Life Cycle Cost Comparison of Rubberized and Conventional HMA in California

CalRecycle

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Executive Summary

Asphalt rubber has been used in the United States since the 1960s. Because the asphalt rubber binder contains the crumb rubber modifier manufactured from waste tires, it has significant environmental advantages. Over the years, laboratory and field performances have shown that the rubberized hot mix asphalt using asphalt rubber can extend pavement life, resist reflective cracking, and reduce noise. This study evaluates the cost benefits of using asphalt rubber hot mixes using current cost and performance data with the life cycle cost analysis (LCCA) approach.

In order to obtain the true performance of the asphalt rubber hot mix asphalt, the Caltrans project database was searched for rubberized hot mix asphalt applications. A total of 126 asphalt rubber projects from Caltrans' 12 districts over the past 15 years have been located and detailed plans were evaluated. The treatment life was estimated from the start of a project until the next surface treatment on the same project location. The cost information was from the Caltrans' office of engineers' cost-bidding website.

The life cycle cost analysis of each project location has been conducted using the current Caltrans life cycle cost analysis approach under local traffic and climate conditions. The Caltrans analysis was based on the Federal Highway Administration's RealCost procedure and using the California's local data. This paper presents the Caltrans life cycle cost analysis results considering both agency costs and user costs.

The final results using Caltrans RealCost software are organized by functional class and size of the project for each Caltrans district. The functional classes are interstate highways, state routes, and U.S. highways. The sizes of the projects are large (more than 10 lane miles) and medium (4 to 10 lane miles). The savings represent the percentage of the total cost saving compared to conventional hot mix asphalt by using rubberized hot mix asphalt. The higher the percent saving, the more cost-effective rubberized hot mix asphalt becomes.

Life cycle cost analysis results show that rubberized hot mix asphalt is more cost-effective than conventional mix for both the large and medium projects on interstate highways for all Caltrans districts. The saving ranges from 5 percent to 30 percent for large projects and from 3 percent to 32 percent for medium projects when compared to conventional hot mix asphalt project costs.

For the large size projects on state routes for Caltrans districts, the rubberized hot mix asphalt is more cost-effective than the conventional hot mix asphalt, except in District 3 (Sacramento, Yolo, El Dorado, Placer, Colusa, Sutter, Yuba, Nevada, Glenn, Butte, and Sierra counties) where the percent cost savings ranged from -5 percent to as high as approximately 40 percent. The current rubberized hot mix asphalt life is about six years in District 3. In order to be cost-effective, the pavement life need to be seven years based on a trial Caltrans RealCost run. The life cycle cost analysis results of the medium-sized projects on state routes in Caltrans districts show that by using asphalt rubber, all districts have cost benefits, with cost savings ranging from 3 percent to 36 percent compared to conventional hot mix.

For the large size projects on U.S. routes for Caltrans districts, the life cycle cost analysis results have shown that the asphalt rubber has significant cost savings over conventional hot mix. The savings over a 20-year period could be as high as 39 percent.

There weren't many small rubberized hot mix asphalt projects because it requires additional equipment and modified plant procedures. Small projects using rubberized hot mix asphalt are not cost-effective for Caltrans.

In addition to the deterministic approach, we also conducted statistical analysis. The life cycle cost analysis probabilistic results can give not only the average comparison, but also variation of results. As an example, the graphic comparison can be presented for the results of a District 4 large interstate highway project. One can also calculate that rubberized hot mix asphalt has a 77 percent chance of more being cost effective than hot mix asphalt (based on that Alt 1 mean value is 0.74 standard deviation to the right of the Alt 2 rubberized asphalt hot mix present worth mean value).

The results of the life cycle cost analysis are highly dependent on the input variables. In the past, these inputs were only best estimates. Obtaining real performance values based on real project data or a pavement management system proved very useful. Based on the information from Caltrans and the results of the analyses, the following conclusions can be drawn:

1. For the scenarios evaluated, asphalt rubber is a cost-effective alternate for most highway pavement applications in California.
2. When variability is considered in the inputs (cost, expected life, etc.), the asphalt rubber alternates would be the best choice in most of the applications considered.
3. Asphalt rubber was not cost-effective in all applications. The life cycle cost analysis allows one to determine when and where asphalt rubber will be cost-effective. For example, in one case, the rubberized hot mix asphalt life needs to increase from six to seven years in order to be cost-effective.
4. The cost-effectiveness of using asphalt rubber depends on the project location and functional class of the road. Different parts of California showed different life cycle cost analysis results.

Agencies intending to use asphalt rubber need to consider performing a life cycle cost analysis to determine whether a proposed application is cost-effective. As shown in this report, the cost-effectiveness of asphalt rubber varies a lot depending on the project location and functional class.

A limitation of this study is the lack of good long-term performance data for comparative sections of conventional and asphalt rubber mixtures. Assumptions were made to assume conventional hot mix asphalt alternative to be at the same rubberized hot mix asphalt location and with average hot mix asphalt pavement life and costs. Data from comparative test sections would provide more accurate results.

Introduction

Crumb rubber modifiers have been used in highway applications since the 1960s.[1] Numerous technologies have been evaluated, with varying degrees of success. They have contained binders prepared from both the wet process (asphalt rubber) and the dry process (rubber modified). Dense-, open-, and gap-graded aggregates have been used with crumb rubber modifiers.

Asphalt rubber, which has the longest history of use of rubber products in highway applications, must meet the requirements given in ASTM D-6114 "Standard Specification for Asphalt-Rubber Binder" including the following:

- A blend of asphalt cement, extender oil, and crumb rubber.
- The crumb rubber (minimum of 15 percent) is a combination of scrap tire rubber and high natural rubber additive.
- The binder is reacted at elevated temperatures for a minimum of 45 minutes.
- The reacted asphalt rubber binder must meet specified physical properties.

Use of crumb rubber modifiers in hot-mix asphalt increased substantially in the early 1990s due in large part to the mandate imposed in the federal ISTEA transportation funding bill. A survey of state highway administrations conducted by AASHTO in January 1993 indicated that 21 states used crumb rubber modifiers in hot mixes in 1992. However, once the mandate was repealed, the use of asphalt rubber declined or ceased in many parts of the United States.

Currently, the majority of crumb rubber binder used in hot mix asphalt occurs in Arizona, California, Florida, and Texas. Arizona's Department of Transportation and local governments in Arizona primarily use asphalt rubber binder in open- and gap-graded hot mixes.[2] The use of asphalt rubber binder in open-graded friction courses is now the most popular use of this type of binder by the Arizona DOT. Arizona first placed hot mix asphalt containing asphalt rubber in 1975.

The California Department of Transportation (Caltrans) uses asphalt rubber in dense-, gap-, and open-graded hot mix asphalt. California local governments and Caltrans in Southern California utilize asphalt rubber binders in gap- and open-graded mixtures.

Texas DOT uses asphalt rubber primarily in gap-graded mixture identified as coarse matrix, high binder (CMHB).[3] Florida DOT uses a fine ground rubber at typically 6-12 percent by weight of asphalt binder in dense- and open-graded hot mixtures. These binders are not asphalt rubber as defined by ASTM.

This study investigated the cost-effectiveness of using asphalt rubber versus conventional hot mixes.

Objectives

The objectives of this paper include:

- Determine the performance and cost information of the asphalt rubber hot mix.
- Present the Caltrans life cycle cost analysis approach.
- Present examples of the life cycle cost analysis for selected applications.
- Compare life cycle cost analysis results of rubberized with conventional hot mix asphalt used in California.

Life Cycle Cost Analysis Approach

This section presents the background on life cycle cost analysis and describes the process currently being used by Caltrans and the Federal Highway Administration.

Background

Agencies have historically used some form of life cycle cost analysis to assist in the evaluation of alternative pavement design strategies. Since the publication of the 1986 AASHTO Guide for the Design of Pavement Structures, the use of life cycle cost analysis was encouraged and a process spelled out to evaluate the cost-effectiveness of alternative designs.[4] However, until the National Highway System (NHS) Designation Act of 1995, which specifically required agencies to conduct life cycle cost analysis on NHS projects costing $25 million or more, the process was only used routinely by a few agencies.[5] The implementing guidance did not recommend specific life cycle cost analysis procedures, but rather specified the use of good practice. Federal Highway Administration policy indicates that life cycle cost analysis is a decision support tool. As a result, the Federal Highway Administration encourages the use of life cycle cost analysis in analyzing all investment decisions.

Although the Transportation Equity Act for the 21st Century (TEA-21) has removed the requirement for agencies to conduct life cycle cost analysis on high cost projects, it is still the intent of the Federal Highway Administration to encourage the use of life cycle cost analysis for National Highway System projects. As a result, in 1998, the Federal Highway Administration has developed a training course titled “Life Cycle Cost Analysis in Pavement Design” (Demo Project 115) to train agencies about the importance and use of sound procedures to aid in the selection of alternate designs or rehabilitation strategies.[6]

The life cycle cost analysis approach became a very useful tool to evaluate different maintenance and rehabilitation strategies. In 2001, Scholz et. al. compared preventive maintenance versus reconstruction using life cycle cost analysis.[7] Embacher and Snyder compared asphalt and concrete pavement on low volume roads.[8] In 2010, Lee and Kim evaluated performance and cost effectiveness of polymer modified chip seals.[9] In 2011, Pittenger et. al. presented life cycle cost-based pavement preservation treatment design.[10] Finally, Lee et. al. illustrated using life cycle cost analysis to validate California’s Interstate 710 pavement type selection.[11]

The life cycle cost analysis provides the total cost comparison of competing design and maintenance alternatives. All of the relevant costs that occur throughout the life of alternatives are included. Also the effects of the agency’s construction and maintenance activities on users and agency are accounted for. Although the life cycle cost analysis provides critical information to the overall decision-making process, it may not be the final answer due to other restraints .[12]

Probability versus Deterministic Approach

Probabilistic methods of modeling, analysis, and evaluation are the tools of modern engineering. In practice, it is important to quantify the effect of uncertainty and to evaluate its effect on performance and design.[13] In 2002, Reigle and Zaniewski used risk-based life cycle cost analysis for project level pavement management.[14] Tighe provided guidelines for probabilistic pavement life cycle cost analysis.[15] Thus, probability should be included into any engineering system. However, an average or single value is often used as an input variable to simplify the modeling process. The current standard practice for life cycle cost analysis used by Caltrans is based on a deterministic approach. Realizing the importance of uncertainty, this paper conducted the probabilistic analysis as well.

The Federal Highway Administration's life cycle cost analysis program uses Monte Carlo simulation, which allows modeling of uncertain quantities in the model with probabilistic inputs such as mean and standard deviations. The simulation procedure randomly samples these inputs and produces outputs that are described by both a range of potential values and a likelihood of occurrence of specific outputs.[16]

Life Cycle Cost Analysis process

Life cycle cost analysis should be conducted as early in the project development cycle as possible. The level of detail in the analysis should be consistent with the level of investment. Basically, the process involves the following steps:[12,17]

1. Establish design alternatives.
2. Develop rehabilitation and maintenance strategies for the analysis period for each alternative.
3. Establish the timing (or expected life) of various rehabilitation and maintenance strategies.
4. Estimate the agency costs for construction, rehabilitation, and maintenance.
5. Estimate user costs.
6. Develop expenditure streams.
7. Compute the life cycle costs.
8. Analyze the results using either a deterministic or probabilistic approach.
9. Re-evaluate strategies and develop new ones as needed.

The application of the above steps to the present study is described below.

Establish Alternative Design Strategies

The primary purpose of a life cycle cost analysis is to quantify the long-term economic implications of initial pavement decisions. Various maintenance and rehabilitation strategies can be employed over the analysis period illustrated in FIGURE 1. This first step is to identify alternate strategies over the analysis period, typically 20 to 55 years for Caltrans. Alternate design strategies used in California for asphalt pavement were obtained from the Caltrans life cycle cost analysis manual.[18] Typical maintenance and rehabilitation strategies used by Caltrans are summarized in FIGURE 2. For each of the scenarios considered, there is a logical comparison between conventional mixtures and mixtures containing asphalt rubber. The pavement alternates receive different maintenance (or rehabilitation) treatments until the life reaches the analysis period.

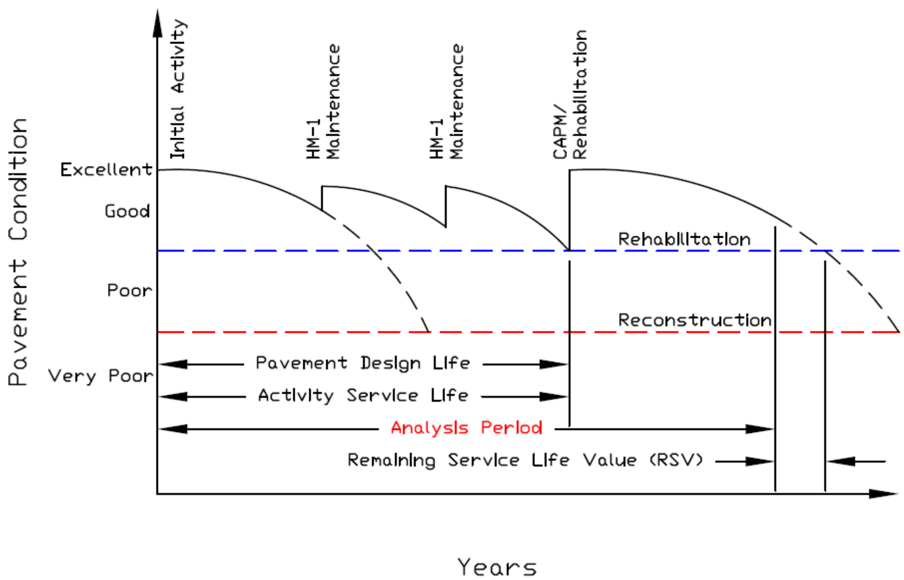

FIGURE 1 Analysis Period for a Pavement Design Alternative

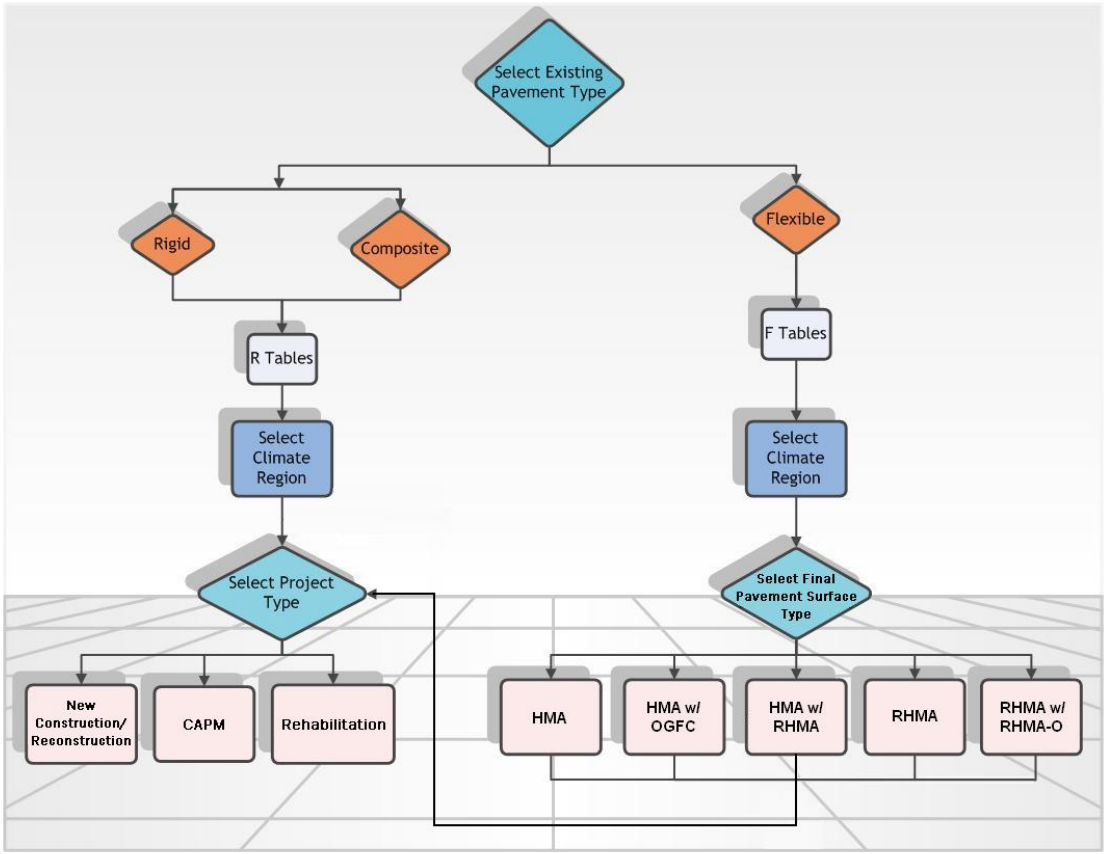

FIGURE 2 Pavement M&R Selection Flow Chart used by Caltrans[18]

Determine expected life of maintenance and rehabilitation strategies

The next step was to obtain estimates of expected lives for the various rehabilitation and maintenance strategies. This can be determined based on surveys or the past project experiences or from a pavement management system. For this study, the estimated lives are based on the past project experiences from Caltrans' database.

Estimate Agency Costs

Agency costs include all costs incurred directly by the agency over the life of the project. These costs typically include expenditures for preliminary engineering, contract administration, construction, including construction supervision, and all future maintenance (routine and preventive), resurfacing and rehabilitation.

Salvage value represents the value of an investment alternative at the end of the analysis period. Caltrans' life cycle cost analysis manual calls it the remaining service life value shown in Figure 1. The salvage value of a project alternative at the end of the analysis period is computed by prorating the total construction cost (agency and user costs) of the last scheduled rehabilitation activity.

Estimate User Costs

User costs are those incurred by the highway user over the life of the project due to the delay of construction and maintenance activities. They include vehicle operating costs, user delay costs, and accident costs. For most pavements on the National Highway System, the vehicle operating costs are considered to be similar for the different alternatives. However, slight differences in vehicle operating costs rates caused by differences in roughness could result in huge differences in vehicle operating costs over the life of the pavement.

Delay cost rates have been derived for both passenger cars and trucks. These can range from $10-$13/vehicle-hour for passenger cars and $17-$24/ vehicle-hour for trucks5. Caltrans uses $10.46/ vehicle-hour for passenger cars and $27.83/ vehicle-hour for trucks.[18] The Caltrans RealCost program's user costs require project specific information for inclusion in a life cycle cost analysis including traffic information, roadway geometry, lane closure time and schedule, etc. These project data were collected and input into the program to compute the user cost for each alternative.

Develop Expenditure Streams

Expenditure streams are graphical or tabular representations of expenditures over time. They are generally developed for each pavement design strategy to visualize the extent and timing of expenditures.

FIGURE 3 is an example of an expenditure stream for a simple 20-year analysis period. Normally, costs are depicted as upward arrows and benefits are reported as negative cost (or downward arrows). The only benefits, or negative cost, included herein are the costs associated with the salvage value.

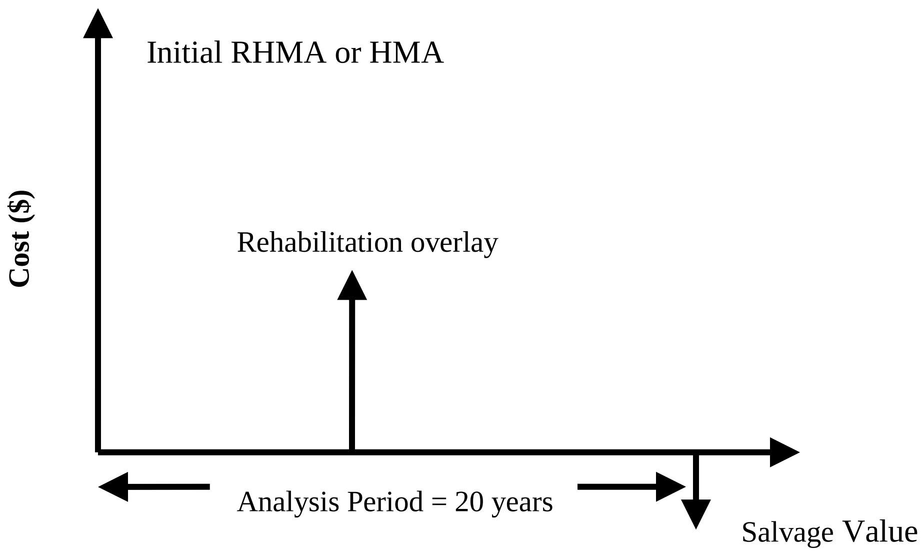

FIGURE 3 Typical Expenditure Stream Diagram for a Pavement Design Alternative

Compute the life-cycle cost values

Life cycle cost analysis 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, which is calculated as follows:

$$NPV = InitialCost + \sum_{k=1}^{N} \text{RehabCost}_k \left\lfloor \frac{1}{(1+i)^{n_k}} \right\rfloor \quad (1)$$

where: i=discount rate

n=year of expenditure

$\left\lfloor \frac{1}{(1+i)^{n}} \right\rfloor$=Present Value (PV)

Equivalent Uniform Annual Cost (EUAC) can also be calculated, which is useful for comparing alternatives with different service lives.

$$EUAC = (A/P, i, n) * NPV = \left(\frac{i(1+i)^n}{(1+i)^n - 1} \right) * NPV \quad (2)$$

where: A/P=ratio of the EUAC to the NPV

i=annual percent increase in cost index

n=analysis period (in years)

Both agency and user cost are incorporated into the analysis. The results can be presented using a deterministic or probabilistic approach as will be discussed in the examples to follow.

Analyze results

Once completed, all life cycle cost analysis results should be subjected to a sensitivity analysis to determine the influence of major input variables. Many times the sensitivity analysis will focus on inputs with the highest degree of uncertainty (i.e., life) in an attempt to bracket outcomes. For example, if a conventional project lasts 10 years, how long must an asphalt rubber design last for it to be cost-effective?

Reevaluate design strategy

After the net present value and Equivalent Uniform Annual Cost have been computed for each alternative, the analyst needs to reevaluate competing design strategies. Questions to be considered include:

1. Are the design lives and maintenance and rehabilitation costs appropriate?
2. Have all the costs been considered (e.g., shoulder and guard rail)?
3. Has uncertainty been adequately treated?
4. Are there other alternates that should be considered?

Many assumptions, estimates, and projections feed the life cycle cost analysis process. The variability associated with these inputs can have a major influence on the results.

Life Cycle Cost Analysis Scenarios Conducted

There are many computer programs available for a life cycle cost analysis study and even spreadsheets can be developed based on standard engineering economic approaches. The life cycle cost analysis calculations presented herein were completed using a Caltrans RealCost program, which was originally developed by the Federal Highway Administration.[19] Caltrans calibrated and revised the program, suited for the California applications. In this study, both the deterministic and probabilistic approaches were analyzed. Before describing the scenarios investigated, an overview of the general features of each is described along with the assumptions.

Scenario overview

Several features were common to each analysis. These are described below:

- A 20-year analysis period was selected based on the maintenance and rehabilitation schedule in Caltrans' life cycle cost analysis manual.
- A discount rate of 4 percent is used in the life cycle cost analysis of Caltrans standard procedures.
- User costs include travel time costs and vehicle operating costs incurred by the traveling public, which is based on the lane closure, traffic volumes, and traffic delays.
- Routine (preventive) maintenance may be applied between major rehabilitation activities based on Caltrans' experience.
- The remaining service life value (salvage value) of a project alternative at the end of the analysis period is calculated by prorating the total construction cost of the last scheduled rehabilitation activity.
- All costs were converted to present worth terms to compare asphalt rubber and non-asphalt rubber alternatives by per lane mile cost.

In addition, several assumptions and simplifications were necessary. These are listed below:

- Maintenance was applied as indicated in Caltrans' life cycle cost analysis manual. Once triggered, maintenance costs continued until the next major rehabilitation activity.
- The rehabilitation hot mix asphalt pavement design lives are from the life cycle cost analysis manual as well as Caltrans' highway design manual.[20]

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

Scenarios investigated

All the rubberized hot mix asphalt project information in the Caltrans project database from the Caltrans' 12 districts shown in FIGURE 4 were collected. Table 1 contains data from Districts 1, 2, and 3 representing Northern California. Table 2 includes Districts 4, 5, 6, 9 and 10 representing Central California. Table 3 contains Districts 7, 8, 11 and 12 representing Southern California. When conducting the detailed project life cycle cost analysis, the following climate regions were considered: coastal, inland valley, desert, low mountains and south mountains, high mountains, and high desert regions.

FIGURE 4 Caltrans' 12 Districts Map

TABLE 1 Northern California RHMA Projects for Life Cycle Cost Analysis Study

District	Contract Number	County	Route	Post Miles	start year	Treatment Life	Functional Class
1	01-2909U4	Lake	20	0.6-5.6	1995	13	Us Route
	01-322104?	Mendocino	101	0.8-5.0	1994	14	Us Route
	01-322104?	Mendocino	101	0.8-5.0	1994	8	Us Route
2	02-372304	SHA	299	96.6-112.7	2000	9	State Route
	02-4C6204	SHA	299	67.8-77.9	2008	in service	State Route
	02-387304	SHA	5	58-67	2006	in service	Interstate
	02-328034	SHA	5	R15.1-R15.7	2008	in service	Interstate
	02-1C8204	PLU	36	R14.0-18.4	2006	in service	State Route
	02-3C2004	LAS	36	24.4-29.4	2006	in service	State Route
	02-381604	LAS	395	30.7-56.7	2007	in service	Us Route
	02-3C4804	MOD	299	37.5-40.6	2007	in service	State Route
3	03-2C5704	NEV	80	0-2.6	2002	8	Interstate
	03-2C5704	NEV	80	0-2.6	2002	9	Interstate
	03-2M1004	YUB	20	R1.9-6.6	2006	6	State Route
	03-2M1004	YUB	20	R1.9-6.6	2006	5	State Route
	03-4A5704	YUB	70	18.9-20	2006	in service	State Route

Note: "In service" means that the rubberized hot mix asphalt-surfaced road is still in good condition. Projects placed later than 2008 were not selected for this study.

TABLE 2 Central California RHMA Projects for Life Cycle Cost Analysis Study

District	Contract Number	County	Route	Post Miles	start year	Treatment Life	Functional Class
4	04-132164	SCR	17	6	1996	15	State Route
	04-0C2604	SOL	12	0-4.8	1997	14	State Route
	04-173744	SON	116	58.6-63.2	1999	12	State Route
	04-045034	ALA	92	3.7-10.3	2000	11	State Route
	04-0C4704	SON	12	17.7-R25.7	2000	9	State Route
	04-0C3804	ALA	13	6.9-15.4	2000	11	State Route
	04-0C3904	ALA	61	R24.1-28.9	2000	11	State Route
	04-0C4804	SON	37	0.5-3.2	2000	11	State Route
	04-0C3404	SON	1	0-13.5	2000	11	State Route
	04-0C5304	ALA	84	R5.2-R9.7	2000	11	State Route
	04-0C4204	CC	580	0-10	2000	11	Interstate
	04-172604	SCl	237	12.1-13.7	2000	11	State Route
	04-0C2704	SOL	780	1.1-11.9	2001	10	Interstate
	04-0T0504	SOL	80	0.9-6.4	2001	10	Interstate
	04-0C7024	ALA	880	24.6-44.5	2000	11	Interstate
	04-0C7014	ALA	880	3.7-24.6	2000	11	Interstate
	04-175904	SM	82	25.4-33.5	2003	8	State Route
	04-2285U4	CC	680	25.1-39.1	2003	8	Interstate
	04-1R9404	ALA	61	30.1-31.9	2003	8	State Route
	04-272614	ALA	84	29.5-32.8	2004	7	State Route
	04-0C7804	SCL	680	0-16	2004	7	Interstate
	04-0C7704	SCL	280	R0-R4.4	2004	7	Interstate
	04-0C7104	CC	4	41.5-49.9	2004	7	State Route
	04-270204	CC	123	0-3.5	2005	6	State Route
	04-0C6804	Ala	24	R2.9-10	2005	6	State Route
	04-0C7604	SCl	152	35.3-48.9	2006	5	State Route
	04-0C6904	ALA	680	R12.4-R18	2006	5	Interstate
	04-0C7204	CC	4	R4.9-R16.8	2008	3	State Route
	04-2A9904	SF	280	0-R7.5	2008	3	Interstate
5	05-486804	SLO	229	0-14.8	2000	11	State Route
6	06-387504	KER	58	R50.6-R64.3	1997	14	State Route
	06-375504	FRE	168	VAR	1997	14	Interstate
	06-380904	TUL,FRE	99, 201, 245	VAR	1998	13	State Route
	06-413104	TUL,FRE	201, 168, 198	VAR	1999	12	State Route
	06-427604	KER	14, 58	VAR	1999	12	State Route
	06-486004	FRE	5	48.6-65.8	2004	5	Interstate
	06-493104	FRE	33	42-60.5	2004	7	State Route
	06-479904	FRE	168	40.4-46.6	2004	7	State Route
	06-480104	KER	58	R129-R139	2004	7	State Route
	06-493504	TUL	99, 201	42-47	2005	6	State Route
	06-480004	KER	58	136.4-143.8	2005	6	State Route
	06-0F4304	KIN	33	12.5-17.1	2006	5	State Route
9	09-233704	Mono	395	69.6-75.0	1995	10	Us Route
	09-233704	Mono	395	69.6-75.0	1995	13	Us Route
10	10-426014	San Joaquin	4	25.6-31.5	1998	10	State Route
	10-279604	San Joaquin	26	1.8-24.0	1999	12	State Route
	10-0A9004	Stanislaus	132	27.0-45.1	2000	7	State Route
	10-461204	Merced	33	21.6-26.1	1997	13	State Route
	10-489804	Merced	99	8.8-12.8	1996	10	State Route
	10-380004	Amador	88	8.8-23.0	1997	13	State Route
	10-1A0904	Mariposa	49	0.5-29.8	1999	12	State Route

TABLE 3 Southern California RHMA Projects Selected for Life Cycle Cost Analysis Study

District	Contract Number	County	Route	Post Miles	start year	Treatment Life	Functional Class
7	07-176304	Los Angeles	1	0.2-10.9	2000	8	State Route
	07-176304	Los Angeles	1	0.2-10.9	2000	9	State Route
	07-176304	Los Angeles	1	0.2-10.9	2000	6	State Route
	07-115534	Los Angeles	1	9.1-11.6	1996	12	State Route
	07-199804	Los Angeles	1	18.7-35.3	2000	7	State Route
	07-203304	Los Angeles	5	37.9-46.2	2000	9	Interstate
	07-1Y0204	Los Angeles	5	60.2-68.7	2003	7	Interstate
	07-115044	Los Angeles	60	25.4-30.5	1996	9	State Route
	07-201104	Los Angeles	101	0.0-43.8	2000	10	Us Route
	07-1Y1704	Los Angeles	138	25.8-33.8	2001	10	State Route
	07-184404	Los Angeles	213	5.5-11.3	2000	9	State Route
	07-1384U4	Los Angeles	710	10.7-15.5	2000	7	Interstate
	07-4E5204	Ventura	101	6.3-37.2	2000	10	Us Route
	07-4E5204	Ventura	101	6.3-37.2	2000	11	Us Route
	07-211104	Ventura	118	0.8-17.2	2005	5	State Route
	07-1Y3804	Ventura	126	27.7-33.1	2006	3	State Route
8	08-000414	Riverside	74	71.4-75.5	1996	10	State Route
	08-495104	San Bernardino	40	4.8-24.1	2000	9	Interstate
	08-407104	San Bernardino	95	92.3-129.4	1996	9	Us Route
	08-360704	San Bernardino	395	29.1-68.7	1996	10	Us Route
	08-360704	San Bernardino	395	29.1-68.7	1996	13	Us Route
11	11-211714	San Diego	5	1.9-10.1	1999	11	Interstate
	11-076504	San Diego	8	0.8-1.9	2000	9	Interstate
	11-241134	San Diego	15	34.9-75.3	2001	10	State Route
	11-202804	San Diego	67	6.3-14.8	1997	7	State Route
	11-067704	San Diego	67	22.1-24.4	1996	8	State Route
	11-241184	San Diego	67	6.3-29.8	2004	4	State Route
	11-231904	San Diego	78	0.0-9.2	1998	8	State Route
	11-231904	San Diego	78	0.0-9.2	1998	9	State Route
	11-231904	San Diego	78	0.0-9.2	1998	10	State Route
	11-077104	San Diego	78	9.2-18.8	2000	10	State Route
	11-077104	San Diego	78	9.2-18.8	2000	7	State Route
	11-059004	San Diego	78	45.2-51.1	1995	4	State Route
	11-059004	San Diego	78	45.2-51.1	1995	8	State Route
	11-241154	San Diego	78	43.1-57.1	2003	8	State Route
	11-178504	San Diego	78	57.1-60.0	2001	7	State Route
	11-217404	San Diego	79	0.0-32.5	1997	12	State Route
	11-222904	San Diego	94	39.6-62.8	1998	9	State Route
	11-222904	San Diego	94	39.6-62.8	1998	11	State Route
	11-237204	Imperial	8	16.2-66.0	2000	7	Interstate
	11-067604	Imperial	78	34.1-43.9	1998	10	State Route
	11-228404	Imperial	86	0.0-9.2	2000	10	State Route
	11-194854	Imperial	86	27.7-33.6	1995	16	State Route
	11-172504	Imperial	115	3.2-9.2	1994	13	State Route
12	12-064614	ORA	1	6.3-11.8	1997	12	State Route
	12-030004	ORA	1	R23.1-26.1	1997	14	State Route
	12-0G0004	ORA	1	31.8-38.2	2005	6	State Route
	12-0F2004	ORA	39	5.3-14.2	2003	8	State Route
	12-087204	ORA	133	0.5-15.3	1998	13	State Route
	12-087504	ORA	74	0.4-3.2	1998	13	State Route
	12-083504	ORA	74	4.2-26.7	1998	13	State Route
	12-0F1904	ORA	5	48.8-50.5	2003	8	Interstate
	12-0F9504	ORA	5	23.9-R24.8	2006	5	Interstate

The material cost information was summarized by district shown in TABLE 4 which shows that the cost of the project for rubberized hot mix asphalt and hot mixed asphalt varies based on the historical Caltrans data over the past three years. The costs will be depending on the size and location of the projects. Generally, the rubberized asphalt project will be more expensive than the conventional asphalt, which is reasonable. However, sometime, a rubberized asphalt project during construction session may cost less than an asphalt project in an off construction season. For the purpose of comparison analysis, rubberized asphalt should use the higher cost.

TABLE 4 Summarized Cost Information Based on Size of Projects for Each District

Districts	Size of Project	HMA		RHMA	
		Average ($/ton)	Standard Deviation($/ton)	Average ($/ton)	Standard Deviation($/ton)
1	Large	93.43	21.89	113.01	20.99
2	Large	92.82	16.46	92.82	16.46
	Medium	98.40	15.67	91.00	22.64
	Small	104.49	16.84	103.33	16.84
3	Large	70.93	18.10	84.10	14.38
	Medium	79.47	19.61	80.29	19.61
4	Large	77.37	12.59	97.75	8.86
	Medium	84.71	16.68	105.18	11.60
5	Large	92.82	16.42	85.65	4.26
	Medium	98.50	15.61	91.05	22.60
	Small	104.79	16.86	103.50	16.86
6	Large	71.60	15.47	91.25	6.23
	Medium	90.76	12.30	86.98	4.63
7	Large	86.47	10.2	95.97	15.85
	Medium	82.9	30.15	108.86	12.49
	Small	87.78	14.33	91.17	19.93
8	Large	68.8	10.13	82.49	14.39
	Medium	85.65	31.44	85.85	11.81
	Small	88.42	18.36	102.07	19.81
9	Large	95.97	10.2	98.23	15.6
10	Large	67.81	19.97	79.75	14.45
	Medium	69.54	16.63	85.25	16.01
	Small	113.12	54.7	99.2	44.12
11	Large	78.99	12.4	95.5	15.69
	Medium	79.08	7.9	102.09	10.16
	Small	115.58	33.25	141.82	30.48
12	Large	63.03	3.53	83.82	6.41
	Medium	69.59	0.57	78.19	18.53
	Small	87.83	16.30	95.02	19.69

Results

The final results using Caltrans' RealCost software are summarized in Tables 5 to 9. The results are organized by functional class and size of the project for each Caltrans district. The functional classes are interstate highways, state routes, and U.S. highways. The sizes of the projects are large (more than 10 lane miles) and medium (4 to 10 lane miles). For each table, Alternative 1 is the Caltrans capital maintenance conventional overlay and Alternative 2 is the Caltrans capital maintenance rubberized hot mix asphalt overlay. Both Deterministic and Probabilistic results are presented. The percent savings represent the percentage of the total cost saving over conventional hot mix asphalt by using rubberized hot mix asphalt. The higher the percent saving, the more cost-effective the rubberized asphalt becomes. The undiscounted sum means the costs without discount rate considered. Also, Caltrans District 1 didn't have enough information for interstate highway and state route rubberized hot mix asphalt life cycle cost analyses.

Table 5 shows the comparison results of the large projects on interstate highways for each district. The life cycle cost analysis results illustrate that rubberized hot mix asphalt is more cost-effective than conventional mix over the 20-year analysis period. The percent saving are ranging from 5 percent to 30 percent of the conventional hot mix asphalt project costs.

Table 6 shows the life cycle cost analysis results of the medium-size projects on interstate highways for all Caltrans districts. The results demonstrate the cost saving of the rubberized hot mix asphalt using asphalt rubber. The percent of savings ranges from 3 percent to 32 percent.

Table 7 shows the life cycle cost analysis results of the large-size projects on state routes for Caltrans districts. In almost all cases the rubberized hot mix asphalt is more cost-effective than the conventional hot mix asphalt except in District 3. The percent cost savings are ranged from -5 percent to as high as about 40 percent. The current rubberized hot mix asphalt life is about six years. In order to be cost-effective, the pavement life needs to be seven years, based on a trial Caltrans RealCost run.

Table 8 shows the life cycle cost analysis results of the medium-size projects on state routes for Caltrans districts. All districts have shown to have cost benefits by using Asphalt Rubber. The life cycle cost analysis results have shown the cost savings from 3 percent to 36 percent over conventional hot mix.

Table 9 shows the life cycle cost analysis results of the large-size projects on U.S. routes for Caltrans districts. Only Districts 1 and 9 have used rubberized hot mix asphalt. The results have shown that the asphalt rubber has significant cost savings over conventional hot mix. The percent saving over 20 years could be as high as 39 percent.

There weren't many small rubberized hot mix asphalt projects because they require additional equipment and modified plant procedures. It is not cost-effective to do small projects for Caltrans.

TABLE 5 Life Cycle Cost Analysis Results for Large Interstate Projects

Large Project												
District	**Deterministic Results**						**Probabilistic Results**					
2		**Alternative 1: 5 year CAPM HMA Overlay**		**Alternative 2: 6 yr CAPM RHMA overlay**				**Alternative 1: 5 year CAPM HMA Overlay**		**Alternative 2: 6 yr CAPM RHMA overlay**		
	Total Cost (Present Value)	**Agency Cost/ln mile ($1000)**	**User Cost/ln mile ($1000)**	**Agency Cost/ln mile ($1000)**	**User Cost/ln mile ($1000)**	**Percent Savings**	**Total Cost (Present Value)**	**Agency Cost/ln mile ($1000)**	**User Cost/ln mile ($1000)**	**Agency Cost/ln mile ($1000)**	**User Cost/ln mile ($1000)**	**Percent Savings**
	Undiscounted Sum	$466.50	$1.65	$422.32	$0.70	10%	Mean	$417.60	$1.52	$396.65	$0.68	5%
	Present Value	$417.18	$1.52	$396.13	$0.68	5%	Standard Deviation	$38.60	$0.11	$39.14	$0.04	
	EUAC	$30.70	$0.11	$29.15	$0.05	5%						
3		**Alternative 1: 5 year CAPM HMA Overlay**		**Alternative 2: 8 year CAPM RHMA Overlay**				**Alternative 1: 5 year CAPM HMA Overlay**		**Alternative 2: 8 year CAPM RHMA Overlay**		
	Undiscounted Sum	$406.55	$1.57	$349.27	$0.59	14%	Mean	$359.52	$1.44	$311.94	$0.55	13%
	Present Value	$359.35	$1.44	$311.51	$0.55	14%	Standard Deviation	$39.14	$0.11	$26.46	$0.03	
	EUAC	$26.44	$0.11	$22.92	$0.04	14%						
4		**Alternative 1: 5 year CAPM HMA Overlay**		**Alternative 2: 8 year CAPM RHMA Overlay**				**Alternative 1: 5 year CAPM HMA Overlay**		**Alternative 2: 8 year CAPM RHMA Overlay**		
	Sum	$385.73	$2.71	$325.51	$1.12	16%	Mean	$353.33	$2.59	$306.26	$1.09	14%
	Present Value	$353.24	$2.59	$303.52	$1.09	14%	Standard Deviation	$37.03	$0.19	$64.01	$0.14	
	EUAC	$25.99	$0.19	$22.33	$0.08	14%						
6		**Alternative 1: 5 year CAPM HMA Overlay**		**Alternative 2: 10 year CAPM RHMA Overlay**				**Alternative 1: 5 year CAPM HMA Overlay**		**Alternative 2: 10 year CAPM RHMA Overlay**		
	Undiscounted Sum	$412.55	$3.25	$291.39	$1.22	30%	Mean	$364.65	$2.97	$269.56	$1.17	26%
	Present Value	$363.23	$2.97	$262.19	$1.16	28%	Standard Deviation	$39.41	$0.17	$66.34	$0.15	
	EUAC	$26.73	$0.22	$19.29	$0.09	28%						
7		**Alternative 1: 5 year CAPM HMA Overlay**		**Alternative 2: 8 year CAPM RHMA Overlay**				**Alternative 1: 5 year CAPM HMA Overlay**		**Alternative 2: 8 year CAPM RHMA Overlay**		
	Undiscounted Sum	$407.82	$4.30	$332.78	$1.79	19%	Mean	$368.39	$4.02	$304.34	$1.73	18%
	Present Value	$368.45	$4.03	$304.03	$1.73	18%	Standard Deviation	$37.62	$0.29	$26.23	$0.08	
	EUAC	$27.11	$0.30	$22.37	$0.13	18%						
8		**Alternative 1: 5 year CAPM HMA Overlay**		**Alternative 2: 9 year CAPM RHMA Overlay**				**Alternative 1: 5 year CAPM HMA Overlay**		**Alternative 2: 9 year CAPM RHMA Overlay**		
	Undiscounted Sum	$415.15	$1.62	$328.72	$0.63	21%	Mean	$364.89	$1.49	$291.32	$0.60	20%
	Present Value	$364.23	$1.49	$289.47	$0.60	21%	Standard Deviation	$39.25	$0.13	$49.59	$0.06	
	EUAC	$26.80	$0.11	$21.30	$0.04	21%						
11		**Alternative 1: 5 year CAPM HMA Overlay**		**Alternative 2: 9 yr CAPM RHMA overlay**				**Alternative 1: 5 year CAPM HMA Overlay**		**Alternative 2: 9 yr CAPM RHMA overlay**		
	Undiscounted Sum	$386.68	$1.69	$303.03	$0.66	22%	Mean	$354.09	$1.62	$280.96	$0.65	21%
	Present Value	$354.19	$1.62	$280.07	$0.64	21%	Standard Deviation	$36.86	$0.14	$45.40	$0.07	
	EUAC	$26.06	$0.12	$20.61	$0.05	21%						
12		**Alternative 1: 5 year CAPM HMA Overlay**		**Alternative 2: 6 year CAPM RHMA Overlay**				**Alternative 1: 5 year CAPM HMA Overlay**		**Alternative 2: 6 year CAPM RHMA Overlay**		
	Sum	$377.53	$225.47	$360.03	$125.39	19%	Mean	$345.21	$250.80	$342.88	$122.77	22%
	Present Value	$345.04	$213.89	$341.58	$123.29	17%	Standard Deviation	$36.18	$79.78	$48.04	$35.99	
	EUAC	$25.39	$15.74	$25.13	$9.07	17%						

TABLE 6 Life Cycle Cost Analysis Results for Interstate Medium Projects

Medium Project												
District	Deterministic Results						Probabilistic Results					
		Alternative 1: 5 year		Alternative 2: 6 yr				Alternative 1: 5 year		Alternative 2: 6 yr		
2	Total Cost (Present Value)	Agency Cost/ln mile ($1000)	User Cost/ln mile ($1000)	Agency Cost/ln mile ($1000)	User Cost/ln mile ($1000)	Percent Savings	Total Cost (Present Value)	Agency Cost/ln mile ($1000)	User Cost/ln mile ($1000)	Agency Cost/ln mile ($1000)	User Cost/ln mile ($1000)	Percent Savings
	Undiscounted Sum	$518.40	$1.73	$482.00	$0.78	7%	Mean	$466.70	$1.59	$454.52	$0.76	3%
	Present Value	$466.76	$1.59	$454.94	$0.76	3%	Standard Deviation	$45.46	$0.12	$43.08	$0.05	
	EUAC	$34.35	$0.12	$33.48	$0.06	3%						
3		Alternative 1: 5 year CAPM HMA Overlay		Alternative 2: 8 year CAPM RHMA overlay				Alternative 1: 5 year CAPM HMA Overlay		Alternative 2: 8 year CAPM RHMA overlay		
	Undiscounted Sum	$430.17	$1.70	$362.80	$0.72	16%	Mean	$382.81	$1.56	$325.87	$0.69	15%
	Present Value	$381.20	$1.56	$323.59	$0.68	15%	Standard Deviation	$41.87	$0.12	$25.04	$0.03	
	EUAC	$28.05	$0.12	$23.81	$0.05	15%						
4		Alternative 1: 5 year CAPM HMA Overlay		Alternative 2: 8 year CAPM RHMA Overlay				Alternative 1: 5 year CAPM HMA Overlay		Alternative 2: 8 year CAPM RHMA Overlay		
	Undiscounted Sum	$407.06	$2.76	$343.48	$1.15	16%	Mean	$374.18	$2.64	$325.73	$1.12	13%
	Present Value	$373.72	$2.64	$320.95	$1.12	14%	Standard Deviation	$40.28	$0.19	$69.36	$0.15	
	EUAC	$27.50	$0.20	$23.62	$0.08	14%						
6		Alternative 1: 5 year CAPM HMA Overlay		Alternative 2: 10 year CAPM RHMA Overlay				Alternative 1: 5 year CAPM HMA Overlay		Alternative 2: 10 year CAPM RHMA Overlay		
	Undiscounted Sum	$443.77	$3.11	$301.48	$1.24	32%	Mean	$393.67	$2.84	$278.92	$1.18	29%
	Present Value	$392.14	$2.84	$271.13	$1.18	31%	Standard Deviation	$41.01	$0.17	$70.02	$0.16	
	EUAC	$28.85	$0.21	$19.95	$0.09	31%						
7		Alternative 1: 5 year CAPM HMA Overlay		Alternative 2: 8 year CAPM RHMA Overlay				Alternative 1: 5 year CAPM HMA Overlay		Alternative 2: 8 year CAPM RHMA Overlay		
	Undiscounted Sum	$433.95	$3.19	$345.73	$1.37	21%	Mean	$393.35	$2.98	$316.76	$1.32	20%
	Present Value	$392.96	$2.99	$315.92	$1.32	20%	Standard Deviation	$43.28	$0.22	$26.68	$0.06	
	EUAC	$28.92	$0.22	$23.25	$0.10	20%						
8		Alternative 1: 5 year CAPM HMA Overlay		Alternative 2: 9 year CAPM RHMA Overlay				Alternative 1: 5 year CAPM HMA Overlay		Alternative 2: 9 year CAPM RHMA Overlay		
	Undiscounted Sum	$444.17	$1.59	$344.81	$0.71	22%	Mean	$391.87	$1.46	$306.73	$0.68	22%
	Present Value	$391.21	$1.46	$304.18	$0.67	22%	Standard Deviation	$45.00	$0.13	$49.62	$0.06	
	EUAC	$28.79	$0.11	$22.38	$0.05	22%						
11		Alternative 1: 5 year CAPM HMA Overlay		Alternative 2: 9 yr CAPM RHMA overlay				Alternative 1: 5 year CAPM HMA Overlay		Alternative 2: 9 yr CAPM RHMA overlay		
	Undiscounted Sum	$403.81	$1.15	$319.31	$0.47	21%	Mean	$370.62	$1.10	$296.82	$0.46	20%
	Present Value	$370.47	$1.10	$295.74	$0.46	20%	Standard Deviation	$38.39	$0.10	$47.46	$0.05	
	EUAC	$27.26	$0.08	$21.76	$0.03	20%						
12		Alternative 1: 5 year CAPM HMA Overlay		Alternative 2: 6 year CAPM RHMA Overlay				Alternative 1: 5 year CAPM HMA Overlay		Alternative 2: 6 year CAPM RHMA Overlay		
	Undiscounted Sum	$398.53	$182.07	$372.81	$109.77	17%	Mean	$365.43	$176.34	$355.27	$89.16	18%
	Present Value	$365.18	$171.90	$354.07	$107.71	14%	Standard Deviation	$37.97	$66.18	$51.78	$35.10	
	EUAC	$26.87	$12.65	$26.05	$7.93	14%						

TABLE 7 Life Cycle Cost Analysis Results for State Route Large Projects

Large Project												
District	Deterministic Results						Probabilistic Results					
2		Alternative 1: 5 year CAPM HMA Overlay		Alternative 2: 6 yr CAPM RHMA overlay				Alternative 1: 5 year CAPM HMA Overlay		Alternative 2: 6 yr CAPM RHMA overlay		
	Total Cost (Present Value)	Agency Cost/ln mile ($1000)	User Cost/ln mile ($1000)	Agency Cost/ln mile ($1000)	User Cost/ln mile ($1000)	Percent Savings	Total Cost (Present Value)	Agency Cost/ln mile ($1000)	User Cost/ln mile ($1000)	Agency Cost/ln mile ($1000)	User Cost/ln mile ($1000)	Percent Savings
	Undiscounted Sum	$466.50	$0.38	$422.32	$0.16	10%	Mean	$417.60	$0.35	$396.65	$0.16	5%
	Present Value	$417.18	$0.35	$396.13	$0.16	5%	Standard Deviation	$38.60	$0.03	$39.14	$0.01	
	EUAC	$30.70	$0.03	$29.15	$0.01	5%						
3		Alternative 1: 5 year CAPM HMA Overlay		Alternative 2: 6 year CAPM RHMA overlay				Alternative 1: 5 year CAPM HMA Overlay		Alternative 2: 6 year CAPM RHMA Overlay		
	Undiscounted Sum	$378.40	$0.40	$375.57	$0.17	1%	Mean	$332.97	$0.37	$350.15	$0.17	-5%
	Present Value	$332.62	$0.37	$349.38	$0.17	-5%	Standard Deviation	$36.21	$0.03	$26.79	$0.01	
	EUAC	$24.47	$0.03	$25.71	$0.01	-5%						
4		Alternative 1: 5 year CAPM HMA Overlay		Alternative 2: 9 yr CAPM RHMA overlay				Alternative 1: 5 year CAPM HMA Overlay		Alternative 2: 9 yr CAPM RHMA overlay		
	Sum	$397.12	$0.77	$317.16	$0.30	20%	Mean	$358.14	$0.73	$292.44	$0.29	18%
	Present Value	$357.75	$0.73	$287.93	$0.29	20%	Standard Deviation	$38.10	$0.06	$69.47	$0.05	
	EUAC	$26.32	$0.05	$21.19	$0.02	20%						
5		Alternative 1: 5 year CAPM HMA Overlay		Alternative 2: 11 year CAPM RHMA Overlay				Alternative 1: 5 year CAPM HMA Overlay		Alternative 2: 11 year CAPM RHMA Overlay		
	Undiscounted Sum	$394.63	$0.16	$259.01	$0.06	34%	Mean	$362.25	$0.15	$236.31	$0.06	35%
	Present Value	$362.14	$0.15	$235.63	$0.06	35%	Standard Deviation	$37.62	$0.01	$43.55	$0.01	
	EUAC	$26.65	$0.01	$17.34	$0.00	35%						
6		Alternative 1: 5 year CAPM HMA Overlay		Alternative 2: 9 year CAPM RHMA Overlay				Alternative 1: 5 year CAPM HMA Overlay		Alternative 2: 9 year CAPM RHMA Overlay		
	Undiscounted Sum	$416.75	$1.54	$333.77	$0.60	20%	Mean	$366.50	$1.41	$298.28	$0.56	19%
	Present Value	$365.83	$1.41	$294.52	$0.56	20%	Standard Deviation	$39.61	$0.10	$71.88	$0.08	
	EUAC	$26.92	$0.10	$21.67	$0.04	20%						
7		Alternative 1: 5 year CAPM HMA Overlay		Alternative 2: 8 year CAPM RHMA Overlay				Alternative 1: 5 year CAPM HMA Overlay		Alternative 2: 8 year CAPM RHMA Overlay		
	Undiscounted Sum	$396.43	$1.82	$319.06	$0.77	20%	Mean	$364.18	$1.75	$298.71	$0.76	18%
	Present Value	$363.94	$1.74	$297.07	$0.76	19%	Standard Deviation	$36.69	$0.15	$60.01	$0.10	
	EUAC	$26.78	$0.13	$21.86	$0.06	19%						
8		Alternative 1: 5 year CAPM HMA Overlay		Alternative 2: 10 year CAPM RHMA Overlay				Alternative 1: 5 year CAPM HMA Overlay		Alternative 2: 10 year CAPM RHMA Overlay		
	Undiscounted Sum	$392.22	$0.13	$286.34	$0.05	27%	Mean	$352.96	$0.12	$257.98	$0.05	27%
	Present Value	$352.85	$0.12	$257.14	$0.05	27%	Standard Deviation	$37.10	$0.01	$44.98	$0.01	
	EUAC	$25.96	$0.01	$18.92	$0.00	27%						
10		Alternative 1: 5 year CAPM HMA Overlay		Alternative 2: 11 year CAPM RHMA Overlay				Alternative 1: 5 year CAPM HMA Overlay		Alternative 2: 11 year CAPM RHMA Overlay		
	Sum	$410.40	$2.34	$241.92	$0.81	41%	Mean	$362.25	$2.15	$223.75	$0.78	38%
	Present Value	$361.08	$2.15	$222.66	$0.77	38%	Standard Deviation	$40.73	$0.17	$40.15	$0.08	
	EUAC	$26.57	$0.16	$16.38	$0.06	38%						
11		Alternative 1: 5 year CAPM HMA Overlay		Alternative 2: 9 yr CAPM RHMA overlay				Alternative 1: 5 year CAPM HMA Overlay		Alternative 2: 9 yr CAPM RHMA overlay		
	Undiscounted	$386.68	$0.13	$303.03	$0.05	22%	Mean	$354.59	$0.13	$282.84	$0.05	20%
	Value	$354.19	$0.13	$280.07	$0.05	21%	Deviation	$36.84	$0.01	$67.71	$0.01	
	EUAC	$26.06	$0.01	$20.61	$0.00	21%						
12		Alternative 1: 5 year CAPM HMA Overlay		Alternative 2: 11 year CAPM RHMA Overlay				Alternative 1: 5 year CAPM HMA Overlay		Alternative 2: 11 year CAPM RHMA Overlay		
	Undiscounted	$377.53	$6.85	$253.86	$16.48	30%	Mean	$345.56	$6.78	$234.22	$11.07	30%
	Present Value	$345.04	$6.56	$230.48	$15.39	30%	Standard Deviation	$37.61	$1.96	$62.63	$4.54	
	EUAC	$25.39	$0.48	$16.96	$1.13	30%						

TABLE 8 Life Cycle Cost Analysis Results for State Routes Medium Size Projects

Medium Project												
Distric	**Deterministic Results**						**Probabilistic Results**					
2		**Alternative 1: 5 year**		**Alternative 2: 6 yr**				**Alternative 1: 5 year**		**Alternative 2: 6 yr**		
	Total Cost	**Agency Cost/ln mile ($1000)**	**User Cost/ln mile ($1000)**	**Agency Cost/ln mile ($1000)**	**User Cost/ln mile ($1000)**	**Percent Savings**	**Total Cost (Present Value)**	**Agency Cost/ln mile ($1000)**	**User Cost/ln mile ($1000)**	**Agency Cost/ln mile ($1000)**	**User Cost/ln mile ($1000)**	**Percent Savings**
	Undiscounted Sum	$518.40	$0.44	$482.00	$0.20	7%	Mean	$466.70	$0.40	$454.52	$0.19	3%
	Present Value	$466.76	$0.40	$454.94	$0.19	3%	Standard Deviation	$45.46	$0.03	$43.08	$0.01	
	EUAC	$34.35	$0.03	$33.48	$0.01	3%						
3		**Alternative 1: 5 year CAPM HMA Overlay**		**Alternative 2: 6 year CAPM RHMA Overlay**				**Alternative 1: 5 year CAPM HMA Overlay**		**Alternative 2: 6 year CAPM RHMA Overlay**		
	Undiscounted Sum	$437.27	$0.39	$390.79	$0.18	11%	Mean	$386.75	$0.36	$365.73	$0.18	5%
	Present Value	$385.64	$0.36	$363.74	$0.18	6%	Standard Deviation	$42.61	$0.03	$25.05	$0.01	
	EUAC	$28.38	$0.03	$26.77	$0.01	6%						
4		**Alternative 1: 5 year CAPM HMA Overlay**		**Alternative 2: 9 yr CAPM RHMA overlay**				**Alternative 1: 5 year CAPM HMA Overlay**		**Alternative 2: 9 yr CAPM RHMA overlay**		
	Undiscounted Sum	$420.07	$0.76	$335.20	$0.30	20%	Mean	$379.42	$0.71	$309.81	$0.29	18%
	Present Value	$379.08	$0.71	$304.85	$0.29	20%	Standard Deviation	$40.40	$0.05	$72.97	$0.04	
	EUAC	$27.89	$0.05	$22.43	$0.02	20%						
5		**Alternative 1: 5 year CAPM HMA Overlay**		**Alternative 2: 11 year CAPM RHMA Overlay**				**Alternative 1: 5 year CAPM HMA Overlay**		**Alternative 2: 11 year CAPM RHMA Overlay**		
	Sum	$414.94	$0.16	$268.11	$0.06	35%	Mean	$381.67	$0.15	$244.56	$0.06	36%
	Present Value	$381.60	$0.15	$244.04	$0.06	36%	Standard Deviation	$39.34	$0.01	$46.72	$0.01	
	EUAC	$28.08	$0.01	$17.96	$0.00	36%						
6		**Alternative 1: 5 year CAPM HMA Overlay**		**Alternative 2: 9 year CAPM RHMA Overlay**				**Alternative 1: 5 year CAPM HMA Overlay**		**Alternative 2: 9 year CAPM RHMA Overlay**		
	Undiscounted Sum	$447.27	$1.55	$310.50	$0.61	31%	Mean	$395.86	$1.42	$290.07	$0.57	27%
	Present Value	$394.31	$1.42	$284.92	$0.57	28%	Standard Deviation	$42.02	$0.11	$68.93	$0.08	
	EUAC	$29.01	$0.10	$20.97	$0.04	28%						
7		**Alternative 1: 5 year CAPM HMA Overlay**		**Alternative 2: 8 year CAPM RHMA Overlay**				**Alternative 1: 5 year CAPM HMA Overlay**		**Alternative 2: 8 year CAPM RHMA Overlay**		
	Undiscounted	$420.94	$1.31	$330.73	$0.56	22%	Mean	$387.54	$1.25	$310.09	$0.55	20%
	Present Value	$387.60	$1.25	$308.20	$0.55	21%	Standard Deviation	$42.34	$0.11	$63.14	$0.07	
	EUAC	$28.52	$0.09	$22.68	$0.04	21%						
8		**Alternative 1: 5 year CAPM HMA Overlay**		**year CAPM RHMA Overlay**				**Alternative 1: 5 year CAPM HMA Overlay**		**Alternative 2: 10 year CAPM RHMA Overlay**		
	Undiscounted	$420.67	$0.13	$300.80	$0.05	29%	Mean	$380.27	$0.12	$272.41	$0.05	28%
	Present Value	$379.68	$0.12	$270.45	$0.05	29%	Standard Deviation	$43.83	$0.01	$46.33	$0.01	
	EUAC	$27.94	$0.01	$19.90	$0.00	29%						
10		**Alternative 1: 5 year CAPM HMA Overlay**		**Alternative 2: 11 year CAPM RHMA Overlay**				**Alternative 1: 5 year CAPM HMA Overlay**		**Alternative 2: 11 year CAPM RHMA Overlay**		
	Undiscounted	$431.42	$2.27	$277.27	$0.81	36%	Mean	$379.90	$2.08	$248.19	$0.77	35%
	Present Value	$379.79	$2.08	$247.43	$0.77	35%	Standard Deviation	$41.11	$0.16	$46.61	$0.09	
	EUAC	$27.95	$0.15	$18.21	$0.06	35%						
11		**Alternative 1: 5 year CAPM HMA Overlay**		**Alternative 2: 9 yr CAPM RHMA overlay**				**Alternative 1: 5 year CAPM HMA Overlay**		**Alternative 2: 9 yr CAPM RHMA overlay**		
	Sum	$403.91	$0.19	$319.31	$0.08	21%	Mean	$370.65	$0.18	$300.71	$0.08	19%
	Present Value	$370.56	$0.18	$295.74	$0.08	20%	Standard Deviation	$38.86	$0.01	$71.80	$0.01	
	EUAC	$27.27	$0.01	$21.76	$0.01	20%						
12		Alternative 1: 5 year		Alternative 2: 11 year				Alternative 1: 5 year		Alternative 2: 11 year		
	Undiscounted	$398.53	$4.42	$260.73	$1.65	35%	Mean	$365.36	$4.23	$240.64	$1.61	34%
	Present Value	$365.18	$4.23	$236.66	$1.59	36%	Standard Deviation	$36.31	$0.34	$71.12	$0.27	
	EUAC	$26.87	$0.31	$17.41	$0.12	36%						

TABLE 9 Life Cycle Cost Analysis Results for U.S. Routes Large Projects

Large Project												
District	**Deterministic Results**						**Probabilistic Results**					
		Alternative 1: 5 year CAPM HMA Overlay		Alternative 2: 12 yr CAPM RHMA overlay				Alternative 1: 5 year CAPM HMA Overlay		Alternative 2: 12 yr CAPM RHMA overlay		
1	Total Cost (Present Value)	Agency Cost /ln mile($1000)	User Cost /ln mile($1000)	Agency Cost /ln mile($1000)	User Cost /ln mile($1000)	Percent Savings	Total Cost (Present Value)	Agency Cost /ln mile($1000)	User Cost /ln mile($1000)	Agency Cost /ln mile($1000)	User Cost /ln mile($1000)	Percent Savings
	Undiscounted Sum	$406.37	$0.52	$259.75	$0.18	36%	Mean	$367.51	$0.49	$235.80	$0.17	36%
	Present Value	$367.00	$0.49	$232.04	$0.17	37%	Standard Deviation	$39.87	$0.03	$65.84	$0.03	
	EUAC	$27.00	$0.04	$17.07	$0.01	37%						
9		Alternative 1: 5 year CAPM HMA Overlay		Alternative 2: 12 year CAPM RHMA Overlay				Alternative 1: 5 year CAPM HMA Overlay		Alternative 2: 12 year CAPM RHMA Overlay		
	Undiscounted Sum	$420.95	$0.13	$262.98	$0.04	38%	Mean	$373.90	$0.12	$229.87	$0.04	39%
	Present Value	$373.75	$0.12	$229.17	$0.04	39%	Standard Deviation	$37.70	$0.01	$44.79	$0.01	
	EUAC	$27.50	$0.01	$16.86	$0.00	39%						

The life cycle cost analysis probabilistic results can give not only the average comparison, but also variation of results. Life cycle cost analysis gives both mean and standard deviation of the results. As an example, the graphic comparison can be presented for the results of a District 4 large project on Interstate 280 shown in Figure 5. Both probability density curve and cumulative density curve show that Alt 2 rubberized hot mix asphalt costs less (smaller net present value) than Alt 1 conventional hot mix asphalt. One can also calculate that rubberized hot mix asphalt has a 77 percent chance of more being cost-effective than hot mix asphalt (based on that Alt 1 mean value is 0.74 standard deviation to the right of the Alt 2 rubberized hot mix asphalt present worth mean value).

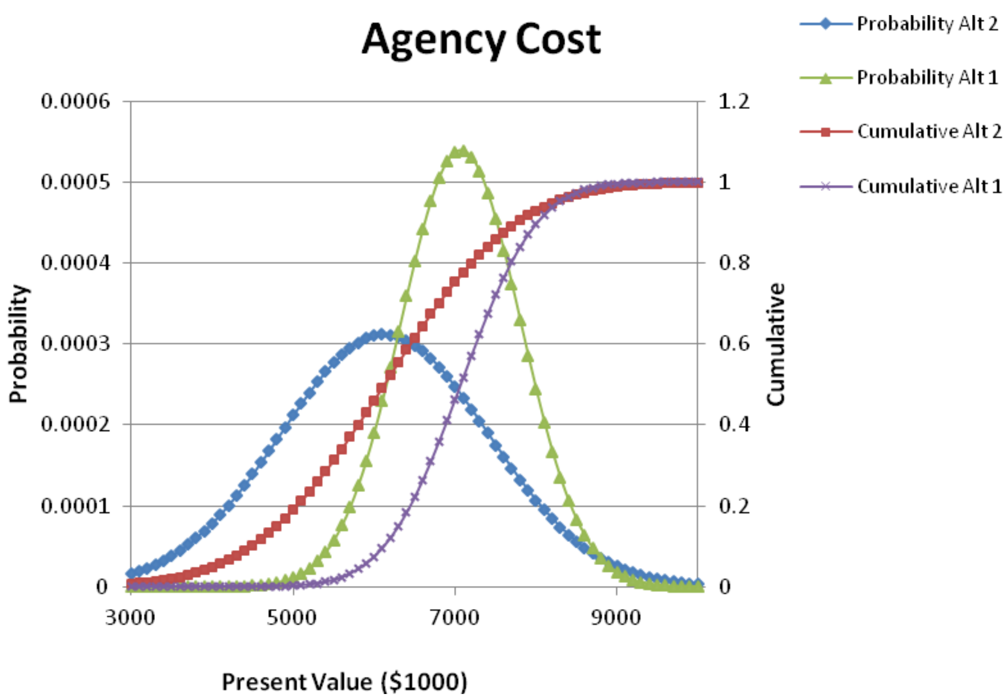

FIGURE 5 LCCA Probabilistic Comparison of Alt 1 Conventional vs Alt 2 rubberized hot mix asphalt

Conclusions and Recommendations

Conclusions

The results of a life cycle cost analysis are highly dependent on the input variables. In the past, these inputs were only best estimates. Obtaining real performance values based on real project data or a pavement management system proved very useful. Based on the information from Caltrans and the results of the analyses, the following conclusions can be drawn:

1. For the scenarios evaluated, asphalt rubber is a cost-effective alternate for most highway pavement applications in the state of California.
2. When variability is considered in the inputs (cost, expected life, etc.), the asphalt rubber alternates would be the best choice in most of the applications considered.
3. Asphalt rubber was not cost-effective in all applications. A life cycle cost analysis allows one to determine when and where asphalt rubber will be cost-effective. For example, in one case, the rubberized hot mix asphalt life needs to increase from six to seven years in order to be cost-effective.
4. The cost-effectiveness of using asphalt rubber depending on the project location and functional class of the road. Different parts of California showed different life cycle cost analysis results.

Recommendations

Agencies intending to use asphalt rubber need to consider performing a life cycle cost analysis to determine whether a proposed application is cost-effective. As demonstrated in this report, the cost-effectiveness of asphalt rubber varies a lot depending on a project's location and functional class.

A limitation of this study is the lack of good long-term performance data for comparative sections of conventional and asphalt rubber mixtures. Assumptions were made to assume conventional hot mix asphalt alternative to be at the same rubberized hot mix asphalt location and with average hot mix asphalt pavement life and costs. Data from comparative test sections would provide more accurate results.

Abbreviations, Acronyms, and Glossary Terms

AASHTO—American Association of State Highway and Transportation Officials

Alt—Alternative

ASTM D-6114—American Society for Testing and Materials "Standard Specification for Asphalt-Rubber Binder"

Caltrans—California Department of Transportation

CHMB—Coarse matrix, high binder

CRM—Crumb rubber modifiers

Demo Project 115—FHWA training course *"*Life Cycle Cost Analysis in Pavement Design*"*

DOT—Department of Transportation

EUAC—Equivalent Uniform Annual Cost

FHWA—Federal Highway Administration

ISTEA—Intermodal Surface Transportation Efficiency Act of 1991

LCCA—Life Cycle Cost Analysis

M&R—maintenance and rehabilitation

NHS—National Highway System

NPV—Net present value

PV—Present value

TEA-21—Transportation Equity Act for the 21st Century

VOC—Vehicle operating costs

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