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COMPARATIVE LIFE CYCLE ASSESSMENT BETWEEN WARM SMA AND CONVENTIONAL SMA

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16. Abstract

This report presents the comparative life cycle assessment (LCA) between warm stone mastic asphalt (SMA) and conventional SMA. Specifically, the study evaluated and compared the life cycle environmental and economic performances of two mixtures: a warm SMA binder course mixture with a chemical additive and a control hot SMA binder course mixture. Both of these mixtures were utilized as part of a complete overlay project on the Veterans Memorial Expressway (I-355) near Chicago as part of the Illinois Tollway system.

The results of this study indicate that the warm SMA provides significant environmental benefits compared to the control hot SMA. When the mixing temperature was decreased from 325 to 280 ^{o}F (168 to 138 ^{o}C), the overall environmental impact of the material, production, transportation, and placement was reduced by 6.4% due to the use of warm mix additive. More environmental benefits can be expected if the mixing temperature is further lowered. It was also concluded that using warm mix additive slightly increases the initial construction cost of SMA pavement. However, the warm SMA overlay allows for traffic to be opened earlier, so the user cost caused by traffic delay is reduced, and the total economic cost of the warm SMA is lower than that of the control SMA. In addition, the warm SMA allows for the use of a higher percentage of RAP because of less binder aging. With a 10% increase in RAP usage, the initial construction cost of the warm SMA becomes 3.5% lower than that of the control SMA. The overall performances of the control SMA and the warm SMA were compared by calculating a weighted environmental and economic score and the total cost (environmental, agency, and user costs). Both the weighted score and total cost data show that the warm SMA provides better overall performance compared to the control SMA. Therefore, besides being more environmentally friendly, the warm SMA is also economically competitive compared to the control SMA.

This study didn’t include the cost benefits of the warm SMA due to an extended paving season and longer hauling distance because these benefits are difficult to quantify. In addition, the warm SMA may reduce the risk of poor compaction during construction, which ensures long-term pavement performance, and therefore saves costs related to maintenance and rehabilitation.

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EXECUTIVE SUMMARY

This report presents the comparative life cycle assessment (LCA) between warm stone mastic asphalt (SMA) and conventional SMA. Specifically, the study evaluated and compared the life cycle environmental and economic performances of two mixtures: a warm SMA binder course mixture with a chemical additive and a control hot SMA binder course mixture. Both of these mixtures were utilized as part of a complete overlay project on the Veterans Memorial Expressway (I-355) near Chicago as part of the Illinois Tollway system.

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1. INTRODUCTION

In recent years, increasing environmental awareness and rising energy costs have encouraged the hot-mix asphalt (HMA) facilities to consider the development of technologies designed to lower emissions and reduce energy consumption. Warm-mix asphalt (WMA) technology, which was originally developed in Europe, has recently gained increased attention in the U.S., due to its environmental benefits associated with lower mixture production and compaction temperatures. Compared to traditional HMA, WMA provides less energy consumption, lower environmental impact, and extended construction season. However, despite these promising benefits, some agencies and contractors are still hesitant to apply this new technology, mainly because of its possible higher initial costs caused by additives and possible equipment modification. In addition, the long-term performance of WMA is still being investigated.

Traditionally, the life cycle performance of a pavement material or technology is evaluated based on its economic performance through a life cycle cost analysis (LCCA). However, conventional LCCA may omit environmental factors which are critical to a sustainable pavement system and should be considered in the decision-making process. To provide a realistic and complete evaluation of a new pavement material or technology, both the environmental and economic impacts at each stage of the material life cycle, from resource extraction through manufacturing, transportation, construction, and final disposal, should be assessed. Life cycle assessment (LCA) is such a tool that has been recently introduced to determine the overall performance of a given technology by quantifying both its environmental and economic impacts.

To provide the decision-makers with quantitative information about the overall performance of WMA, this study aims to determine the LCA of WMA compared to traditional HMA. Specifically, the environmental and economic performance of the following two mixtures were evaluated and compared: 1) a warm stone mastic asphalt (SMA) binder course mixture with a chemical additive; and 2) a control hot SMA binder course mixture. Both mixtures were utilized as part of a complete overlay project on the Veterans Memorial Expressway (I-355) near Chicago as part of the Illinois Tollway system. A life cycle inventory (LCI) was developed to quantify the energy, material inputs, and emission during aggregate and asphalt binder production, and mixture plant production, transportation, and placement. Subsequently, the life cycle model was applied to compare the environmental impacts and the economic costs (agency cost and user cost) of the control SMA mixture and the warm SMA mixture. The environmental impacts of factors such as global warming, air pollutants, etc. were computed using the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) developed by the US Environmental Protection Agency (USEPA 2008). Finally, the overall performances of the control SMA and the warm SMA were compared by calculating a weighted environmental and economic score and the total cost (environmental, agency, and user costs).

2. BACKGROUND ON LCA

LCA is a methodology that is used to assess potential environmental burdens and impacts of a product, including climate change, fossil fuel depletion, human health, etc. (Rebitzer et al. 2004). It provides metrics that can be used to measure progress toward environmental sustainability (Keoleian et al. 2006). LCA studies the environmental aspects and potential impacts throughout a product's life from material acquisition through production, use and disposal (ISO 1997).

As illustrated in Figure 1, an LCA includes four basic phases, according to the international organization for standardization (ISO) 14040 series (ISO 1997). Goal and scope definition describes the system in terms of its boundaries and selection of a functional unit. The functional unit provides the basis of comparison between alternative products. Life-cycle inventory (LCI) estimates the consumption of resources and the quantities of waste and emission associated with the production of asphalt mixture and its different components. Life cycle impact assessment evaluates the impact of the product life cycle in terms of selected impact categories, which may include factors such as global warming potential, fossil fuel depletion, impact on human health, and smog potential. The final step of the process is life cycle interpretation, where the results are evaluated by comparing the performance scores for all impact categories. In this study, interpretation will be conducted based on a combined environmental and economic performance approach.

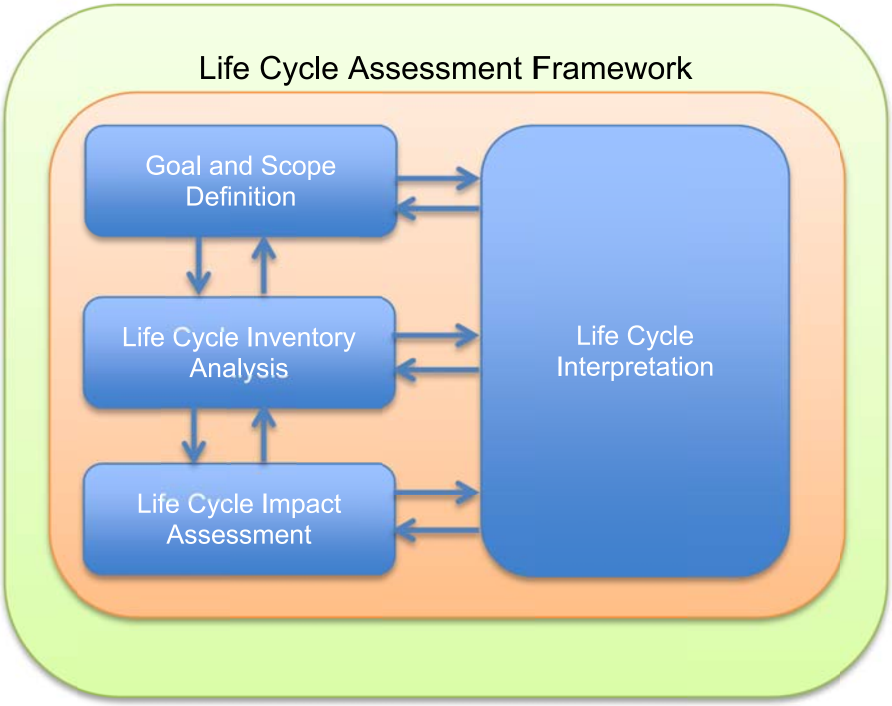

Figure 1. Basic LCA framework.

An LCA can be conducted using one of three different approaches: 1) process LCA, which aims to quantify the inputs and emissions of each discrete process within a life-cycle system boundary; 2) economic input-output LCA (EIO-LCA), which is a top-down approach that includes all sectors of an economy in the analysis; and 3) hybrid LCA, which is a combination of the first two approaches. This study was conducted using approach #1.

Pavement LCA is an expanding research topic, and only a few efforts have already been documented in the literature. The Swedish Environmental Research Institute conducted an LCA of concrete and asphalt pavements based on process flows, including pavement construction, maintenance and operation (Stripple 2001). Additionally, the University of Texas Center for Transportation Research performed a LCA to quantify the differential costs of alternative investment options for concrete pavement (Wilde et al. 2001). Horvath and Hendrickson (1998) used the EIO-LCA model to study the environmental impacts of asphalt and steel-reinforced concrete pavements.

3. SYSTEM DEFINITIONS AND METHODOLOGY

3.1 LIFE CYCLE ASSESSMENT MODEL

The methodology used in this study for the life cycle model followed the international standard, ISO 14040, ISO 14041, and ISO 14042 methods (ISO 1997, ISO 1998, ISO 2000). As previously mentioned, an LCI was developed to provide a compilation of the energy requirements, material inputs, and the emissions associated with its production and installation. Prior to developing the LCI, the agency needs to define the system boundary, which provides the limits of the LCI. Figure 2 presents the system boundary for the developed life cycle inventory. As shown in the figure, the LCI considers energy and emissions associated with the manufacture of asphalt binder, production of aggregate, plant operations, transportation and mixture placement.

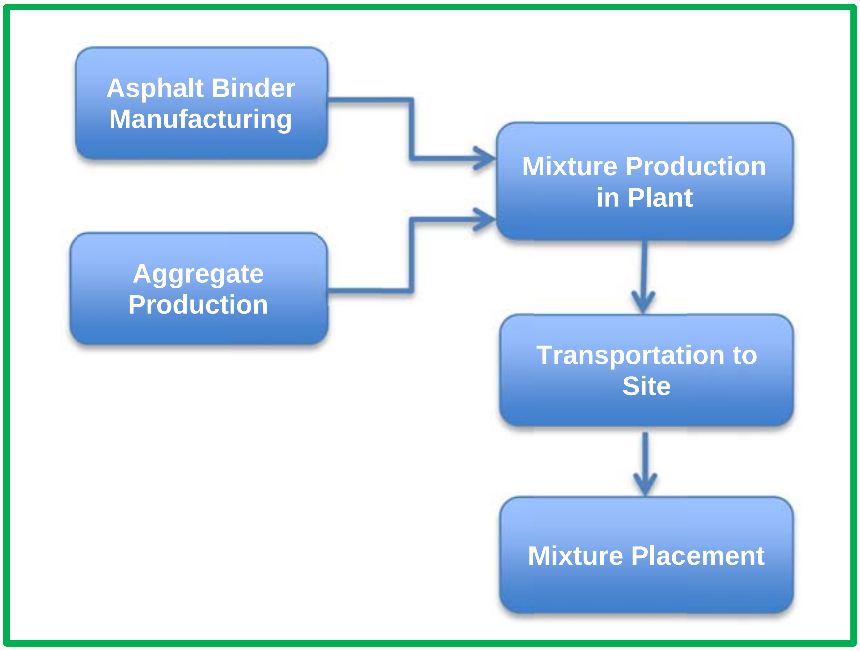

Figure 2. System boundary for the life cycle inventory.

The selected functional unit in this study was one lane-mile of delivered and installed asphalt mixture. According to the design information of the construction site on I-355, the lane width is 12 ft (3.6 m) and the layer thickness is 1.75 in (44.5 mm). Thus, one lane-mile of control SMA corresponds to 685.3 ton (621.7 metric ton) control SMA with an air void content of 6%.

The energy and emission data of for each process within the system boundary were obtained from various sources, as shown in Table 2.

Table 2. Sources for Energy and Emission Data

Process	Source
Asphalt Production Energy and Emission	Eurobitume (1999)
Aggregate Production Energy and Emission	Stripple (2000)
Plant Production Energy	Stripple (2000)
Plant Production Emission	USEPA (1995)
Transportation	Argonne National Laboratory (1999)
Construction	USEPA (2005)

Table 3 presents the life cycle inventory for one lane-mile of control SMA, which contains 6.2% asphalt binder (42.5 ton or 38.5 metric ton) and 93.8% (642.8 ton or 583.1 metric ton) crushed aggregate, according to the mixture design information. It was assumed that the transportation distance from the asphalt plant to the construction site was 19 miles (36 km), and the paving speed was 160.0 ton/hr (145.1 metric ton/hr).

Table 3. Life Cycle Inventory for One Lane-Mile of Control SMA

Process	**Material**		**Production**	**Transport**	**Construction**		
	Asphalt	**Aggregate**			**Paving**	**Breakdown Rolling**	**Finish Rolling**
Amount	42.5 ton	642.8 ton	685.3 ton	13021.4 ton-mile	4.3 hr	4.3 hr	4.3 hr
Energy Consumption (BTU)							
Natural Gas	1.19E+08	9.39E+06	1.48E+08	-	-	-	-
Oil	3.98E+07	0.00E+00	0.00E+00	-	-	-	-
Electricity	6.33E+06	1.17E+07	1.47E+07	-	-	-	-
Fuel	-	-	-	2.81E+07	8.78E+06	8.78E+06	3.25E+06
Air Emission (g)							
SOx	6.50E+04	2.73E+02	1.06E+03	2.77E+02	2.99E+01	2.93E+01	1.27E+01
NOx	7.90E+04	1.02E+04	8.09E+03	1.03E+04	2.42E+03	2.43E+03	1.08E+03
CO2	9.90E+06	7.78E+05	1.03E+07	2.19E+06	2.99E+05	2.94E+05	1.27E+05
CO	5.18E+03	5.53E+03	4.12E+04	5.03E+03	7.54E+02	7.67E+02	8.70E+02
Particles	7.52E+03	5.95E+02	1.06E+04	-	-	-	-
PM10	-	-	7.13E+03	2.12E+02	1.49E+02	1.50E+02	1.26E+02
PM2.5	-	-	-	1.95E+02	1.45E+02	1.46E+02	1.22E+02
N2O	-	3.86E+02	-	5.63E+01	-	-	-
CH4	-	7.59E+01	3.82E+03	4.38E+01	-	-	-
VOC	-	-	9.94E+03	9.47E+02	1.83E+02	1.84E+02	1.19E+02

To quantify the energy and emission benefits of WMA, Lecomte et al. (2007) measured the energy consumption and emission at a plant producing a warm asphalt mixture and a conventional asphalt mixture in Italy. They found by reducing the mixing temperature from 356 to 257 °F (180 to 125 °C), the energy consumption was reduced by 35% due to the use of WMA, which is consistent with the findings of other studies (D'Angelo et al. 2008). The percentage reductions of various emission flows, as shown in the second column of Table 4, were also measured. Due to the unavailability of the plant-measured energy consumptions and emissions from the two SMA mixtures, this analysis assumed that the reductions of the energy consumption and emission are proportional to the temperature reduction. In this study, the control SMA was mixed at 325 ^{o}F (163 ^{o}C), while the warm SMA was mixed at 280 ^{o}F (138 ^{o}C). Therefore, the reductions in emissions shown in the last column in Table 4 were obtained and incorporated into a life cycle inventory that describes the energy consumption and emission of the warm SMA mixture.

Table 4. Emission Reduction

Emission Flow	Emission Reduction (356 ^{o}F to 257 ^{o}F)	Emission Reduction (325 ^{o}F to 280 ^{o}F)
SOx	25%	11.4%
NOx	60%	27.3%
CO2	35%	15.9%
CO	8%	3.6%
Particles	28%	12.5%
VOC	83%	37.9%

The resulting data in Table 3 show the individual emissions and energy usage from the control SMA, but they do not give a clear idea of what the environmental impact will be. The use of impact categories allows for the comparison of the environmental impacts for different options (USEPA 2008). In this study, four impact categories were considered: global warming, fossil fuel depletion, criteria air pollutants, and photochemical smog. These categories have been reported as the main impact categories associated with the asphalt mixture (Marwa 2009). For each impact category, characterization factors are used to describe the relative impact of the various environmental flows (ISO 2006). Table 5 lists the characterization factors for each impact category (Weiland 2008; Lippiat 2007). A large characterization factor means a larger impact for that flow. Characterization factors are then multiplied by each of the environmental flows to convert all them into an equivalent amount of the category indicator.

To obtain a single performance score for the environmental impacts of each mixture, calculated impact performance measures were normalized with respect to fixed U.S. scale impact values as shown in Table 6, which were obtained from the Building for Environmental and Economic Sustainability (BEES) mode (Lippiat 2007). Normalized performance measures were then synthesized based on a set of weights reflecting the importance of each environmental factor as perceived by the user. The weights shown in Table 7 reflect the importance of global warming, fossil fuel depletion, criteria air pollutants, and smog in asphalt pavement construction (Lippiat 2007). Applying these weights provides a single environmental performance score for each mixture. A lower score indicates that the mixture is more sustainable and environmentally friendly.

Table 5. Characterization Factors for Each Impact Category

Impact Category Energy/Emission Flow	Global Warming (CO2-e/g)*	Fossil Fuel (MJ/kg)	Criteria Air Pollutant (micro-DALYs/g)	Photochemical Smog (NOx-e/g)*
Coal	0	0.25	0	0
Oil	0	7.80	0	0
Natural Gas	0	6.12	0	0
SOx	0	0	0	0
NOx	0	0	0.0022	1
CO2	1	0	0	0
CO	0	0	0	0.0134
Total PM**	0	0	0.0834	0
PM10**	0	0	0.0834	0
PH2.5**	0	0	0.1391	0
N2O	310	0	0	0
CH4	21	0	0	0.003
VOC***	0	0	0	0.7806

** Letter e represents equivalent; ** PM represents particulate matter,PM10 represents particulate matter 10 microns and smaller in diameter, and PM2.5 represents particulate matter 2.5 microns and smaller in diameter; *** VOC represents volatile organic compounds*

Table 6. Normalization Values for Each Environmental Impact

Impact Category	Normalization Value
Global Warming	25,582,640.09 g CO2 equivalents/year/capita
Fossil Fuel Depletion	35,309.00 MJ surplus energy/year/capita
Criteria Air Pollutants	19,200.00 microDALYs/year/capita
Smog	151,500.03 g NOx equivalents/year/capita

Table 7. Importance Weight of Each Impact Category

Impact Category	Relative Importance Weight (%)
Global Warming	56
Fossil Fuel Depletion	19
Criteria Air Pollutants	17
Smog	8

3.2 ECONOMIC PERFORMANCE ASSESSMENT

The economic performance of the two SMA mixtures was assessed by determining their agency cost and user cost.

3.2.1 Agency Cost

The life cycle agency cost includes the costs for purchase, production, installation, maintenance, and replacement. For the purpose of this analysis, the costs of replacement and maintenance for the control SMA mixture and warm SMA mixture were assumed to be equal, since equivalent long-term performance of WMA with respect to HMA has been reported in many previous studies (Hurley and Prowell 2005, 2006; Diefenderfer et al. 2007; Prowell et al. 2007; Wielinski et al. 2009; Xiao et al. 2010). Thus, the agency cost difference due to the use of WMA is primarily caused by the cost of modifying equipment, purchasing additives, and saving fuel consumption, during the processes of purchase and production.

The use of a warm mix additive in SMA mixtures requires no or very minimal equipment modification in the asphalt plant. Thus, the cost change due to the use of warm SMA is mainly associated with the cost of the additive and the fuel savings during mixture production.

Another factor that may affect the agency cost of the warm mix is the cost savings from using more recycled asphalt pavement (RAP) material, which is less expensive than the virgin material. More RAP can be added to WMA mixes because WMA is produced at lower temperatures, which causes less binder aging compared to HMA mixes. According the data provided by Illinois Tollway, increasing the RAP usage by 10% can save approximate $4.35 for one ton of asphalt mixture in 2007, which corresponds to $4.57 in 2010 based on the Consumer Price Index. Since widespread use of WMA has not yet been initiated by the Tollway, the limits of RAP in Tollway-specified WMA mixtures currently remain equal with the limits specified for HMA mixes.

3.2.2 User Cost

Calculation of the user costs is primarily based on the delay to travelers caused by the pavement construction. According to Walls and Smith (1998), the user costs caused by a construction work zone include seven components. In free flow state, the user costs include speed change delay, speed change vehicle operation cost (VOC), and reduced speed delay. In forced flow state, when a queue of vehicles develops, four additional costs need be considered, including stopping delay, stopping VOC, queue delay, and idling VOC.

In this study, user costs of the two SMA mixtures were computed using FHWA's LCCA software, RealCost, for one-lane mile of work zone at the I-335 construction site. According to the Illinois Tollway, the AADT was approximately 60,120 vehicles north bound and 35,920 vehicles south bound. One of the three lanes in the north bound was closed to facilitate partial-width construction. The speed limit was reduced from 55 mph (89 km/h) to a work zone speed of 45 mph (72 km/h). The values of time (delay costs rate) for passenger vehicles, single unit trucks, and combination trucks were $11.58/Veh-hr (vehicle hour), $18.54/Veh-hr, and $22.31/Veh-hr, respectively, as estimated by the FHWA (Walls and Smith 1998). Costs were in 1996 dollars and updated to 2010 dollars in the LCCA model using the Consumer Price Index.

4. RESULTS AND DISCUSSION

This section presents the results and discussion on the LCA of the control and warm SMA mixtures.

4.1 ENVIRONMENTAL IMPACT

Figure 3 compares the energy consumption between the control SMA and warm SMA. For both SMA mixtures, the components of material and production are the main contributors to the energy consumption. With a mixing temperature decrease from 325 °F (163 °C) to 280 °F (138 °C), the warm SMA reduced the energy consumptions of the production process and all four processes by 15.9% and 6.5%, respectively.

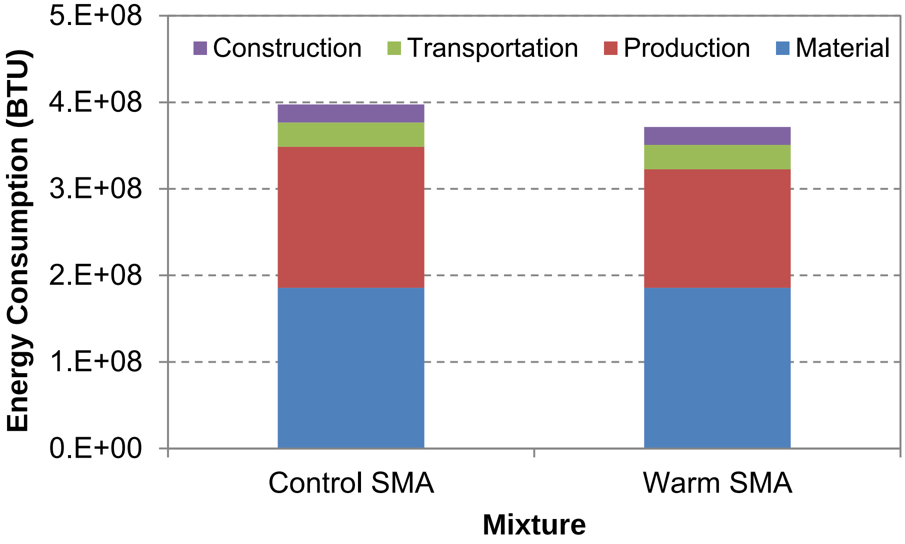

Figure 3. Energy consumptions of control SMA and warm SMA.

Figure 4 presents the contribution of each process to the overall environmental impact for the control SMA. As the figure indicates, the material and production phases are the major source of contributions for all four environmental impact categories.

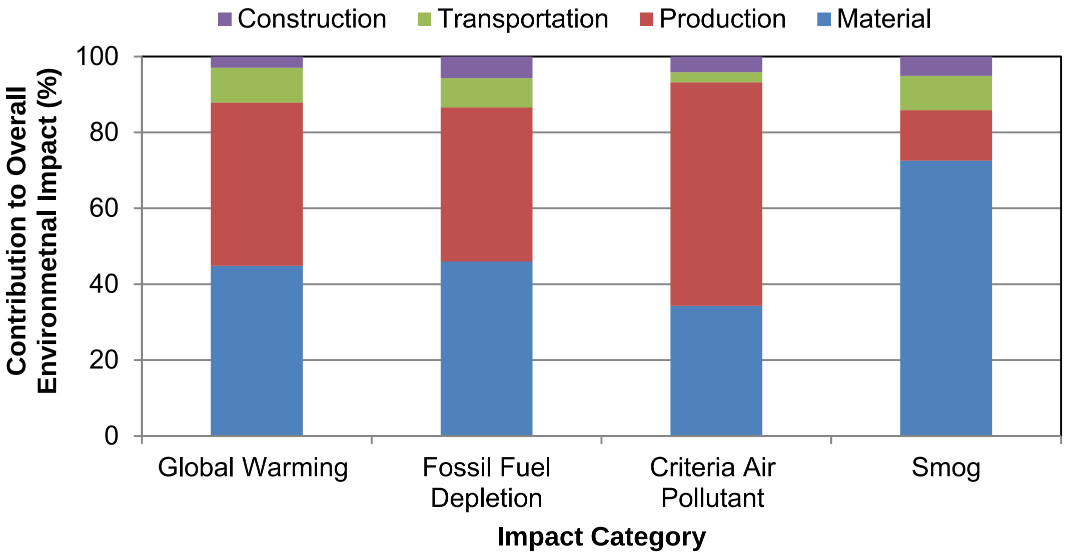

Figure 4. Contribution of main processes to environmental impacts of control SMA.

Figures 5 and 6 show the environmental impact decrease for the production process only and for the entire four processes, respectively, due to the use of WMA. It can be observed that the warm SMA decreased the global warming, fossil fuel depletion, criteria air pollutant, and smog of the plant production by 15.8%, 15.9%, 12.7%, and 31.5%, respectively, compared to the control SMA. For the entire four processes, the reductions for global warming, fossil fuel depletion, criteria air pollutant, and smog were 6.8%, 6.5%, 7.5%, and 4.2%, respectively.

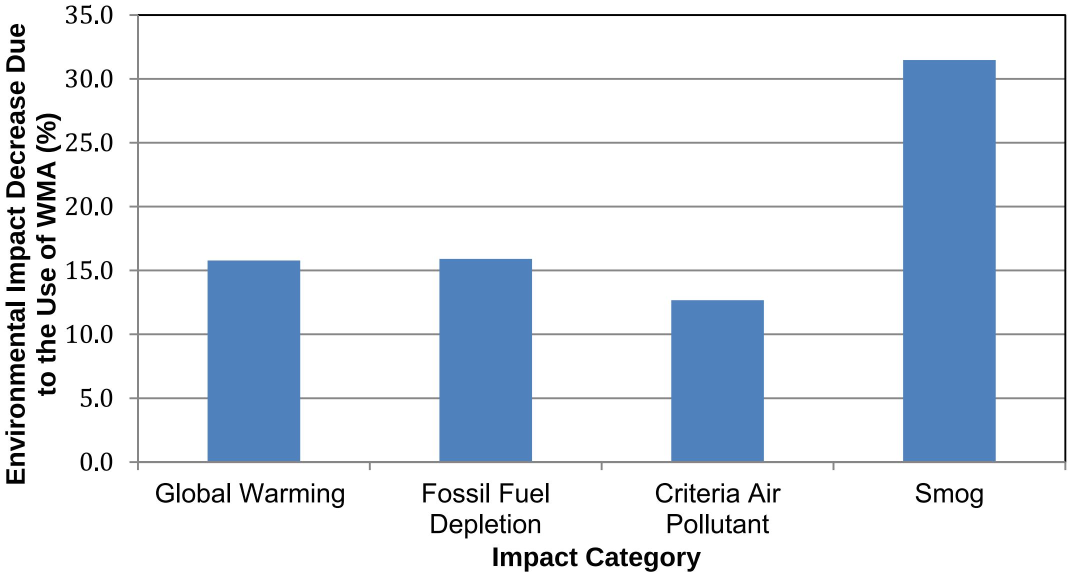

Figure 5. Environmental impact decrease for plant production due to the use of WMA.

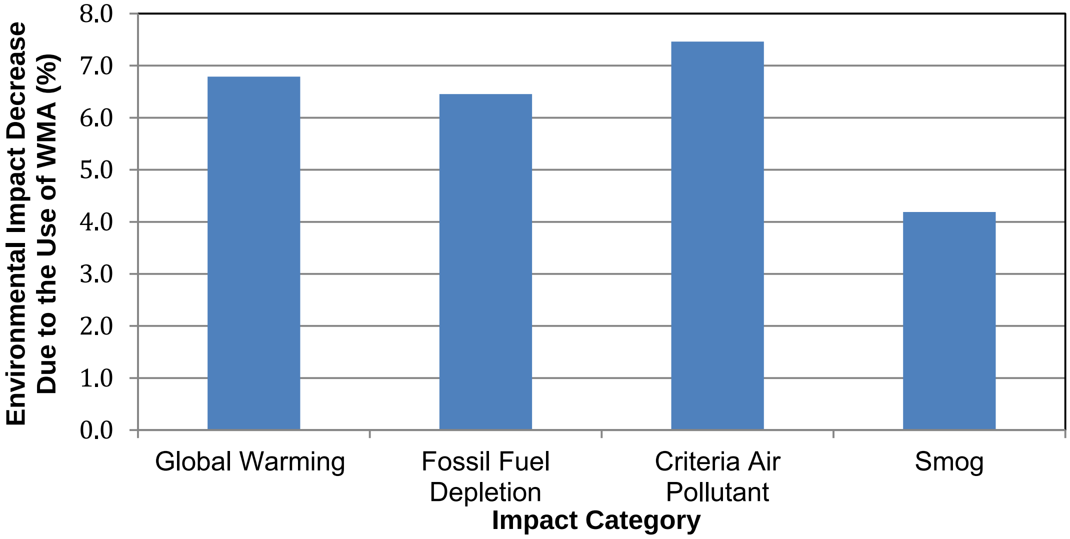

Figure 6. Environmental impact decrease for four main processes due to the use of WMA.

By using the normalization values shown in Table 6 and the importance weights shown in Table 7, the normalized value of each impact category and a single environmental impact score were calculated for both control SMA and warm SMA. As Table 8 shows, the environmental impact score of the warm SMA is 6.4% lower than that of the control SMA, which indicates that the warm SMA is more sustainable and environmentally friendly.

Table 8. Environmental Impact Score of Control SMA and Warm SMA.

Mixture		Control SMA	Warm SMA
Normalized Value	Global Warming	0.942	0.878
	Fossil Fuel Depletion	10.897	10.193
	Criteria Air Pollutant	0.133	0.123
	Smog	0.814	0.780
Environmental Impact Score		1.56	1.46

4.2 ECONOMIC PERFORMANCE

4.2.1 Agency Cost

As previously explained, the agency cost considered in this study is based on the initial cost associated with production of one lane-mile of control SMA mixture and one lane-mile of warm SMA mixture. According to the manufacture of the warm mix additive, the cost of the additive for one ton of warm SMA is approximately $2.50. Material costs using other additive (mineral or chemical) processes from producers would be expected to be similar. By considering the fuel consumption savings due to the decreased mixing temperature, Table 9 shows the costs of one lane-mile of control SMA and one-lane mile of warm SMA. From Table 9, it can be seen that the initial construction cost of the warm SMA is slightly higher than that of the control SMA, although the difference is minor. The initial cost increase caused by using warm mix additive is 3.1%. However, as previously mentioned, WMA allows for the use of increased RAP in the mixture. Assuming 10% more RAP is used in the warm SMA, the cost of the warm SMA can be decreased to 3.5% less than that of the control SMA.

Table 9. Cost of One Lane-Mile of SMA Mixture

Cost / Mixture	Cost of One Ton of Mixture					Cost of One Lane-Mile of Mixture (685.3 ton)
	Control SMA Cost*	Additive Cost	Fuel Saving**	RAP Saving	Total Cost	Total Cost
Control SMA	$69.50	$0.00	$0.00	$0.00	$69.50	$47,628.40
Warm SMA	$69.50	$2.50	-$0.36	$0.00	$71.64	$49,094.90
Warm SMA (with 10% more RAP)	$69.50	$2.50	-$0.36	-$4.57	$67.07	$45,963.07

** According to Illinois Tollway, the cost of one ton of SMA binder course ranges from $66.00 to $73.00*

*** Fuel cost saving was calculated based on a 15.9% energy reduction in a natural-gas plant using the reference by Kristjansdottir et al. (2007)*

Another common process of producing WMA mixtures is to inject water into the liquid asphalt at the contractor's SMA production plant using special nozzles. With the price of water being nearly zero, minor equipment costs to provide the injection of water would be the only basis for slightly higher extra construction costs to produce the WMA mix. With massive mix production projects where WMA is most likely to be used, the equipment costs would be reflected in higher material costs by only a few cents, not dollars. Warm SMA production using the water injection process would result in further cost decreases compared to the costs of the control SMA.

4.2.2 User Cost

User cost due to traffic delay depends on the traffic opening time after the pavement construction. Obviously, shorter traffic opening time will cause less user cost by reducing traffic delays. However, if a pavement is opened to traffic too early before it gains sufficient strength or modulus, its long-term performance will be compromised, which in turn results in considerable extra agency cost in maintenance and rehabilitation.

In this analysis, the control SMA and warm SMA were considered to have the same surface modulus at the time of traffic opening to ensure equivalent long term performance. The control SMA pavement was assumed to be opened to traffic at 120 ^{o}F (49 ^{o}C), and the warm SMA pavement was assumed to be opened to traffic at the temperature that provides the same modulus. According to the calculation shown in the laboratory testing and field testing report of this study, the warm SMA pavement can be opened to traffic 0.9 hr earlier than the control SMA pavement.

Table 10 shows the user costs of one-lane mile of work zone when the pavement overlay was constructed using the control SMA and warm SMA. The data show that the user cost of the warm SMA is 25.4% less than that of the control SMA, as a result of earlier traffic opening. It should be noted that the user cost associated with traffic delay is essentially driven by traffic parameters. Because of the high traffic volume on I-355, significant user cost saving would have been achieved with WMA use if extended lane closure were not present.

Table 10. User Costs of One-Lane Mile of Control SMA and Warm SMA Work Zones

Mixture Type	Control SMA	Warm SMA	Difference
User Cost	$18,170	$13,463	$4,707

4.3 OVERALL PERFORMANCE

Based on the environmental impact and economic performance data shown in the previous sections, the weighted environmental impact and economic performance scores were calculated for the control SMA and warm SMA. The sum of the agency cost and user cost was considered when calculating the weighted economic performance score, as shown Table 11. As this table shows, although the initial construction cost of the warm SMA is slightly higher than that of the control SMA, the total economic cost of the warm SMA is lower than that of the control SMA, because of its lower user cost when used for mill and fill overlay situations.

Figure 7 compares the environmental and economic scores between the control SMA and warm SMA. Note that a larger score in this figure indicates either a higher environmental impact or a higher economic cost. Assuming a weight of 50% for economic factors and 50% for environmental factors, the overall performance score for the control SMA is 51.5, and for the warm SMA is 48.5. This indicates that compared to the control SMA, the warm SMA is more environmentally friendly while also being economically competitive.

Table 11. Total Economic Cost of One-Lane Mile of Control SMA and Warm SMA

Mixture Type	Control SMA	Warm SMA	Warm SMA (with 10% more RAP)
Agency Cost	$47,628	$49,094	$45,963
User Cost	$18,170	$13,463	$13,463
Total Economic Cost	$65,798	$62,557	$59,426

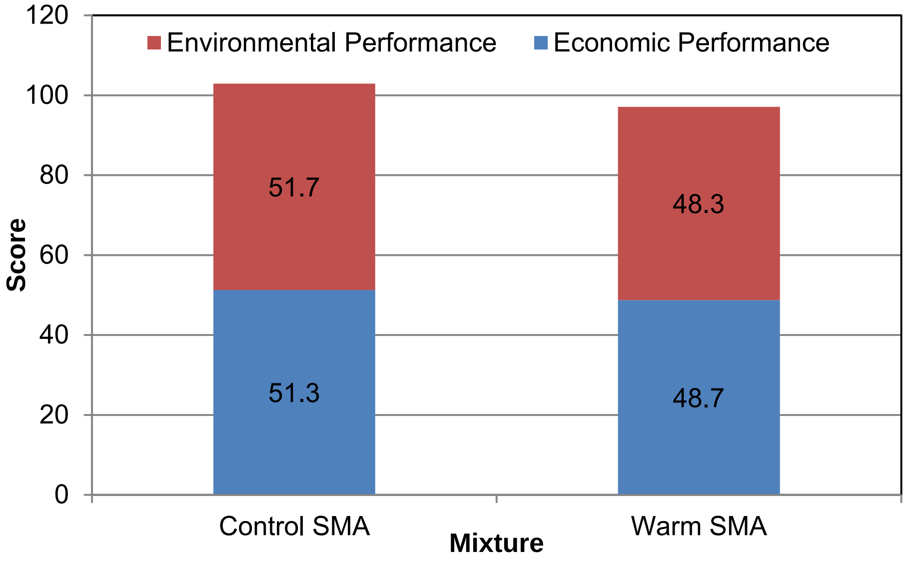

Figure 7. Environmental and Economic Performance Scores of Control SMA and Warm SMA.

Figure 8 compares the environmental and economic performance scores between the control SMA and the warm SMA with 10% more RAP. It can be seen that, with an increased RAP percentage, the economic performance of the warm SMA was further improved. Assuming a weight of 50% for economic factors and 50% for environmental factors, the overall performance score for the control SMA is 52.2, and the overall performance score for the warm SMA with 10% more RAP is 47.9.

To directly consider the environmental impact in monetary values, Wilde et al. (2001) proposed the air pollution costs as shown in Table 12. Six criteria pollutants specified by the EPA which have direct impact on human health were considered, including SOx, NOx, CO, PM, Pb (lead), and VOC. Three major greenhouse gases (GHG) that were inventoried include CO2, CH4, and N2O. Since the criteria pollutants are sensitive to geographic region, values for urban, urban fringe and rural areas were calculated separately. Since GHG emissions have global consequences, global costs were used.

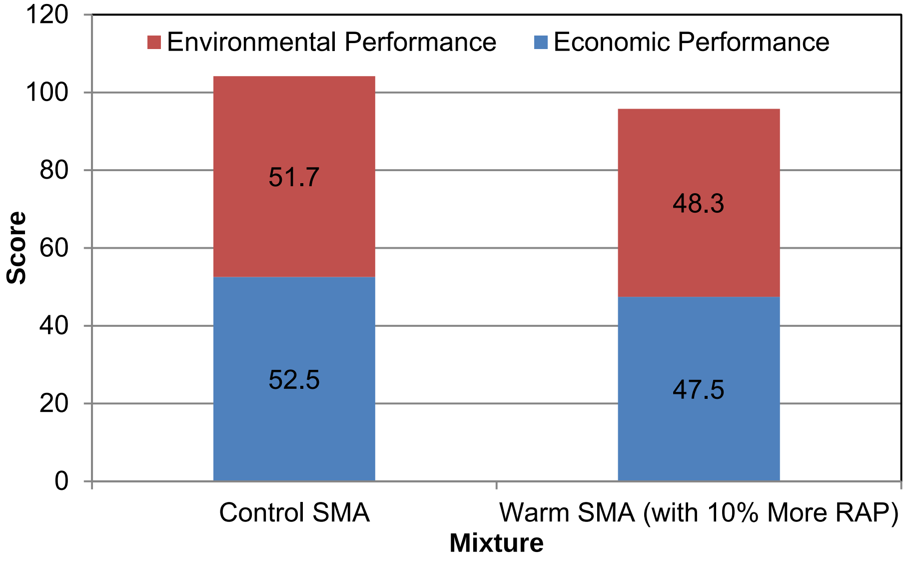

Figure 8. Environmental and Economic Performance Scores of Control SMA and Warm SMA with 10% More RAP

Table 12. Air Pollution Costs by Impacted Region (Wilde et al. 2001)

Pollutant	Average Cost ($/ton)			
	Urban	Urban fringe	Rural	Global
SOx	6,732	3,013	877	-
NOx	171	71	21	-
CO	186	96	23	-
PM	2	1	0	-
Pb	4,333	2,256	526	-
VOC	2,147	2,147	2,147	-
CO2	-	-	-	23
CH4	-	-	-	7,792
N2O	-	-	-	421

By using the air pollution costs shown in Table 12, this analysis calculated the environmental costs of the control and warm SMA mixtures, and then the total costs (agency, user, and environmental costs) of the control and warm SMA mixtures were obtained, as shown in Table 13. It is obvious that the total cost of the warm SMA is lower than that of the control SMA, and if 10% more RAP is used in the warm SMA, its total cost is further decreased.

Table 13. Total Cost Comparison between Control SMA and Warm SMA

	Control SMA	Warm SMA	Warm SMA (with 10% more RAP)
Agency Cost	$47,628	$49,094	$45,963
User Cost	$18,170	$13,463	$13,463
Environmental Cost	$977	$921	$921
Total Cost	$66,775	$63,479	$60,347

5. CONCLUSIONS

This study compared the life cycle environmental and economic performance of a conventional SMA mixture and a warm SMA mixture with a chemical additive. The following points summarize the conclusions of this study:

- The warm SMA provides significant environmental benefits compared to the control hot SMA. When the mixing temperature was decreased from 325 to 280 ^{o}F (168 to 138 ^{o}C), the overall environmental impact of the material, production, transportation, and placement was reduced by 6.4% due to the use of warm mix additive. More environmental benefits can be expected if the mixing temperature is further decreased.
- Using warm mix additive slightly increases the initial construction cost of SMA pavement. However, because the warm SMA allows for earlier traffic opening when used as an overlay where the roadway remain open to traffic, which reduces user cost caused by traffic delay, the total economic cost of the warm SMA is still lower than that of the control SMA. In addition, the warm SMA allows using a higher percentage of RAP. With a 10% increase in RAP usage, the initial construction cost of the warm SMA becomes lower than that of the control SMA.
- The warm SMA provides better overall performance compared to the control SMA, which indicates that the warm SMA is more environmentally friendly while at the same time being economically competitive compared to the control SMA.

It is worth noting that this study didn't include the cost benefits of the warm SMA due to an extended paving season and longer hauling distance, because these benefits are difficult to quantify. In addition, the warm SMA may reduce the risk of poor compaction during construction, which ensures long-term pavement performance, and therefore saving costs for maintenance and rehabilitation.

Based on the results of this study, further research is recommended to consider factors omitted in this analysis such as maintenance and rehabilitation activities, end-of-life recycling options, and variation of adopted data with project size and location.

REFERENCES

Argonne National Lab, Energy Systems Division (1999), *Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model*, University of Chicago, Center for Transportation Research.

D'Angelo, J., Harm E., Bartoszek J., Baumgardner G., Corrigan M., Cowsert J., Harman T., Jamshidi M., Jones, W., Newcomb D., Prowell B., Sines R., and Yeaton B. (2008), *Warm-Mix Asphalt: European Practice*, Federal Highway Administration, Washington D.C..

Diefenderfer, S., and Hearon, A. (2009), *Laboratory Evaluation of a Warm Asphalt Technology for Use in Virginia*, FHWA/VTRC 09-R11, Virginia Transportation Research Council, 2008.

Eurobitume (1999). *Partial Life Cycle Inventory or "Eco-Profile" for Paving Grade Bitumen*.

FHWA (2004), *Life Cycle Cost Analysis: RealCost User Manual*, Office of Asset Management, Federal Highway Administration, Washington D.C..

Horvath, A., and Hendrickson, C (1998), "Comparison of environmental implications of asphalt and steel-reinforced pavements," *Transportation Research Record*, 1626, pp.105-113.

Hurley, G.C., and Prowell, B.D. (2005a), *Evaluation of Aspha-Min® Zeolite for Use in Warm Mix Asphalt,* Report NCAT 05-04, National Center for Asphalt Technology, Auburn University, Auburn, Alabama.

Hurley, G., and Prowell, B.D. (2005b), *Evaluation of Sasobit® for Use in Warm Mix Asphalt*, NCAT Report 05-06, National Center for Asphalt Technology, Auburn University, Auburn, Alabama.

Hurley, G. and Prowell, B.D. (2006). *Evaluation of Evotherm® for Use in Warm Mix Asphalt,* NCAT Report 06-02, National Center for Asphalt Technology, Auburn University, Auburn, Alabama.

ISO (1997), *Environmental Management – Life Cycle Assessment – Principals and Framework, ISO 14040,* International Organization for Standardization.

ISO (1998), *Environmental Management: Lifecycle Assessment: Goal and Scope Definition and Inventory Analysis, ISO 14041,* International Organization for Standardization.

ISO (2000), *Environmental Management: Lifecycle Assessment: Life Cycle Impact Assessment, ISO 14042,* International Organization for Standardization.

Keoleian, G.A. and Spitzley, D.V. (2006), "Life Cycle Based Sustainability Metrics," *Chapter 7 in Sustainability Science and Engineering: Defining Principles (Sustainability Science and Engineering, Volume 1)*, M.A. Abraham, Ed. Elsevier, pp.127-159.

Lecomte, M., Deygout F., and Menetti A. (2007), *Emission and Occupational Exposure at Lower Asphalt Production and Laying Temperatures,* Shell Bitumen.

Lippiat, B. (2007), *Building for Environmental and Economic Sustainability (BEES) Technical Manual and User Guide*, National Institute of Standards and Technology, Wellington.

Marwa, H. (2009), "Life-Cycle Assessment of Warm-Mix Asphalt: An Environmental and Economic Perspective", Transportation Research Board 88th Annual Meeting, Transportation Research Board, Washington, D.C..

Prowell, B.D., Hurley, G.C., and Crews, E. (2007). "Field Performance of Warm-Mix Asphalt at National Center for Asphalt Technology Test Track," *Transportation Research Record*, No.1998, Transportation Research Board, Washington, D.C., pp. 96-102.

Rebitzer, G., Ekvall T., Frischknecht R., Hunkler D., Norris T., Rydberg W., Suh S., Weidema B., and Pennington D. (2004), "Life Cycle Assessment Part 1: Framework, Goal and Scope Definition, Inventory Analysis, and Applications," *Environment International* 30, pp.701-720.

Stripple, H. (2000), *Life Cycle Inventory of Asphalt Pavements*, Swedish Environmental Research Institute (IVL), Gothenburg, Sweden.

Stripple, H. (2001), *Life cycle Assessment of Road: A Pilot Study for Inventory Analysis,* Swedish Environmental Research Institute (IVL), Gothenburg, Sweden.

USEPA (1995). *Compilation of Air Pollutant Emission Factors, Volume 1: Stationary Point and Area Sources, AP-42,* Fifth Edition, Volume 1, United States Energy Protection Agency, Retrieved from http://www.epa.gov/ttn/chief/ap42/

USEPA (2008), *Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI)*, United State Energy Protection Agency.

USEPA (2005), *NONROAD Model (Nonroad Engines, Equipment, and Vehicles)*, United States Energy Protection Agency, Retrieved from http://www.epa.gov/oms/nonrdmdl.htm

Walls, J., and Smith, M.R. (1998). *Pavement Division Interim Technical Bulletin: Life-Cycle Cost Analysis in Pavement Design - Interim Technical Bulletin,* FHWA-SA-98-079, U.S. Department of Transportation, Federal Highway Administration, Washington D.C..

Weiland, C. (2008). *Life Cycle Assessment of Portland Cement Concrete Interstate Highway Rehabilitation and Replacement*, Master Thesis, University of Washington.

Wilde, W.J., Waalkes, S., and Harrison, R. (2001), *Life Cycle Cost Analysis of Portland Cement Concrete Pavement*, University of Texas at Austin, Austin, Texas.

Xiao, F., Amirkhanian, S.N., and Putman, B. (2010). "Evaluation of Rutting Resistance in Warm-

Mix Asphalts Containing Moist Aggregate,” *Transportation Research Record*, No. 2180, Transportation Research Board, Washington, D.C., pp.75–84.