Energy, Emissions, Material Conservation and Prices Associated with Construction, Rehabilitation and Material Alternatives for Flexible Pavement

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ABSTRACT

Today, public agencies responsible for roads, streets and highways are experiencing significant increases in 1) price of construction operations, 2) asphalt binder availability, 3) limited available funds and 4) uncertainty of inflation. Coupled with significant pressure to build, maintain and rehabilitate "green," agencies must look to alternative construction, rehabilitation and maintenance methods as well as alternative materials that deliver on both of these seemingly different forces.

This paper uses life cycle assessment to evaluate different roadway construction activities. Life cycle assessment is similar to a life cycle cost analysis, expect environmental impact is considered over the analysis period. The life cycle assessment includes energy consumption, emissions generation and natural resource consumption in addition to the price of the activity. All activities evaluated were compared to conventional materials and means of construction. Materials evaluated that were specific to hot mix asphalt included reclaimed asphalt pavement, asphalt shingles and warm mix asphalt. Aggregate base stabilization and subgrade treatments were evaluated as part of a low and high traffic volume facility. The final evaluation considered rehabilitation/maintenance activities that focus on in-place recycling such as hot in-place and cold in-place recycling.

In most instances these activities can reduce energy consumption, emissions generation and conserve natural resources (aggregate and asphalt binder) with the added benefit of reducing the price of construction. These material and technologies show great promise in helping agencies meet the rising price of construction while addressing the publics concern for our environment.

INTRODUCTION

In the current market place, the price of materials that are necessary for the construction, rehabilitation and maintenance (CRM) of our country's aging transportation infrastructure are increasing at rates that exceed our ability to provide funding. Many highway agencies are finding that a dollar is not going as far and as a result, the level of service of our roadway network is suffering. Stimulus funds are providing a temporary injection of funds, but delays in the new transportation bill could keep funding at current levels into 2011. Increased roadway construction costs today are similar to those experienced during the 1970's, but for different reasons. During the 1970's, inflation coupled with rising costs of crude oil were the major drivers for the increased costs of roadway construction. From 1970 to 1979, the average annual rate of inflation was 7.09-percent [1]. This means that it would take 7.09-percent more money to carry out the same amount of work as that performed in the prior year. By comparison, from 1990 to 2008, the average annual rate of inflation has been 2.95-percent. Although inflation is a concern today, in the 1970's agencies had a harder time financing the costs of constructing, rehabilitating and maintaining our Nation's roadways. This was exacerbated by asphalt binder availability and its high price. Today, the major struggle is the price variability of crude oil and asphalt binder availability. In December of 1979, the inflation adjusted price of crude oil peaked at $106.86/barrel (in June 2009 dollars), whereas the average monthly crude oil price for June 2008 delivery was $124.53/barrel (June 2009 crude oil price is $61.46/barrel) [1].

Recently, there has been emphasis placed on energy conservation, the environment and reduction of greenhouse gases. In a March 26, 2008 poll, Gallup found that "although a recession is looming, Americans continue to favor protecting the environment even at the risk of curbing economic development [2]." The emphasis of building "green" is not lost on the highway construction industry. Today, permit conditions for fixed construction material production facilities include provisions for limitations on emissions like PM-10's (particulate matter finer than 10-μm). State and Federal agencies are also implementing stricter standards on engine requirements in efforts to reduce the production of carbon monoxide (CO), nitrogen oxides (NO_x), non-methane hydrocarbons and particulate matter.

State and Federal agencies as well as contractors must find different CRM methods that deliver on these two seemingly different forces (price of construction and environmental concern). As a result of these two forces, there has been a renewed interest in recycling technologies, many of which were developed during the 1970's. These technologies reduce the consumption of natural resources like asphalt binder, aggregate and energy which ultimately reduce impact on the environment and have the added benefit of reducing the price of construction. In the context of CRM, this paper examines various recycled material options, stabilization/treatment of underlying layers in the pavement structure and rehabilitation/maintenance of existing roadways and their impact on the environment as well as the price of construction.

The objectives of this paper is to analyze recycled materials in HMA (RAP, post industrial and post consumer asphalt shingles), stabilization/treatment of pavement layers and rehabilitation/ maintenance methods (cold and hot-in-place recycling) for flexible pavements against standard construction materials and methods. Benefits of each are analyzed from the standpoint of consumption of energy, generation of emissions, conservation of natural resources and price of CRM.

BACKGROUND

The Arab oil embargo that occurred during the 1970's resulted in reduced supplies of asphalt binder which led to its increased price. These conditions stimulated the development of a number of technologies that reduced the price of CRM of our Nation's roadways. One of the technologies included the popularization of using reclaimed asphalt pavement (RAP) in hot mix asphalt (HMA), which was first employed in the early 1900's [3]. The use of RAP reduced the amount of virgin asphalt binder required in HMA mixtures, led to the development and widespread use of cold milling machines, prompted the development of RAP processing techniques and led to the introduction of the drum mix plant [4]. Since the 1970's, the consumption of asphalt binder and road oil has decreased as a percentage of the total energy consumed in the U.S, and only until recently has asphalt binder and road oil returned to 1970 consumption levels [5]. According to the Energy Information Administration (EIA), in 2008, over 1.01×10^{15}-Btu (equivalent to 174.1MM barrels of oil) of energy in the form of asphalt and road oil were consumed mainly in roadway construction activities (1.08×10^{15}-Btu or 186.2-MM barrels of oil in 1970) [5].

There are recycled materials that may be used in the production of HMA that conserve natural resources and preserve the environment. As previously mentioned, RAP is a commonly recycled material incorporated in the production of new HMA. RAP can be generated from a number of different sources including cold milling and full-depth removal operations of existing flexible pavements, as well as plant cross-over (i.e. switching between mixtures and during start-up and shut-down). Utilization of RAP in HMA is the most efficient use of this material as it provides a reduction in virgin asphalt binder and aggregate demand, thus conserving natural resources. Currently, around 75-percent of all State Standard Specifications allow at least 10-percent RAP in HMA surface course mixes and allow for greater than or equal percentages in lower pavement lifts. RAP may also be used as recycled aggregate base and provides an opportunity to reduce the pavement structural section due to its increased strength in comparison to conventional aggregate base.

Another material alternative is recycled asphalt shingles (RAS) in HMA. Depending on the source of the asphalt shingles, the asphalt content may be between 18- and 40-percent, which can significantly reduce the virgin asphalt binder demand of an HMA mixture. At this time, 14 States Standard Specifications or Special Provisions allow for up to 5-percent manufactured and/or tear-off shingles in HMA. There are two types of asphalt shingles: post industrial and post consumer. Post industrial asphalt shingles are rejected asphalt shingles or shingle tabs that are discarded in the manufacturing process of new asphalt shingles. Post consumer asphalt shingles is scrap derived from re-roofing projects whereby the old shingle layers are removed to prepare the roof surface for new shingles and/or other roofing materials [8].

Warm mix asphalt (WMA) is another material related technology that reduces the mixing temperature in comparison to that of HMA and can allow for higher percentages of recycled material to be used. This technology is in its infancy, so information on energy and emissions reductions is limited.

In the construction of new pavements, soft subgrades may be encountered. Such soils offer the opportunity to treat with either lime or cement. By this process issues with plastic clays can be addressed and the strength of the material increased which can be taken advantage of in the pavement design process. Similarly, aggregate bases can be stabilized with an asphalt emulsion or cement. These alternative pavement layers will consume additional natural resources (asphalt emulsion, lime and/or cement), but may be overcome due to a reduced pavement section. Stabilization/treatment of pavement layers is considered in its own section.

During the middle of the 1970's, other recycling technologies were further developed, but because they were not akin to the production and placement of HMA, they did not gain wide acceptance. These technologies include cold in-place recycling (partial depth), full depth reclamation and various forms of hot in-place recycling. For those States that adopted specifications, acceptance was the result of equipment improvements, large cost savings over conventional construction methods and further implementation. The following defines these different in-place recycling technologies and will be considered as rehabilitation/maintenance alternatives in the analyses.

1. **Cold Recycling (CIPR)** (cold in-place recycling-partial depth) – partial depth pulverization of the asphalt bound layers in a pavement, addition of a stabilizer (typically an asphalt emulsion), mixing of the stabilizer and pulverized/sized material, laydown and compaction.
2. **Full Depth Reclamation (FDR)** (cold in-place recycling-full depth) – pulverization of the asphalt bound layers of the pavement and a portion of the granular base course, with or without the addition of a stabilizer (portland cement, lime or asphalt emulsion), spreading and compaction.
3. **Hot In-Place Recycling (HIPR) - Surface Recycling** – softening of the asphalt bound surface through heating and scarified with tines or a milling head. The scarified material is mixed with a recycling agent, placed with standard HMA paver and compacted.
4. **Hot In-Place Recycling - Remixing** – similar to surface recycling, except the scarified/milled material is mixed with new HMA, typically 18- to 23-percent and placed in one layer.
5. **Hot In-Place Recycling - Repaving** – similar to surface recycling however a lift of HMA is placed directly on top of the loose surface recycled material and compacted as one layer.

Nationwide, cold in-place recycling (partial depth) has been employed on four or more projects in 18 States with 12 States having standard specifications or special provisions for CIPR [6]. Ten States have used HIPR for a number of projects while an additional 22 States consider it to be in the experimental stage [7]. Although States specify these technologies, the frequency of their use is varied. The advantage of these technologies is that the recycling occurs at the roadway being rehabilitated, thus reducing the amount of material that must be hauled to the job-site. Natural resources, like asphalt binder and aggregate are conserved as a result. Table 1 summarizes the application of in-place recycling activities.

The environmental advantages of these technologies and materials should be evaluated in the same manner that roadway engineers use life cycle cost analysis (LCCA) to identify the most economical option among CRM alternatives. By coupling environmental impact and the price of construction into one analysis, agencies can identify material, construction and rehabilitation alternatives that meet the publics' desire for protecting the environment while considering their budgets.

Table 1. Advantages, Candidate Roadway Distresses and Limitations of Rehabilitation Alternatives [9].

Rehabilitation and Maintenance Methods	Advantages	Candidates for Recycling	Limitations
Cold In-Place Recycling – Partial Depth	• Significant structural improvements • Addresses most pavement related distresses • Improves ride quality • Hauling costs minimized • Minimal air quality problems • Pavement widening possible • Opportunity to correct geometric/smoothness deficiencies	• Raveling • Potholes • Bleeding • Rutting • Corrugations • Shoving • Ride quality • Cracking (fatigue, longitudinal and transverse)	• Ideal for rural areas due to long recycling train • Ideal for AADT's between 1,000 and 10,000 • Requires significant structural sections • Requires a wearing surface • Must identify cause of distress(es)
Cold In-Place Recycling – Full Depth	• Significant structural improvements • Addresses most pavement related distresses • Improves ride quality • Hauling costs minimized • Minimal air quality problems • Pavement widening possible • Minimal traffic interruptions – short construction time • Opportunity to correct geometric/smoothness deficiencies	• Severe cracking (fatigue, longitudinal and transverse) • Ride quality • Rutting • Corrugations • Shoving • Debonding of layers • Raveling • Potholes • Bleeding • Inadequate structural capacity	• Ideal for low to high volume facilities • Requires a wearing surface
Hot In-Place Recycling	• Eliminates surface cracks • Rutting, shoving and bumps corrected • Aged asphalt is rejuvenated • Aggregate gradation and asphalt content can be modified • Reduced traffic interruption • Hauling costs minimized • Pavement geometrics preserved • Improve surface frictional resistance	• Raveling • Potholes (depending on extent) • Bleeding • Rutting • Corrugations • Shoving • Ride quality	• Ideal for rural areas due to long recycling train • Ideal for AADT's between 1,000 and 10,000 • Pavement should not exhibit extensive cracking • Presence of surface treatments • Some geometric/smoothness deficiencies can not be corrected

SOURCES OF INFORMATION

The analysis requires four sources of information to be reviewed and synthesized which includes energy consumption, emission generation, conservation of natural resources and the price of CRM.

Energy Consumption

The researchers of National Cooperative Highway Research Program (NCHRP) 214 synthesized information available in 1980 for the energy requirements of various construction activities and materials [10]. The NCHRP synthesis provided a complete breakdown of the energy requirements for construction materials processing, construction material production and energy estimates for individual CRM methods. The study also displayed a LCCA approach for various construction alternatives and showed that in-place recycling is an attractive alternative to conventional construction methods in terms of energy conservation (Table 2).

In 2003, the Colas Group synthesized available information on the energy requirements of various CRM methods [11]. The analysis provided an energy requirements breakdown for the manufacture of aggregate and binding agents, production of the material, transport of the material to the project and laydown. The analysis showed that the greatest consumption of energy occurs with the manufacturing of the asphalt binder and production of HMA, approximately 41- and 40-percent, respectively in conventional HMA. The analysis further showed that CIPR and HIPR consumed 83- and 20-percent of the energy required for the production of conventional HMA, respectively. Finally, the analysis showed that by incorporating 20-percent RAP into HMA, that energy requirements for production and placement can be reduced by 14-percent, mainly due to the reduction in virgin asphalt binder demand.

The program Pavement Life-cycle Assessment Tool for Environmental and Economic Effects (PaLATE) provides the framework for the calculation of energy consumption for various construction operations [11]. PaLATE is described as a “life-cycle assessment framework that draws on engineering, environmental, and economic information and data to evaluate the use of virgin and recycled materials in the construction and maintenance of pavements that use different percentages of virgin and recycled materials in the subgrade/subbase and wearing course layers [12].” Energy consumption estimates for materials production in PaLATE are based on information obtained from the Economic Input-Output Life Cycle Assessment (EIO-LCA) model [12, 13]. The energy consumption for a ton of liquid asphalt binder appears to be different than those used in the NCHRP and Colas studies. The NCHRP synthesis gives a ton of asphalt binder an energy value of 600,000-Btu whereas the EIO-LCA indicates a value of 18,000,000-Btu. The difference between the two information sources is that the EIO-LCA model considers the fuel value of asphalt binder. The analysis used in this paper does not consider the fuel value (or sequestered energy) of the asphalt binder. The fuel value of the asphalt binder is the amount of energy that would be released had it been burned. The energy requirements for trucking material are estimated based on the fuel efficiency of the hauling truck and distance from the production facility to the project site. Finally, PaLATE utilizes a methodology that accounts for the horsepower and production of construction equipment to estimate energy consumption. Standard equipment for each operation was identified based on contractor experience and personal contacts.

Granite Construction has developed estimates of energy consumption for various CRM activities based on a synthesis of available information. The estimates include the production of the raw materials, transportation of materials, production and laydown of the materials at the project. Estimates were developed based on typical material constituents and transportation distances.

Based on the available information, a representative range has been identified and a representative value selected for use in the analysis (Table 2). From the four datasets it can be seen that there are differences in the energy requirements for each operation. Data is presented in terms of units per square yard-inch for ease of use when evaluating a roadway. For reference, typical percentages of RAP and asphalt shingles in HMA have been presented.

Emission Generation

The most common measure of greenhouse gas emissions is CO_{2eq}. This unit of measure includes not only the gas CO_2, but also methane (CH_4) and nitrous oxide (N_2O) which the Intergovernmental Panel on Climate Change considers to be contributors to greenhouse gas emissions. The analysis performed in this paper considers only CO_{2eq}, however other emissions are of concern like CO, NO_x, SO_2 and PM-10. These emissions can be determined by methodologies developed by the U.S. Environmental Protection Agency (EPA) and the spreadsheet PaLATE [12].

Two information sources have been used in the following analyses, the Colas study and emissions estimates generated by Granite Construction's analysis [11]. Both sources are syntheses of available information for greenhouse gas emissions in terms of CO_{2eq} for various roadway CRM activities (Table 3). The estimates include the production of the raw materials, transportation of materials, production and laydown of the materials at the project. Note that there are differences in emissions as calculated from the two sources which is likely indicative of differences in assumptions (e.g. haul distance to the project).

Conservation of Natural Resources

The natural resources considered in the analysis were asphalt binder and aggregate. Asphalt binder and aggregate consumption for each CRM method is dependent upon a number of factors and numerous assumptions. Assumptions utilized in the analyses were based on typical values and industry standards.

Table 2. Energy Consumption by CRM Method and Material Alternatives.

Operations	NCHRP 214 (1980) [Ref. 10]	Colas Group (2003) [Ref. 11]	PaLATE (2003) [Ref. 12]	Granite Construction[1]	Representative (Rep.) Range	Rep. Value (Value Used in Analysis)
Construction and Rehabilitation, Btu/yd^2-in						
Cold Milling Asphalt Pavement	1,000 - 2,500		1,800	1,300	1,000 – 2,500	1,800
Hot Mix Asphalt	27,000 - 29,000	32,400	76,108	29,250	27,000 – 34,000	30,000
CIPR - Partial Depth		6,400	24,600	3,100	3,000 – 24,000	12,000
CIPR - Full Depth[2]	15,000 – 20,000	6,200	34,700	1,300 – 11,100	1,300 – 15,000	3,900
HIPR - Scarifying	13,300 - 26,700[2]	26,200[3]	5,700	3,750	3,500 – 27,000	10,500
HIPR – Remixing	13,300 - 26,700[2]	26,200[3]	21,100	9,260	9,000 – 27,000	16,000
HIPR - Repaving	13,300 - 26,700[2]	26,200[3]	43,800	17,460	13,000 – 44,000	24,000
Conventional Aggregate Base	10,000 - 11,500	5,000	9,400	7,260	5,000 – 12,000	10,000
Recycled Aggregate Base			7,800	4,280	4,000 - 8,000	7,800
Emulsion Stabilized Aggregate Base	15,600	16,200	33,000	9,600	9,000 – 33,000	9,600
Cement Stabilized Aggregate Base		14,130		14,020	13,000 - 15,000	14,000
Cement Treated Subgrade				7,922		7,900
Lime Treated Subgrade		3,300		6,937	3,000 – 7,000	5,100
Maintenance, Btu/yd^2						
Crack Seal	1,080 – 2,280			1,900	1,080 – 2,280	1,750
Slurry Seal	1,340			1,620 – 2,830		1,480
Recycled Materials/Additives for Hot Mix Asphalt, Btu/yd^2-in						
RAP	*15% RAP in HMA*		*25% RAP in HMA*		*40% RAP in HMA*	
4% Asphalt Binder Content	28,225		27,042		25,267	
5% Asphalt Binder Content	27,874		26,457		24,332	
Recycled Asphalt Shingles (RAS) - Post Industrial	*2% RAS in HMA*		*5% RAS in HMA*		*7.5% RAS in HMA*	
18% Asphalt Binder Content	29,201		27,772		26,658	
23% Asphalt Binder Content	28,875		27,071		25,781	
RAS - Post Consumer	*2% RAS in HMA*		*5% RAS in HMA*		*7.5% RAS in HMA*	
32% Asphalt Binder Content	28,454		26,136		24,203	
40% Asphalt Binder Content	28,080		25,201		22,801	
Warm Mix Asphalt [Ref. 11][4]	28,742					

[1]Operations involving transportation of materials from the production facility to the job-site include energy consumption for a 20-mile round trip haul distance.

[2]Dependent upon stabilizing agent used (if used).

[3]Does not define the HIPR method.

[4]Does not define the warm mix asphalt additive/method.

Table 3. Emissions Generation By Operation and Material.

Operations	**Colas Group (2003) [Ref. 11]**	**Granite Construction[1]**	**Representative (Rep.) Range**	**Rep. Value (Value Used in Analysis)**
Construction and Rehabilitation, CO_{2eq} lbs/yd^2-in				
Cold Milling Asphalt Pavement	0.084	3.377	0.080 - 3.500	1.730
Hot Mix Asphalt	5.615	5.862	5.600 – 5.900	5.900
CIPR - Partial Depth		0.710		0.711
CIPR - Full Depth[2]	1.082	0.932 – 4.017	0.900 – 4.100	1.354
HIPR - Scarifying	4.425[3]	1.389		1.389
HIPR – Remixing	4.425[3]	2.341		2.341
HIPR - Repaving	4.425[3]	3.759		3.759
Conventional Aggregate Base	1.494	1.553	1.400 – 1.600	1.553
Recycled Aggregate Base		1.436		1.436
Emulsion Stabilized Aggregate Base		2.457		2.457
Cement Stabilized Aggregate Base	5.212	4.267	4.200 - 5.200	4.700
Cement Treated Subgrade		1.868		1.868
Lime Treated Subgrade		1.421		1.421
Maintenance, CO_{2eq} lbs/yd^2				
Crack Seal		0.260		0.307
Slurry Seal		0.742 - 1.332		1.332
Recycled Materials/Additives for Hot Mix Asphalt, CO_{2eq} lbs/yd^2-in				
RAP	*15% RAP in HMA*	*25% RAP in HMA*	*40% RAP in HMA*	
4% Asphalt Binder Content	5.546	5.309	4.955	
5% Asphalt Binder Content	5.499	5.232	4.831	
RAS - Post Industrial	*2% RAS in HMA*	*5% RAS in HMA*	*7.5% RAS in HMA*	
18% Asphalt Binder Content	5.766	5.565	5.398	
23% Asphalt Binder Content	5.735	5.473	5.282	
RAS - Post Consumer	*2% RAS in HMA*	*5% RAS in HMA*	*7.5% RAS in HMA*	
32% Asphalt Binder Content	5.680	5.349	5.073	
40% Asphalt Binder Content	5.630	5.225	4.888	
Warm Mix Asphalt [Ref. 11][4]	5.788			

[1]Operations involving transportation of materials from the production facility to the job-site include emissions generation for a 20-mile round trip haul distance.
[2]Dependent upon stabilizing agent used (if used).
[3]Does not define the HIPR method.
[4]Does not define the warm mix asphalt additive/method.

TABLE 4. Bid Summary.

Operations	California	Colorado	Indiana	Iowa	New Hampshire	New Mexico	South Dakota	Tennessee	Texas	Utah	Washington	Wyoming	Rep. Range	Rep. Value (Value Used in Analysis)
Reference	14	15	16	17	18	19	20	21	22	23	24	25		
New Construction and Rehabilitation, $/yd^2-in														
Cold Milling Asphalt Pavement			0.53			0.52		0.65	0.49	0.23	0.63	0.31	0.30 - 0.70	0.51
Hot Mix Asphalt	5.59	4.16	2.76		3.51			4.29	3.27	4.09	3.94	3.77	2.75 - 5.60	3.65
CIPR - Partial Depth		0.85		1.19			0.88			1.17			0.80 - 1.20	1.24
CIPR - Full Depth		0.31		0.79									0.30 - 0.80	0.55
HIPR - Scarifying		2.30												2.30
HIPR - Remixing		2.81												2.81
HIPR - Repaving		3.00												3.00
Conventional Aggregate Base	0.93	0.99	0.81	0.78	1.01	0.73	0.51	0.80			0.88	0.78	0.50 - 1.05	0.79
Recycled Aggregate Base							0.16							0.43
Emulsion Stabilized Aggregate Base									5.60		3.89		3.80 - 5.60	3.89
Cement Stabilized Aggregate Base	1.89		1.03					0.32	0.80				0.30 - 1.90	1.01
Cement Treated Subgrade						0.42			0.12				0.10 - 0.50	0.27
Lime Treated Subgrade						0.23								0.23
Maintenance, $/yd^2														
Crack Seal	0.83		0.69										0.65 - 0.85	0.76
Slurry Seal	1.76									4.10			1.35 - 2.00	1.76

Construction Price Information

A review of publicly available information from State Department of Transportations was performed to determine typical bid prices for each CRM method considered in the analyses. Prices for CRM alternatives can vary by location, thus a representative range has been provided. Based on the price information from the various sources, a representative value was selected for use in the life cycle assessment (LCA) analyses (Table 4).

Utilizing information derived from State bid prices can be problematic. Bid prices may or may not include factors like asphalt binder, traffic control or mobilization because agencies have separate bid items for these materials and activities. Using information from different forms of CRM must include all relevant prices in order perform accurate comparisons.

The value of RAP and asphalt shingles is dependent upon local market conditions: price of virgin asphalt binder, price of crushed virgin aggregate and the price of processing RAP (or asphalt shingles). Because the price of asphalt binder fluctuates, the value of RAP (and asphalt shingles) is changing almost on a daily basis. The value of RAP and both post industrial and post consumer asphalt shingles were based on 2008 market conditions. It was necessary to use 2008 market conditions as all bid summary information was in 2008 dollars.

PAVEMENT DESIGN

To evaluate alternative CRM activities, the entire pavement structure must be considered by conducting pavement designs specific to the material incorporated (recycled materials will be evaluated on a per ton basis as differences in material strength and performance are considered to be negligible in comparison to conventional materials). Most State agencies use empirical pavement design procedures to determine the appropriate pavement structure given local loading, soils and climatic conditions. The standard pavement design procedures are outlined in the AASHTO Guide for Design of Pavement Structures with States using either the 1972, 1986, 1993 edition or a combination thereof. The 1993 Edition of the AASHTO Guide for Design of Pavement Structures is the current version accepted by AASHTO. The 1993 Edition outlines the pavement design procedure for both new construction as well as rehabilitation of existing flexible pavements [26]. To complement the 1993 Edition, the software package DARWin was developed. DARWin simplifies the empirical design procedure outlined in the 1993 Edition which uses nomographs to determine pavement structural requirements.

Two pavement designs were developed to analyze different traffic levels. The pavement design parameters follow.

ESALs	1,000,000 and 20,000,000
Initial Serviceability	4.2
Terminal Serviceability	2.5
Reliability, percent	95
Overall Standard Deviation	0.45
Roadbed Soil Resilient Modulus, psi	7,500 (CBR of 5)
Needed Structural Number (1,000,000-ESALs)	3.69
Needed Structural Number (20,000,000-ESALs)	5.75

Table 5 provides the structural coefficients for each material for both initial construction and at the time of rehabilitation along with estimated service life of the structural and functional pavement layers. Although the authors have selected a representative value from the representative range for the analyses, designers should select structural coefficients (and energy consumption and emissions generation) that are appropriate for their situation. Using the pavement design parameters above along with the structural coefficients outlined in Table 5, pavement designs were developed using DARWin for analysis of the CRM methods. Analysis of the stabilization/treatment alternatives were evaluated as new construction, whereas rehabilitation/maintenance methods were evaluated as reconstruction of an existing facility.

The 20,000,000-ESAL facility is considered to be a high volume divided freeway with two 12-ft lanes in each direction with a 6-ft paved inside shoulder and 10-ft paved outside shoulder. The 1,000,000-ESAL facility is considered to be a low volume highway which has a single 12-ft lane in each direction with 6-ft paved shoulders.

The results are presented in terms of equivalent square yards. This term reflects the price of construction across the entire width of the pavement. This is the case for cold milling where only the travel lanes are milled. Overlays on the other hand would be placed on the travel lanes as well as the shoulders. Each alternative presented has been normalized to an equivalent square yard by dividing the running yard of highway price by its full width.

Note that all pavement designs for new construction and later rehabilitation/maintenance are based on a design life of 20-years. In other words, all designs consider deterioration of the pavement over time and are reflected in a reduction in the layer coefficient. Based on the reduction in the layer coefficient, rehabilitation alternatives are developed to bring the pavement structure back up to the required structural number (based on methodology outlined in Part III Section 5.4 of the 1993 AASHTO pavement design guide for SN_{eff} from condition Survey for AC pavements) [26]. Although all designs are developed based on a 20-year design life (i.e. perform for 20-years until terminal serviceability is reached), field performance indicates that this is not always realized in the field. The authors recognize the difference in design life and performance life when performing the LCA as a shortcoming of the analysis, however in lieu of better alternative this approach was selected.

LIFE CYCLE ASSESSMENT (LCA)

To perform an LCA, a number of factors must be determined: 1) determine initial construction alternatives, 2) estimate initial life for each alternative, 3) estimate price of each initial alternative, 4) rehabilitation and maintenance options and schedules, 5) estimate life of rehabilitation and maintenance options, 6) estimated price of rehabilitation and maintenance alternatives, 7) discount rate, 8) analysis period and 9) determination of salvage value. Most of these factors have been outlined above. What follows is the selection of the discount rate and the analysis period over which the alternatives were evaluated.

The discount rate accounts for the interest rate (the cost of borrowing money) and the inflation rate (buying power of money). Typically, State agencies use a discount rate between 3- and 5-percent for LCA [28]. However, the Office of Management and Budget suggest that for a 30-year analysis period that a real discount rate of 2.7-percent be used for economic assumptions for the 2009 calendar year (2.7-percent was used in the analysis) [29].

The Federal Highway Administration suggests that the analysis period for an LCA be long enough to include "the initial construction or major rehabilitation action and at least one subsequent rehabilitation action for each alternative [30].” A 40-year analysis period was selected for this study as it will capture at least one major rehabilitation for each alternative.

Non-financial information (emissions, natural resources and energy) is a summation over the analysis period. The price of CRM is discounted back to a net present value. At the end of the analysis period, the existing facility still has residual value and is referred to a salvage value. The salvage value is based on the remaining service life of the pavement and is discounted back to a net present value. Since the analysis uses a real interest rate (yield minus inflation), a constant dollar was used in the analyses.

SPREADSHEET

The analyses presented hereafter were generated from a Microsoft Excel workbook developed by the Granite West Engineering Services Group. All inputs outlined previously for an LCA can be changed to meet individual user needs. Coupled with the software package Crystal Ball, the spreadsheet has the flexibility of performing deterministic and probabilistic analyses. Outputs from the workbook include energy consumption, emissions generation, natural resource consumption (asphalt binder and aggregate) and the price of construction.

LIFE CYCLE ASSESSMENT RESULTS

The tables presented hereafter contain the results of the LCA for the CRM methods. The LCA has been segmented into recycled materials, stabilization/treatment and rehabilitation/maintenance. The recycled materials section evaluates RAP and asphalt shingles in HMA in comparison to conventional HMA. Stabilization/treatment reviews the benefits of stabilizing aggregate base and treatment of subgrades in comparison to conventional pavement sections. Rehabilitation/maintenance evaluates the usage of cold and hot in-place recycling activities in comparison to conventional rehabilitation and maintenance activities.

Recycled Materials in HMA Analysis

Table 6 presents the various recycled materials that were considered in the analysis (RAP, post industrial and post consumer asphalt shingles as well as warm mix asphalt). All comparisons presented are made against conventional HMA. Presented are sensitivities to changes in recycled material content as well as recycled material asphalt binder content, so typical values have been presented.

The use of recycled materials in HMA was assumed not to affect material stiffness as the virgin asphalt binder would be selected to meet local requirements. Recycled aggregates (from RAP or shingles) were considered to be similar to virgin aggregates used in the mixture. Additionally, the analysis did not include a change the price of the virgin asphalt binder when higher percentages of RAP were used in the mix.

The analysis shows that the use of recycled materials in HMA provides both a price savings as well as reduces overall environmental impact. Note that the shown price savings will likely only be obtained when every contractor is able to recycle the material and has a ready supply. Additional savings will also be recognized when different recycled materials and/or WMA are combined. As more information becomes available about WMA, additional environmental savings could be recognized (i.e. NCHRP 9-47 study).

TABLE 5. Pavement Design and Life Cycle Analysis Parameters.

Pavement Layer	Condition	Structural Coefficients			Estimated Service Life, yrs		
		Rep. Range	**Rep. Value**	**ref.**	**Rep. Range**	**Rep. Value**	**ref**
New Construction and Rehabilitation							
Hot Mix Asphalt[1]	New	0.20 – 0.45	0.44	10, 26	12 - 18	14	
	Existing - good condition	0.25 – 0.40	0.34	26			
	Existing – fair condition	0.20 – 0.30	0.25	26			
	Existing - poor condition	0.08 – 0.30	0.15	26			
CIPR – Partial Depth		0.20 – 0.44	0.30	9, 27	7 - 15	11[2]	9
CIPR – Full Depth		0.15 – 0.40	0.20	9	12 - 18	14[2]	9
HIPR - Scarifying			0.40		6 - 10	8	9
HIPR - Remixing			0.40		7 - 14	11	9
HIPR - Repaving			0.40		6 - 15	11	9
Conventional Aggregate Base[1]	New	0.00 – 0.20	0.14	26			
	Existing	0.00 – 0.14	0.08	26			
Recycled Aggregate Base		0.15 – 0.25	0.16				
Emulsion Stabilized Aggregate Base		0.10 – 0.30	0.22	26			
Cement Stabilized Aggregate Base			0.22				
Cement Treated Subgrade			0.16				
Lime Treated Subgrade			0.15				
Maintenance							
Crack Sealing					2 -5	4	
Slurry Seal					3 - 7	4	

[1]Differences in pavement condition are considered during life cycle assessment future rehabilitation and maintenance.
[2]Estimated service life for cold in-place recycling is based on the inclusion of an overlay or surface treatment.

Stabilization/Treatment Analysis

Table 7 present the various alternatives considered for the low and high traffic volume facilities where the supporting pavement structure has either been stabilized or treated. Savings additionally will be dependent upon whether the project being evaluated is a net import or export job. The analysis presented in this paper considers that the pavement structure will be built directly on original grade.

All comparisons are made against the first alternative where all conventional materials have been used. Price of construction and/or environmental savings is recognized with each stabilization/treatment alternative. Similar percent savings are recognized between high and low traffic volume facilities. The HMA layer does not include any recycled materials; additional savings could be recognized with their introduction.

The analysis shows that stabilization or treatment of various pavement layers, savings can be recognized either in the form of price and/or environmental impact. Because there are differences in material strength as measured by resilient modulus, some advantages are available to reduce the pavement structural section in terms of the HMA and/or supporting pavement structure. For instances, States like Colorado and Michigan give credit to the improved load carrying capabilities of recycled aggregate base in comparison to conventional aggregate base by using an increased layer coefficient.

It should be pointed out that during the 2008 construction season there was a considerable spike in the price of asphalt binder which is a component of an emulsion and is reflected in the price of the asphalt emulsion stabilized base. Additionally, the manufacture of cement and emulsion are energy intensive processes and as a consequence there may be more energy consumed when used to stabilize aggregate base, but there are other environmental benefits that should be considered with their use.

Treatment of existing subgrades with either a cement or lime will be dependent upon material gradation and plasticity index. Treatment of the subgrade significantly reduces the amount of import material to the jobsite as reflected in the aggregate quantity savings, with the added benefit of reducing the price of construction.

Rehabilitation/Maintenance Analysis

Tables 8 and 9 show the results of the analysis for the rehabilitation and maintenance alternatives for high and low volume facilities, respectively. These designs were developed based on specific traffic, subgrade soil condition, roadway configuration and rehabilitation approach and are for illustration purposes only. Savings associated with the different technologies will vary based on project specific criteria. Readers should apply previously presented estimates to their project to develop savings.

The analyses have been segmented by the relative condition of the existing facility as measured by a pavement condition index (PCI). Pavement rehabilitation/maintenance activities have been selected based on the distress extent and severity that could be expected to yield those PCI values. The first alternative in each pavement condition segmentation represents the conventional method of rehabilitation/maintenance and forms the basis of comparison for all other alternatives. In almost all respects (energy, emissions, natural resource consumption and price), the alternative rehabilitation/maintenance activities are favorable over conventional methods. Additionally, a comparison between Tables 8 and 9 indicates that savings for both high and low traffic volume facilities are comparable. Note that additional savings could be recognized with the introduction of recycled materials into the HMA.

Readers will likely note that some alternatives do not appear comparable (e.g. Alternatives 1 and 2 in Tables 8 and 9). The designs are based on structural design to provide equivalent pavement sections considering the deterioration of the pavement structure over time. What results are pavement structures that are structurally equivalent, not functionally equivalent.

Designers should consider the pros and cons of each alternative when selecting rehabilitation and maintenance alternatives. Specifically, the distresses found during visual condition surveys should be considered during the LCA process. For instance, facilities that show signs of transverse cracking prior to rehabilitation/maintenance that receives a simple overlay can expect this distress to reflect through to the surface within a couple of years. However, cold in-place recycling – partial depth may be used as a stress absorbing interlayer to retard, if not eliminate the occurrence of reflective cracking.

CONCLUSIONS

Current practices by roadway agencies are to consider the LCCA of various construction alternatives and to select the one that is most economically appealing. In light of the recent changing market conditions and environmental pressures, agencies need to consider adding energy and natural resource consumption as well as emissions generation to the analysis when evaluating construction alternatives.

A number of recycling technologies were developed during the 1970's that helped to reduce the consumption of natural resources and control costs. These technologies include RAP in HMA, cold in-place recycling and hot in-place recycling. Asphalt shingle recycling has also become another source of recycled material for use in HMA. As a result of crude oil price variability and 2008's price spike, there has been a renewed interest in these technologies.

Based on the analyses that were conducted, savings is dependent upon the recycled material and CRM activity employed. Although the technologies presented do not always show across the board savings, there are advantages to the use of alternative materials as well as alternative CRM methods that can deliver on price savings and reduce environmental impact.

Table 6. Recycled Materials in Hot Mix Asphalt Alternative Analysis.

Material / Process	**Recycled Material Content, %**	**RAP / Shingle Asphalt Binder Content, %**	**Value Per Ton of Mix (% Savings)**				
			Price, $	**Energy, Btu**	**CO_{2eq}, lb**	**Asphalt, ton**	**Agg, ton**
Conventional Hot Mix Asphalt	0.0	N/a	64.87 -	533,333 -	104.89 -	0.052 -	0.948 -
Reclaimed Asphalt Pavement (RAP)	15.0	4.0	61.17 (5.71)	501,778 (5.92)	98.59 (6.01)	0.046 (11.54)	0.804 (15.19)
	15.0	5.0	60.43 (6.85)	495,544 (7.09)	97.76 (6.79)	0.045 (14.42)	0.806 (15.03)
	25.0	4.0	58.70 (9.52)	480,741 (9.86)	94.39 (10.01)	0.042 (19.23)	0.708 (25.32)
	25.0	5.0	57.47 (11.41)	470,352 (11.81)	93.01 (11.32)	0.040 (24.04)	0.711 (25.05)
	40.0	4.0	55.00 (15.23)	449,186 (15.78)	88.09 (16.02)	0.036 (30.77)	0.564 (40.51)
	40.0	5.0	53.03 (18.26)	432,563 (18.89)	85.89 (18.11)	0.032 (38.46)	0.568 (40.08)
Post Industrial Asphalt Shingles	2.0	18.0	63.15 (2.65)	517,490 (2.97)	102.51 (2.27)	0.048 (6.92)	0.932 (1.73)
	2.0	23.0	62.66 (3.41)	513,334 (3.75)	101.96 (2.79)	0.047 (8.85)	0.933 (1.62)
	5.0	18.0	60.57 (6.64)	493,724 (7.43)	98.94 (5.67)	0.043 (17.31)	0.907 (4.32)
	5.0	23.0	59.09 (8.91)	481,256 (9.76)	97.29 (7.25)	0.040 (23.08)	0.910 (4.01)
	7.5	18.0	58.41 (9.96)	473,919 (11.14)	95.96 (8.51)	0.039 (25.96)	0.887 (6.49)
	7.5	23.0	56.57 (12.80)	458,335 (14.06)	93.90 (10.48)	0.035 (33.17)	0.890 (6.09)
Post Consumer Asphalt Shingles	2.0	32.0	61.77 (4.78)	505,853 (5.15)	100.97 (3.74)	0.046 (12.31)	0.934 (1.43)
	2.0	40.0	60.98 (5.99)	499,204 (6.40)	100.09 (4.58)	0.044 (15.38)	0.936 (1.27)
	5.0	32.0	57.12 (11.95)	464,633 (12.88)	95.09 (9.34)	0.036 (30.77)	0.914 (3.59)
	5.0	40.0	55.15 (14.98)	448,009 (16.00)	92.89 (11.44)	0.032 (38.46)	0.918 (3.16)
	7.5	32.0	53.24 (17.92)	430,283 (19.32)	90.19 (14.01)	0.028 (46.15)	0.897 (5.38)
	7.5	40.0	50.29 (22.48)	405,347 (24.00)	86.89 (17.16)	0.022 (57.69)	0.903 (4.75)
Warm Mix Asphalt[1]	0.0	N/a	64.37 (0.77)	510,977 (4.19)	102.89 (1.91)	0.052 (0.00)	0.948 (0.00)

[1]Based on limited data.

Table 7. Stabilized Aggregate Base and Treated Subgrade Alternative Analysis.

Alternative	Description	Total Pavement Thickness, in	Value Per Equivalent Square Yard (% Savings)				
			Price, $	Energy, Btu	CO_{2eq}, lb	Asphalt, ton	Agg, ton
Low Volume Facility - 1,000,000-ESALs							
1	5.0-in of Asphalt Concrete on 11.0-in of Conventional Aggregate Base	16.0	26.95 -	229,870 -	46.59 -	0.015 -	0.844 -
2	5.0-in of Asphalt Concrete on 9.5-in of Recycled Aggregate Base	14.5	22.32 (17.17)	201,617 (12.29)	43.40 (6.84)	0.015 (0.00)	0.765 (9.33)
3	5.0-in of Asphalt Concrete on 7.0-in of Emulsion Stabilized Aggregate Base[1]	12.0	45.48 (-68.76)	217,200 (5.51)	46.70 (-0.24)	0.022 (-52.77)	0.626 (25.79)
4	5.0-in of Asphalt Concrete on 7.0-in of Cement Stabilized Aggregate Base	12.0	25.32 (6.03)	248,000 (-7.89)	62.40 (-33.94)	0.015 (0.00)	0.634 (24.88)
5	5.0-in of Asphalt Concrete on 9.5-in of Cement Treated Subgrade	14.5	20.79 (22.83)	225,050 (2.10)	45.75 (1.79)	0.015 (0.00)	0.267 (68.41)
6	5.0-in of Asphalt Concrete on 10.0-in of Lime Treated Subgrade	15.0	20.51 (23.88)	201,000 (12.56)	43.71 (6.17)	0.015 (0.00)	0.267 (68.41)
High Volume Facility - 20,000,000-ESALs							
1	9.0-in of Asphalt Concrete on 13.0-in of Conventional Aggregate Base	22.0	43.13 -	364,392 -	73.30 -	0.026 -	1.162 -
2	8.5-in of Asphalt Concrete on 13.0-in of Recycled Aggregate Base	21.5	36.59 (15.15)	325,634 (10.64)	69.18 (5.62)	0.025 (5.56)	1.136 (2.29)
3	7.5-in of Asphalt Concrete on 11.5-in of Emulsion Stabilized Aggregate Base[1]	19.0	72.10 (-67.19)	335,400 (7.96)	72.51 (1.07)	0.035 (-31.50)	0.991 (14.75)
4	7.5-in of Asphalt Concrete on 11.5-in of Cement Stabilized Aggregate Base	19.0	39.00 (9.58)	386,000 (-5.93)	98.30 (-34.12)	0.022 (16.67)	1.004 (13.66)
5	8.0-in of Asphalt Concrete on 14.0-in of Cement Treated Subgrade	22.0	32.95 (23.60)	350,600 (3.78)	71.15 (2.92)	0.023 (11.11)	0.427 (63.30)
6	9.0-in of Asphalt Concrete on 14.0-in of Lime Treated Subgrade	23.0	36.01 (16.49)	341,400 (6.31)	73.00 (0.40)	0.026 (0.00)	0.480 (58.71)

[1]Price estimate for emulsion stabilized aggregate based on limited tonnages placed in Texas and Washington in 2008.

Table 8. Rehabilitation/Maintenance Alternative Analysis for a High Traffic Volume Roadway (20,000,000 ESALs).

Rehabilitation/Maintenance Alternatives		Value Per Equivalent Square Yard (% Savings)									
		Initial Construction					40-Year Life Cycle Assessment				
		Price, $	**Energy, Btu**	**CO_{2eq}, lb**	**Asphalt, ton**	**Agg, ton**	**Price, $**	**Energy, Btu**	**CO_{2eq}, lb**	**Asphalt, ton**	**Agg, ton**
Pavement in Good Condition (Pavement Condition Index greater than 70)											
1	Mill and Fill 2.0-in and 3.5-in Overlay	18.31 -	147,000 -	29.23 -	0.014 -	0.258 -	32.09 -	308,314 -	60.53 -	0.034 -	0.524 -
2	3.75-in HMA Overlay	13.87 (24.24)	120,000 (18.37)	22.58 (22.77)	0.011 (21.99)	0.200 (22.39)	28.19 (12.17)	325,860 (-5.69)	61.98 (-2.40)	0.034 (0.59)	0.540 (-2.96)
3	CIPR-Partial Depth w/ 2.0-in cut 4.0-in HMA Overlay	16.25 (11.28)	129,799 (11.70)	24.55 (16.03)	0.013 (5.67)	0.213 (17.23)	30.03 (6.44)	291,113 (5.58)	55.84 (7.74)	0.033 (2.64)	0.480 (8.49)
4	HIPR-Surface w/ 1.0-in scarification 3.75-in HMA Overlay	15.22 (16.91)	119,500 (18.71)	23.05 (21.15)	0.011 (21.99)	0.200 (22.39)	30.14 (6.11)	323,610 (-4.96)	62.19 (-2.76)	0.033 (2.05)	0.540 (-2.96)
5	HIPR-Remix w/ 2.0-in scarification 3.5-in HMA Overlay	16.52 (9.81)	126,333 (14.06)	23.77 (18.68)	0.011 (21.28)	0.202 (21.81)	30.30 (5.60)	287,647 (6.70)	55.07 (9.02)	0.031 (9.09)	0.468 (10.74)
6	HIPR-Repave w/ 0.75-in scarification 3.75-in HMA Overlay	17.68 (3.44)	144,500 (1.70)	27.14 (7.17)	0.013 (8.51)	0.237 (8.23)	31.46 (1.97)	305,814 (0.81)	58.43 (3.46)	0.033 (3.52)	0.503 (4.06)
Pavement in Fair Condition (Pavement Condition Index between 55 and 70)											
7	Mill and Fill 4.0-in and 4.0-in Overlay	25.68 -	204,000 -	40.76 -	0.020 -	0.356 -	39.46 -	365,314 -	72.06 -	0.040 -	0.622 -
8	CIPR-Partial Depth w/ 4.0-in cut 5.25-in HMA Overlay	22.46 (12.54)	177,099 (13.19)	32.87 (19.37)	0.019 (5.13)	0.280 (21.24)	36.24 (8.16)	338,413 (7.36)	64.16 (10.96)	0.039 (2.53)	0.547 (12.14)
9	5.75-in HMA Overlay	21.27 (17.16)	184,000 (9.80)	34.62 (15.08)	0.017 (13.85)	0.307 (13.76)	35.59 (9.82)	389,860 (-6.72)	74.02 (-2.72)	0.040 (-0.76)	0.647 (-3.94)
10	2.0-in Mill, 2.0-in HIPR-Remix, 2.0-in Fill, 4.25-in Overlay	24.80 (3.44)	190,833 (6.45)	36.78 (9.78)	0.017 (11.79)	0.313 (12.07)	37.89 (3.99)	348,694 (4.55)	67.15 (6.81)	0.036 (9.62)	0.573 (7.97)
Pavement in Poor Condition (Pavement Condition Index less than 55)											
11	9.0-in HMA on 13.0-in Conv. AB (Remove & Replace)	54.31 -	397,392 -	85.10 -	0.026 -	1.211 -	71.52 -	651,252 -	133.54 -	0.054 -	1.631 -
12	Mill and Fill 7.0-in and 3.25-in Overlay	31.26 (42.44)	244,500 (38.47)	49.21 (42.17)	0.023 (11.79)	0.422 (65.14)	48.22 (32.58)	453,814 (30.32)	89.54 (32.95)	0.048 (11.55)	0.769 (52.87)
13	CIPR-Full Depth w/ 11.0-in cut 6.25-in HMA Overlay	26.83 (50.59)	216,100 (45.62)	46.80 (45.00)	0.027 (-2.28)	0.333 (72.48)	38.57 (46.08)	373,960 (42.58)	77.18 (42.21)	0.046 (15.27)	0.593 (63.63)

Table 9. Rehabilitation/Maintenance Alternative Analysis for a Low Traffic Volume Roadway (1,000,000 ESALs).

Rehabilitation/Maintenance Alternatives		Value Per Equivalent Square Yard (% Savings)									
		Initial Construction					40-Year Life Cycle Assessment				
		Price, $	Energy, Btu	CO_{2eq}, lb	Asphalt, ton	Agg, ton	Price, $	Energy, Btu	CO_{2eq}, lb	Asphalt, ton	Agg, ton
Pavement in Good Condition (Pavement Condition Index greater than 70)											
1	Mill and Fill 2.0-in and 2.0-in Overlay	12.84 -	102,000 -	20.38 -	0.010 -	0.178 -	26.62 -	263,314 -	51.68 -	0.030 -	0.444 -
2	2.5-in HMA Overlay	9.25 (27.97)	80,000 (21.57)	15.05 (26.16)	0.007 (25.51)	0.133 (25.03)	23.56 (11.48)	285,860 (-8.56)	54.45 (-5.37)	0.030 (-2.02)	0.473 (-6.50)
3	CIPR-Partial Depth w/ 2.0-in cut 2.75-in HMA Overlay	11.69 (8.99)	92,299 (9.51)	17.17 (15.75)	0.010 (2.04)	0.147 (17.55)	25.47 (4.34)	253,613 (3.68)	48.47 (6.21)	0.030 (0.34)	0.413 (7.00)
4	HIPR-Surface w/ 1.0-in scarification 2.25-in HMA Overlay	9.74 (24.12)	74,500 (26.96)	14.20 (30.33)	0.007 (31.63)	0.120 (32.51)	24.66 (7.36)	278,610 (-5.81)	53.34 (-3.23)	0.029 (2.36)	0.460 (-3.49)
5	HIPR-Remix w/ 2.0-in scarification 2.25-in HMA Overlay	11.96 (6.88)	88,833 (12.91)	16.40 (19.55)	0.007 (24.49)	0.120 (32.51)	25.74 (3.32)	250,147 (5.00)	47.69 (7.71)	0.027 (7.74)	0.387 (13.01)
6	HIPR-Repave w/ 0.75-in scarification 2.25-in HMA Overlay	9.71 (24.38)	79,500 (22.06)	15.15 (25.65)	0.007 (25.51)	0.134 (24.80)	23.49 (11.76)	240,814 (8.54)	46.45 (10.12)	0.027 (8.08)	0.400 (9.92)
Pavement in Fair Condition (Pavement Condition Index between 55 and 70)											
7	Mill and Fill 4.0-in and 1.75-in Overlay	17.47 -	136,500 -	27.49 -	0.013 -	0.236 -	31.25 -	297,814 -	58.78 -	0.033 -	0.502 -
8	CIPR-Partial Depth w/ 3.0-in cut 3.25-in HMA Overlay	14.34 (17.94)	112,199 (17.80)	20.59 (25.08)	0.012 (7.75)	0.173 (26.41)	28.12 (10.03)	273,513 (8.16)	51.89 (11.73)	0.032 (3.34)	0.440 (12.39)
9	3.5-in HMA Overlay	12.95 (25.88)	112,000 (17.95)	21.07 (23.35)	0.010 (20.93)	0.187 (20.76)	27.26 (12.76)	317,860 (-6.73)	60.47 (-2.87)	0.033 (-0.91)	0.527 (-4.88)
10	2.0-in Mill, 2.0-in HIPR-Remix, 2.0-in Fill, 2.0-in Overlay	16.59 (5.06)	123,333 (9.65)	23.50 (14.50)	0.011 (17.83)	0.178 (24.50)	29.68 (5.04)	281,194 (5.58)	53.88 (8.35)	0.029 (11.55)	0.438 (12.83)
Pavement in Poor Condition (Pavement Condition Index less than 55)											
11	5.0-in HMA on 11.0-in Conv. AB (Remove & Replace)	35.08 -	253,870 -	55.18 -	0.015 -	0.885 -	46.81 -	411,731 -	85.55 -	0.033 -	1.145 -
12	Mill and Fill 3.0-in and 2.75-in Overlay	18.35 (47.69)	145,500 (42.69)	29.10 (47.26)	0.014 (4.79)	0.253 (71.39)	32.13 (31.36)	306,814 (25.48)	60.39 (29.41)	0.034 (-2.11)	0.520 (54.61)
13	CIPR-Full Depth w/ 6.0-in cut 4.0-in HMA Overlay	16.79 (52.13)	135,600 (46.59)	29.02 (47.41)	0.016 (-12.33)	0.213 (75.91)	28.52 (39.06)	293,460 (28.73)	59.39 (30.58)	0.035 (-5.42)	0.473 (58.67)

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