. If a treatment was triggered in the final year of the analysis period, the lane rental fee was not included in the calculation of the salvage value. (The authors recognize that more accurate

cost could be determined if actual average daily traffic (ADT) were known and delays were computed; however, this was beyond the scope of this project. Users of the software can use costs determined by ADT, if available.)

Several inputs were consistent for all scenarios:

Variable	Value
Discount rate	4.0 (2.5 to 5.5) %[*]
Analysis period	40 yrs.
Lane rental costs	
– Interstate projects	\$5000/lane-mile/day
– State DOT projects	\$1000/lane-mile/day
Project length and width	10 mi × 24 ft
Production rates (rehabilitation activities)	Open-graded mixes: 3.8 lane-miles/day[**]
	Dense- and gap-graded mixes: 5.0 lane-miles/day

The maintenance and rehabilitation strategies and the expected lives and costs varied as described below.

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[*] Four percent was used for all deterministic runs; when variability was considered in the probabilistic analysis, 4% was used as the mean with values ranging randomly from 2.5 to 5.5%.

[**] Typical production rates are about 300-400 tons/hr for 8 to 10 hours per day for HMA laydown. Values shown are for a 2-inch overlay (production rates for overlays with thickness different from 2 inches were adjusted accordingly). User costs (lane rental fees) for maintenance activities were not included in the analyses.

4.2 Scenarios Investigated

Maintenance and rehabilitation scenarios for HMA mixtures with and without lime placed on interstates and state highways are provided in Volume II, Appendix C. Mean values for treatment costs, treatment lives, and discount rates were used in the deterministic analyses, whereas means and standard deviations were used in the probabilistic analyses. For the probabilistic analysis, standard deviations were derived from the ranges of costs and lives shown in Appendix C assuming the ranges are representative of the true costs and true lives in 80% of all cases. In addition, the distribution of costs and lives within the ranges shown in Appendix C were assumed to follow a normal distribution.

Although many states use lime for selected situations in which stripping is a concern, the following states use lime-treated HMA exclusively: Georgia, Mississippi, Nevada, South Carolina, and Utah. For most of these agencies, analyses were conducted assuming the life of the non-lime alternative was 2 years (i.e., 10 to 25%) less than the alternative with lime. This is a conservative assumption based on experience of other states, where lime-treatment increases pavement life by 2 to 10 years (i.e., 25 to 50%) as shown in Volume II, Table B.6. Nevada and Utah were able to provide lives for the non-lime alternatives and these values were used in the analysis.

4.3 Results

Results for the deterministic and probabilistic scenarios are summarized in Tables 4.1 and 4.2. Volume II, Appendix C details the scenarios modeled and Volume II, Appendix D details the results. An example of the calculations involved in the deterministic analysis for Mississippi state highway pavements with lime is shown in Figure 4.1.

Table 4.1. Summary of Results of *Deterministic* Analyses.

Agency	Life Cycle Cost, $/yd^2 (Net Present Value)		Savings Associated with Using Lime	
	Lime-Treated Alternative	Non-Lime Treated Alternative	$/yd^2	$/lane-mile
a) Interstates				
Arizona	14.18	15.34	1.16	8,188
California	24.83	28.25	3.42	24,075
Colorado	20.52	24.51	3.99	28,067
Georgia	20.65	24.79**	4.14	29,155
Mississippi	7.65	9.05**	1.40	9,897
Nevada	11.48	19.69***	8.21	57,775
Oregon	12.34	13.91	1.57	11,019
South Carolina	20.90	21.53**	0.63	4,421
Texas	8.11	8.40	0.29	2,100
Utah	17.30	22.92***	5.62	39,530
b) State/Federal Lands Highways				
Arizona	5.37	7.61	2.24	15,769
California	24.18	27.45	3.27	23,018
Colorado	9.47	10.50	1.03	7,256
FHWA	7.69*	8.01*	0.32	2,297
Georgia	7.71	9.28**	1.57	11,093
Mississippi	7.20	7.74**	0.54	3,786
Nevada	10.01	10.92***	0.91	6,426
Oregon	11.68	14.59	2.91	20,519
South Carolina	21.71	25.96**	4.25	29,958
Texas	9.03	9.60	0.57	3,974
Utah	15.99	18.81***	2.82	19,904

* Federal Lands Highways only.
** Not used by agency; life of non-lime alternative estimated to be 2 years less than lime-treated alternative.
*** Not used by agency, but agency estimated relative life of non-lime alternative.

Table 4.2. Summary of Results of *Probabilistic* Analyses.

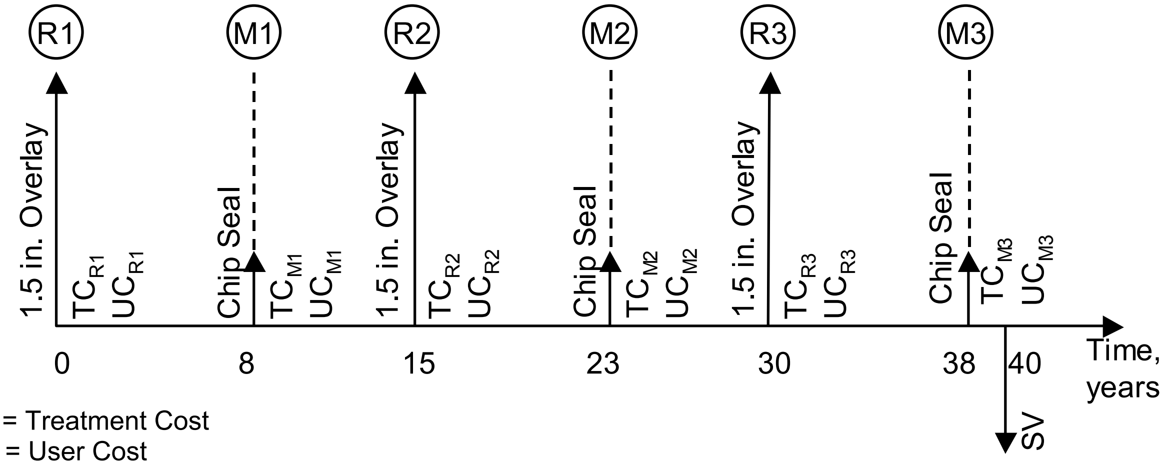
Agency	Mean Life Cycle Cost, $/sq. yd. (Net Present Value)		Percent of Simulations Lime Less Costly Than Non-Lime*	Savings Associated with Using Lime	
	Lime-Treated	Non-Lime Treated		$\$/\text{yd}^2$	$/ lane-mile
a) Interstates					
Arizona	14.46	15.93	86	1.47	10,407
California	27.96	30.81	79	2.85	20,040
Colorado	22.93	26.80	91	3.87	27,217
Georgia	21.93	26.50***	85	4.57	32,215
Mississippi	8.16	9.61***	79	1.45	10,217
Nevada	12.56	16.86****	96	4.30	30,263
Oregon	12.73	14.53	85	1.80	12,678
South Carolina	21.13	23.87***	87	2.74	19,309
Texas	8.30	9.14	82	0.84	5,935
Utah	20.11	25.35****	96	5.24	36,926
b) State/Federal Lands Highways					
Arizona	6.74	7.95	96	1.21	8,496
California	27.35	30.21	80	2.86	20,154
Colorado	4.77	5.61	92	0.84	5,933
FHWA	8.05	9.13	92	1.08	7,580
Georgia	7.95	9.78***	96	1.83	12,847
Mississippi	7.54	8.17***	81	0.63	4,380
Nevada	10.45	11.86****	96	1.41	9,939
Oregon	12.59	15.66	99	3.07	21,632
South Carolina	24.18	28.16***	87	3.98	28,062
Texas	9.45	10.91	95	1.46	10,281
Utah	18.71	21.01****	80	2.30	16,216

* Number of times the life cycle cost of lime-treated design was less than that of non-lime treated design, as percent of the total number of iterations utilized in the Monte Carlo simulation process (see Relative Cumulative Probability Distribution charts in Volume II, Appendix D).

** Federal Lands Highways only.

*** Not used by agency; life of non-lime alternative estimated to be 2 years less than lime-treated alternative.

**** Not used by agency, but agency estimated relative life of non-lime alternative.



TC = Treatment Cost
UC = User Cost
R1, R2, R3 = Rehabilitation Treatments
M1, M2, M3 = Maintenance Treatments
SV = Salvage Value (Credit for Remaining Life)

Analysis Inputs:
  Project Length: 10 miles = 52,800 ft
  Project Width: 2 lanes @ 12 ft/lane = 24 ft
  Project Area: 20 lane-mi. = 52,800 ft x 24 ft = 1,267,200 ft^2 = 140,800 yd^2
  Rehabilitation Treatment Unit Cost: \$3.31/yd^2
  Rehabilitation Treatment Production Rate: 6.7 lane-mi./day
  Maintenance Treatment Unit Cost: \$0.90/yd^2
  Lane Rental Fee: \$1,000/lane-mi./day
  Analysis Period: 40 years
  Real Discount Rate: 4.0%

Calculations:
  Future Costs (Constant Dollars):
    TC$_{R1, R2, R3}$ = 3.31/yd^2 x 140,800 yd^2 = \$466,048.00
    UC$_{R1, R2, R3}$ = (\$1,000/lane-mi./day x 20 lane-mi.)/6.7 lane-mi./day = \$2,985.07
    TC$_{M1, M2, M3}$ = \$0.90/yd^2 x 140,800 yd^2 = \$126,720.00
    UC$_{M1, M2, M3}$ = \$0.00 (User costs not included for maintenance treatments)
    SV = (-1) x (TC$_{R3}$) x (1 - 10/15) = -\$155,349.33 (User costs not included)
  Present Worth Costs (PWC):
    PWC$_{R1}$ = PWC of TC$_{R1}$ & UC$_{R1}$ = (\$466,048.00 + \$2,985.07) x [1/(1 + 0.04)^{0}] = \$469,033.07
    PWC$_{R2}$ = PWC of TC$_{R2}$ & UC$_{R2}$ = (\$466,048.00 + \$2,985.07) x [1/(1 + 0.04)^{15}] = \$260,437.41
    PWC$_{R3}$ = PWC of TC$_{R3}$ & UC$_{R3}$ = (\$466,048.00 + \$2,985.07) x [1/(1 + 0.04)^{30}] = \$144,611.65
    PWC$_{M1}$ = PWC of TC$_{M1}$ & UC$_{M1}$ = (\$126,720.00 + \$0.00) x [1/(1 + 0.04)^{8}] = \$92,593.06
    PWC$_{M2}$ = PWC of TC$_{M2}$ & UC$_{M2}$ = (\$126,720.00 + \$0.00) x [1/(1 + 0.04)^{23}] = \$51,413.64
    PWC$_{M3}$ = PWC of TC$_{M3}$ & UC$_{M3}$ = (\$126,720.00 + \$0.00) x [1/(1 + 0.04)^{38}] = \$28,548.17
    PWC$_{SV}$ = PWC of SV = -\$155,349.33 x [1/(1 + 0.04)^{40}] = -\$32,357.56
  Life Cycle Cost (LCC):
    LCC = PWC$_{R1}$ + PWC$_{R2}$ + PWC$_{R3}$ + PWC$_{M1}$ + PWC$_{M2}$ + PWC$_{M3}$ + PWC$_{SV}$
      = \$469,033.07 + \$260,437.41 + \$144,611.65 + \$92,593.06 + \$51,413.64 + \$28,548.17
       - \$32,357.56
      = **\$1,014,279.44**
    LCC (\$/yd^2) = \$1,014,279.44/140,800 yd^2 = **\$7.20/yd^2**
    LCC (\$/lane-mi.) = \$1,014,279.44/20 lane-mi. = **\$50,713.97/lane-mi.**

Figure 4.1. Example Life Cycle Cost Calculations (for Mississippi State Highways With Lime)

The deterministic results indicate that use of lime was cost effective in all cases. For the scenarios involving interstates, the savings associated with the use of lime ranged from \$0.29/yd^2 to \$8.21/yd^2 with an average savings of \$3.04/yd^2. For the scenarios involving state/federal lands highways, the savings ranged from \$0.32/yd^2 to \$4.25/yd^2 with an average savings of \$1.86/yd^2.

The probabilistic results indicate that use of lime was cost effective for both interstates and state highways. For interstates, the savings associated with the use of lime ranged from \$0.84/yd^2 to \$5.24/yd^2 with an average savings of \$2.91/yd^2. Life cycle costs were less for lime-treated pavement in 87% of the simulations investigated. For state highways, the savings ranged from \$0.63/yd^2 to \$3.98/yd^2 with an average savings of \$1.88/yd^2. Life cycle costs were less for lime-treated pavement in 90% of the simulations investigated.

In Tables 4.1 and 4.2, there are some large differences in life cycle costs between agencies due to differences in treatment lives (application frequencies) and treatment costs. For example, Table 4.1 indicates that the life cycle cost of the lime treated alternative on Mississippi interstates is \$7.65/yd^2 whereas the lime treated alternative on California interstates is \$24.83/yd^2. However, as shown in Volume II, Appendix C, the cost of rehabilitation treatments as reported by Caltrans is nearly 3 times that of rehabilitation treatments as reported by Mississippi DOT. In addition, the analysis for California included maintenance treatments whereas for Mississippi maintenance treatments were not included. The information provided by the agencies was most consistent for a given road category within the state, which is the level at which the authors expect most users will apply LCCA—i.e., comparing lime-treated mixtures to other mixtures for a given road type in a given location.

4.4 Guidelines for Use

Lime in HMA was shown to be cost effective for all the scenarios presented in this report. The savings range, on average, from about \$2 to \$3 per square yard (or \$13,000 to \$21,000 per lane mile). The savings quantified in this analysis are based only on the reduction of moisture sensitivity problems in HMA. These savings do not include other benefits of lime in HMA.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Based on the information provided by the agencies and the results of the analyses, the following conclusions are warranted:

1) For the scenarios evaluated, use of lime in HMA was the most cost effective alternative for all highway pavement applications investigated.
2) When variability was considered in the inputs (cost, expected life, discount rate), the lime alternatives were the best choice in all of the applications considered.
3) For some agencies, lime in HMA is the only alternative used. When agencies could not provide an estimate of the life of non-lime alternatives, an LCCA was performed assuming that the life of the lime-treated alternative exceeded that of the non-lime treated alternative by only two years. Under this assumption, the lime-treated alternative, in all cases, had a lower life cycle cost than that of the unmodified mixture.

LCCA is highly dependent on input variables. To conduct a more tailored LCCA, site-specific estimates of the average value and expected variability for each input variable should be used. The results summarized here are generally based on information reported as "best estimates" by those responding to the survey (Volume II, Appendix B). At this time, more site-specific data are not universally available.

5.2 Recommendations

Nonetheless, FHWA recommends that agencies should perform a life cycle cost analysis to determine whether a proposed application is cost effective. Use of this software program and site-specific parameters will facilitate such evaluations.

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Appendix: Methods of Adding Lime

Lime can be added to HMA using a number of different methods: dry lime to aggregate, lime slurry to aggregate, or lime to bitumen. Some states “marinate” the lime-aggregate mixture before use.

Lime is typically delivered by truck. The lime is off-loaded pneumatically into field storage equipment, which include “upright” silos, horizontal tanks, and a variety of truck trailers. The storage capacity should be large enough to allow the hot mix plant to continue to operate without interruption during the off-loading of lime.

Lime transfer, lime metering, water metering, and mixing systems are needed to add lime to aggregate. Dry lime transfer methods include the use of pneumatic methods and screw conveyors. The most popular method presently used is the screw conveyor to transfer dry lime from the storage silo to the mixing area. Lime metering devices include vane feeders, hoppers and vane feeders, belt scales, weigh hoppers, load cell hoppers, load cell screw conveyors and in-line flow meters. Vane feeders and hoppers are used frequently in the United States.

Water is needed to activate the lime and to help in the dry lime-aggregate mixing process. Most plants do not use water-metering systems other than simple water valves. Calibration of these valves should be performed. Metering systems are desirable. Continuous pugmill mixers commonly used for stabilization projects have been used extensively in the United States for adding lime to HMA. “End of belt” mixers have been used when the lime-treated aggregate is stockpiled prior to entering the HMA mixing operation.

After mixing, the lime-treated aggregate is usually placed on the weigh belt of a drum plant or on a charging belt for the dryer of the batch plant. Some agencies allow for the introduction of lime into the drum after the aggregate has been mostly dried and just prior to the application of the asphalt cement. Although this method increases the resistance of the mixture to stripping, the maximum antistripping benefit of using lime will be achieved when it is mixed with the aggregate in the presence of water.

As with other dry bulk materials, precautions should be taken to avoid the creation of dust. All transfer points for the lime should be equipped with dust abatement equipment. Personal protection clothing and safety equipment should be available. Material safety data sheets should be reviewed and available. The other HMA construction operations of storage of the hot mix, transportation, lay down, and compaction are the same as for typical operations.

Following are the most common methods of adding lime to HMA:

1) Dry lime is added to dry aggregate. Lime is typically added to the drum mixer at a point in the drum where the asphalt binder is introduced.
2) Dry lime is added to wet aggregate. Moisture levels in wet aggregates are typically 2-3% higher than the saturated surface dry (SSD) condition of the aggregate. The moisture dissolves the lime and helps distribute it on the aggregate surface. The lime-treated aggregates can be stockpiled for marination or can be conveyed directly to the drying and mixing portion of the hot mix plant.
3) Lime slurry (a mixture of water and lime) is sprayed onto the aggregate, mixed, and conveyed directly to the drying or mixing portion of the plant or placed into stockpiles for marination. Lime slurry with high solids contents can be transported without substantial separation. The use of lime slurry has several advantages including reduced dusting associated with the addition of dry lime to the aggregate; and improved distribution of the lime on the aggregate. However, the use of lime slurry adds more water than is typically used in the other applications, which results

in increased fuel consumption (to dry the aggregate) and reduced plant production. The use of lime slurries also requires specialized equipment to prepare the slurry at the plant site.

4) The addition of dry lime to the asphalt binder prior to mixing with the aggregate has not been practiced in the field. However, recent research by Lesueur and Little (1999) demonstrates the potential effectiveness of this approach.

Marinating and stockpiling treated aggregate prior to use in the hot mix plant is common in some states (California, Nevada, and Utah). Advantages of marination include:

- a reduction in moisture content while the aggregate is stockpiled;
- the lime treatment can be performed separately from the hot mix production; and
- an improvement in the resistance to moisture can result.

Disadvantages of marination include:

- additional handling of the aggregate;
- additional space requirements for aggregate stockpiles;
- lime may be washed from the aggregate while it is marinating, but treated aggregates have been stockpiled for months without reductions in lime content; and
- carbonation of the lime in stockpiles may occur, but normally only on the surface of the stockpile.