Life-Cycle Economic and Environmental Assessment of Warm Stone Mastic Asphalt

Zhen Leng[a*], Imad L. Al-Qadi[b], Ruijun Cao[a]

[a] *Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong SAR, China*

[b] *Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Champaign, IL, USA*

* Corresponding author, Email: zhen.leng@polyu.edu.hk

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In recent years, the increasing concern of energy depletion and awareness of environmental protection have encouraged the hot-mix asphalt (HMA) operational facilities to consider the development of lower-environment-impact technologies, such as warm-mix asphalt (WMA), to achieve a more resilient pavement system. In this study, integrated life-cycle cost analysis (LCCA) and life-cycle assessment (LCA) is introduced to quantify the life-cycle economic and environmental potential impact of WMA when applied to stone mastic asphalt (SMA) in comparison with conventional hot SMA. The results of this study indicated that warm SMA is more environmentally friendly than conventional hot SMA, while it is economically competitive.

Keywords: warm-mix asphalt; life-cycle assessment; life-cycle cost analysis; stone mastic asphalt

Subject classification codes: (include these here if the journal requires them)

1. Introduction

In recent years, increasing environmental awareness and rising energy costs have encouraged the hot-mix asphalt (HMA) operational plants to consider the development of technologies designed to lower emissions and reduce energy consumption. Warm-mix asphalt (WMA) technology, originally developed in Europe, is gaining acceptance in the U.S. and several other counties, due to the environmental benefits associated with lower mixture production and compaction temperatures (Al-Qadi et al. 2012; Leng et al. 2014; Yu et al. 2014). Compared with 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 technology, mainly because of the possibly higher initial costs resulting from the additives used 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 not consider the environmental impact, which is critical for building a sustainable and resilient pavement system. Actually, the environmental impact is being considered as part of the decision-making process by many agencies in Europe and some in the U.S. Hence, to provide a realistic evaluation of a new pavement material or technology, both environmental and economic impacts should be considered at each stage of the material life cycle, from resource extraction through manufacturing, construction, maintenance/rehabilitation, use, and final disposal. To predict the environmental and economic impact of a technology or a product, life-cycle assessment (LCA), a tool used to quantify the overall environmental impact of a given technology, can be coupled with LCCA.

To provide decision-makers with quantitative information about the overall performance of WMA, this study aims to determine the LCA of WMA when compared with 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 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 and the warm

SMA mixtures. Environmental impact factors, such as global warming and air pollutants, were computed using the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) developed by the U.S. Environmental Protection Agency (Bare 2011). Finally, the overall performance of the control SMA and warm SMA was 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 used to assess the 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, construction, maintenance/rehabilitation, 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.

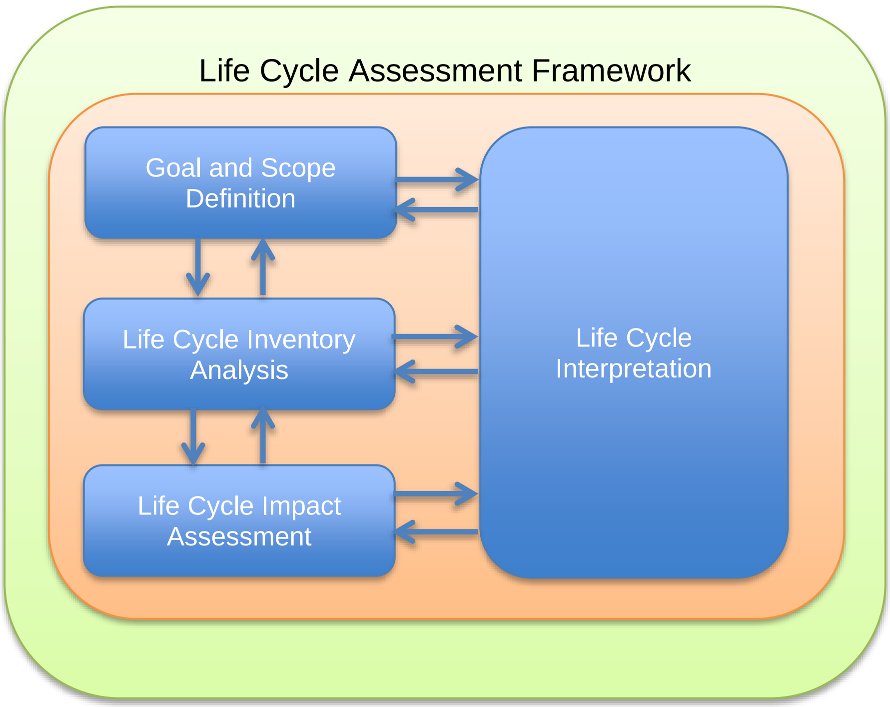

Figure 1. Basic LCA framework.

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), 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 the first approach.

Pavement LCA is an expanding research topic, with only a few efforts 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 Centre for Transportation Research performed an 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. Kang et al. (2014) studied the life-cycle greenhouse gases and energy consumption for material and construction phases of pavement with traffic delay through LCA. Yang et al. (2015) conducted life-cycle environmental and economic analyses of recycled asphalt concrete based on material production and potential performance. Al-Qadi et al. (2015) implemented the LCA approach to quantify the environmental improvements in pavement materials and construction practices employed by the Illinois State Toll Highway.

3. System Definitions and Methodology

3.1 Life-Cycle Assessment Model

The methodology used in this study for the life-cycle model follows 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 construction. 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 LCI. 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.

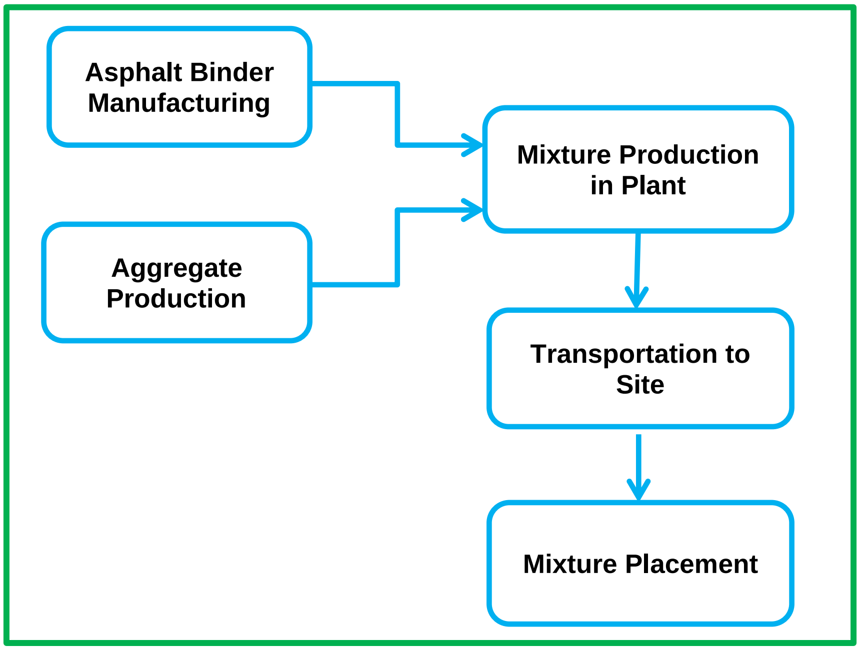

Figure 2. System boundary for the life-cycle inventory.

The selected functional unit in this study was one-lane mile (1.6 lane km) of delivered and paved 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 at an air void content of 6%.

The energy and emission data for each process within the system boundary were obtained from various sources, as shown in Table 1.

Table 1. Sources for Energy and Emission Data

Process	Source
Asphalt Production Energy and Emission	Ecoinvent (2013); USEIA (2015)
Aggregate Production Energy and Emission	Ecoinvent (2013)
Plant Production Energy and Emission	Ecoinvent (2013); Young (2007)
Transportation	Ecoinvent (2013); USEPA (2012)
Construction	Ecoinvent (2013); USEPA (2008)

Table 2 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. The transportation distance from the asphalt plant to the construction site was approximately 19 miles (36 km), and the paving speed was approximately 160.0 ton/hr (145.1 metric ton/hr).

Table 2. Life-Cycle Inventory for One-Lane Mile of Control SMA

Process	Material		Production	Transport	Construction	
	Asphalt	Aggregate			Paving	Rolling
Amount	38.5 metric ton	583.0 metric ton	621.6 metric ton	11810.4 metric ton-mile	4.3 hr	4.3 hr
Energy Consumption (MJ)						
Non Renewable	1.93E+05	8.77E+04	2.43E+05	1.61E+04	4.29E+03	2.56E+03
Air Emission (g)						
SO_x	7.52E+04	1.00E+04	9.73E+04	1.41E+03	1.91E+01	1.19E+01
NO_x	1.96E+04	1.27E+04	1.35E+04	5.67E+03	1.26E+03	8.79E+02
CO_2	1.07E+07	3.98E+06	1.16E+07	1.33E+06	3.32E+05	1.98E+05
CO	1.25E+04	3.87E+03	9.01E+03	1.25E+03	4.25E+02	3.55E+02
PM<10*	9.43E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PM>10*	1.46E+03	3.00E+03	7.77E+02	2.14E+02	0.00E+00	0.00E+00
Unspecified PM	6.97E+02	8.40E-01	1.17E+02	7.23E-04	9.55E+01	8.89E+01
N_2O	8.86E+01	8.22E+01	2.61E+01	2.82E+00	0.00E+00	0.00E+00
CH_4	4.14E+04	1.83E+01	5.01E+04	1.44E+00	1.62E+00	1.13E+03
VOC**	1.04E+03	1.49E-01	3.45E+03	2.13E-02	1.06E+02	7.40E+04

* PM represents particulate matter, ** VOC represents volatile organic compounds

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 that by reducing the mixing temperature from 356 to 257 ^{o}F (180 to 125 ^{o}C), 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 3, were also measured. Due to the unavailability of 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 ^oF (163 ^oC), while the warm SMA was mixed at 280 ^oF (138 ^oC). Therefore, the reductions in emissions shown in the last column of Table 4 were obtained and incorporated into an LCI that describes the energy consumption and emission of the warm SMA mixture.

Table 3. Emission Reduction

Emission Flow	Emission Reduction (356 ^oF to 257 ^oF)	Emission Reduction (325 ^oF to 280 ^oF)
SO_x	25%	11.4%
NO_x	60%	27.3%
CO_2	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 would 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 (Hasan 2009). For each impact category, characterization factors were used to describe the relative impact of the various environmental flows (ISO 2006). Table 4 lists the characterization factors for each impact category (Weiland 2008; Lippiat 2007). A large characterization factor means larger impact for that flow. Characterization factors were then multiplied by each of the environmental flows to be converted into an equivalent amount of the category indicator.

To obtain a single-performance score for the environmental impacts of each mixture, the calculated impact performance measures were normalized with respect to fixed U.S. scale impact values as shown in Table 5, 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 6 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 4. Characterization Factors for Each Impact Category

Energy/Emission Flow \ Impact Category	Global Warming (CO_2-e/g)*	Fossil Fuel (MJ/MJ)	Criteria Air Pollutant (micro-DALYs/g)	Photochemical Smog (NOx-e/g)*
Non renewable	0	1	0	0
SOx	0	0	0.014	0
NOx	0	0	0.002	1.24
CO2	1	0	0	0
CO	0	0	0	0.0134
>PM10**	0	0	0.046	0
<=PM10**	0	0	0.083	0
Unspecified PM	0	0	0.046	
N_2O	296	0	0	0
CH4	23	0	0	0.003
VOC	0	0	0	0.7806

* Letter e represents equivalent; **PM10 represents particulate matter 10 microns and smaller in diameter

Table 5. Normalization Values for Each Environmental Impact

Impact Category	Normalization Value
Global Warming	25,582,640.09 g CO_2 equivalents/year/capita
Fossil Fuel Depletion	35,309.00 MJ surplus energy/year/capita
Criteria Air Pollutants	19,200.00 micro-DALYs/year/capita
Smog	151,500.03 g NO_x equivalents/year/capita

Table 6. 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 and user costs.

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 several 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 obtaining materials 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 because WMA is produced at a lower temperature, which causes less binder aging compared to HMA. According the data provided by Illinois Tollway, increasing the RAP usage by 10% can save approximately $4.35 for one metric ton of asphalt mixture in 2007, which corresponds to $4.57 in 2010, the year when the warm SMA section was built.

3.2.2 User Cost

Calculation of the user costs is primarily based on the delay to travellers caused by 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, the 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, date of construction, 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.

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 energy consumption. With a mixing temperature decrease from 325 ^{o}F (163 ^{o}C) to 280 ^{o}F (138 ^{o}C), the warm SMA reduced the energy consumptions of the production process and all four processes by 15.9% and 6.5%, respectively.

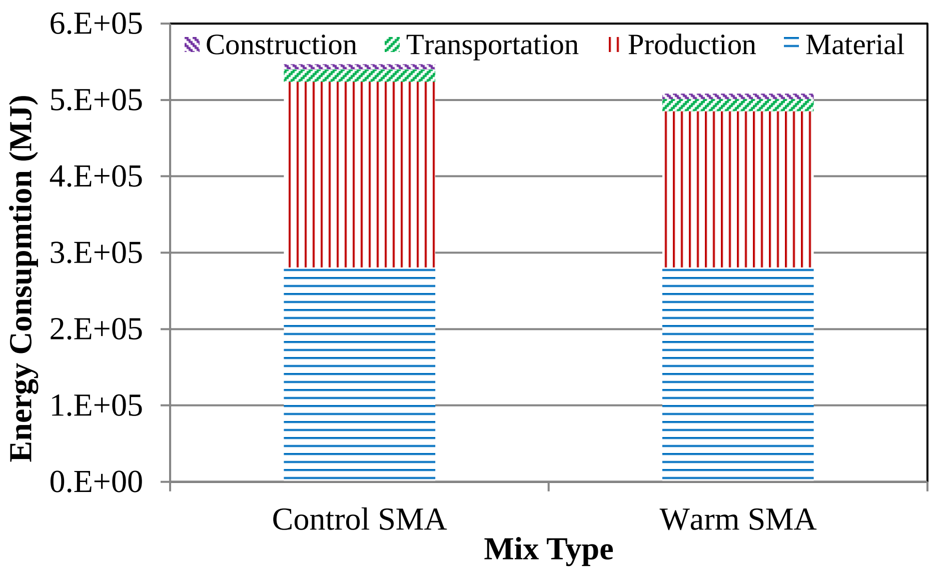

Figure 3. Energy consumptions of control SMA and warm SMA.

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, and the construction phase has the most significant impact on photochemical smog.

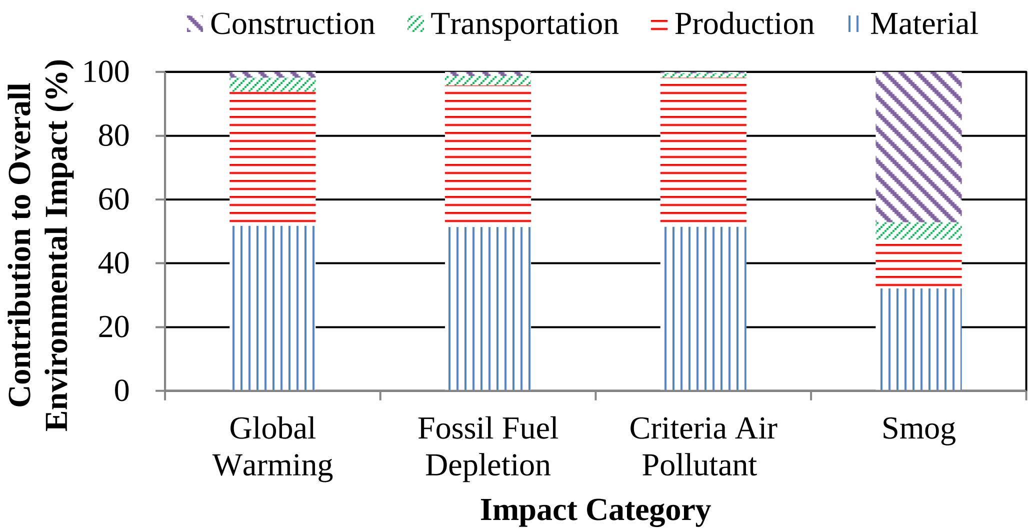

Figure 4. Contribution of main processes to environmental impacts of control SMA.

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 14.5%, 15.9%, 11.7%, and 28.4%, respectively, compared with the control SMA. For the entire four processes, the reductions for global warming, fossil fuel depletion, criteria air pollutant, and smog were 6.1%, 7.1%, 5.5%, and 4.4%, respectively.

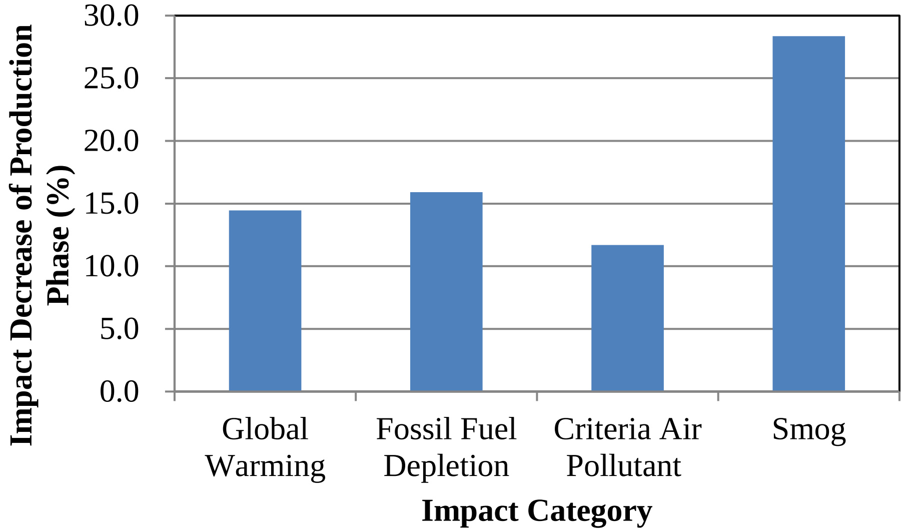

Figure 5. Environmental impact decrease for plant production due to the use of WMA.

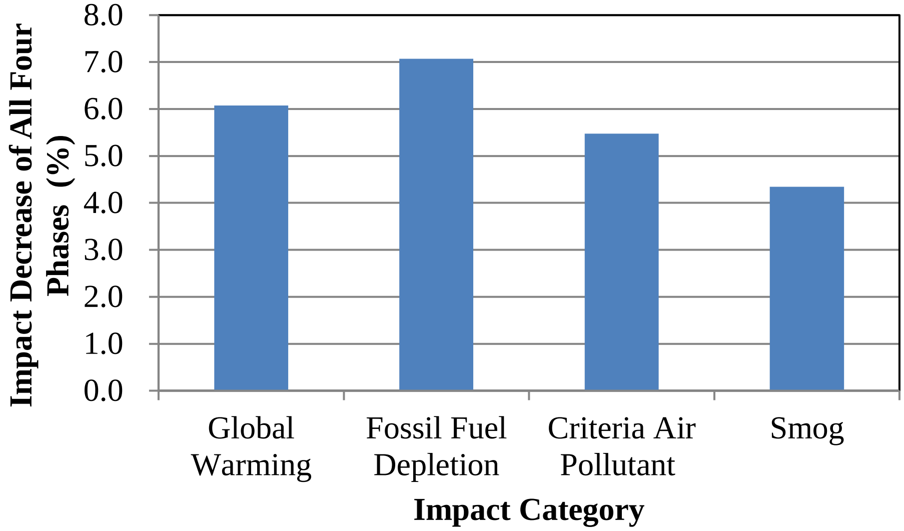

Figure 6. Environmental impact decrease for four main processes due to the use of WMA.

By using the normalization values shown in Table 5 and the importance weights shown in Table 6, the normalized value of each impact category and a single environmental impact score were calculated for both control SMA and warm SMA. As Table 7 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 7. Environmental Impact Score of Control SMA and Warm SMA

Mixture		Control SMA	Warm SMA
Normalized Value	Global Warming	1.184	1.112
	Fossil Fuel Depletion	15.487	14.392
	Criteria Air Pollutant	0.159	0.151
	Smog	0.848	0.811
Environmental Impact Score		3.70	3.45

4.2 Economic Impact

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 metric ton of warm SMA is approximately $ 2.76. Material costs using other additive (mineral or chemical) processes are expected to be similar. Considering fuel consumption savings due to the decreased mixing temperature, Table 8 shows the costs of one-lane mile of control SMA and one-lane mile of warm SMA. From Table 8, it can be seen that the initial construction cost of the warm SMA is slightly higher than that of the control SMA. 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 could be 3.5% less than that of the control SMA.

Table 8. Cost of One-Lane Mile of SMA Mixture

Mixture \ Cost	Cost of One Metric Ton of Mixture					Cost of One-Lane Mile of Mixture (755.6 metric ton)
	Control SMA Cost*	Additive Cost	Fuel Saving**	RAP Saving	Total Cost	Total Cost
Control SMA	$76.63	$0.00	$0.00	$0.00	$76.63	$47,628.40
Warm SMA	$76.63	$2.76	-$0.40	$0.00	$78.99	$49,094.90
Warm SMA (with 10% more RAP)	$76.63	$2.76	-$0.40	-$5.04	$73.94	$45,963.07

* According to Illinois Tollway, the cost of one metric ton of SMA binder course ranges from $72.77 to $80.49

** Fuel cost saving was calculated based on a 15.9% energy reduction in a natural-gas plant (after 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 associated with the injection of water would be the only reason for the slightly higher construction costs for the production of WMA. Hence, foamed warm SMA production would even cost less given the same mix performance is achieved.

4.2.2 User Cost

User cost due to traffic delay depends on the traffic opening time after pavement construction. Obviously, shorter traffic opening time causes less user cost by reducing traffic delays. However, if a pavement is opened to traffic too early before it gains sufficient structural capacity, 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 open to traffic at 120 ^oF (49 ^oC), which is the common practice for HMA pavement construction in Illinois, and the warm SMA pavement was assumed to be open to traffic at the temperature that provides the same modulus. Based on laboratory and field testing results for this study, the warm SMA pavement can be open to traffic 0.9 hr earlier than the control SMA pavement (Al-Qadi et al. 2012).

Table 9 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 for less lane closure time.

Table 9. User Costs of One-Lane Mile of Control SMA and Warm SMA Work Zones

Mixture Type	Control SMA	Warm SMA	Difference
User Cost	$18170	$13463	$4707

4.3 Overall Performance

Based on the aforementioned environmental and economic impact results, the weighted environmental impact and economic performance scores were calculated for the control SMA and warm SMA. The sum of the agency and user costs was considered when calculating the weighted economic performance score, as shown Table 10. 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 (associated with construction delays only).

Table 10. 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

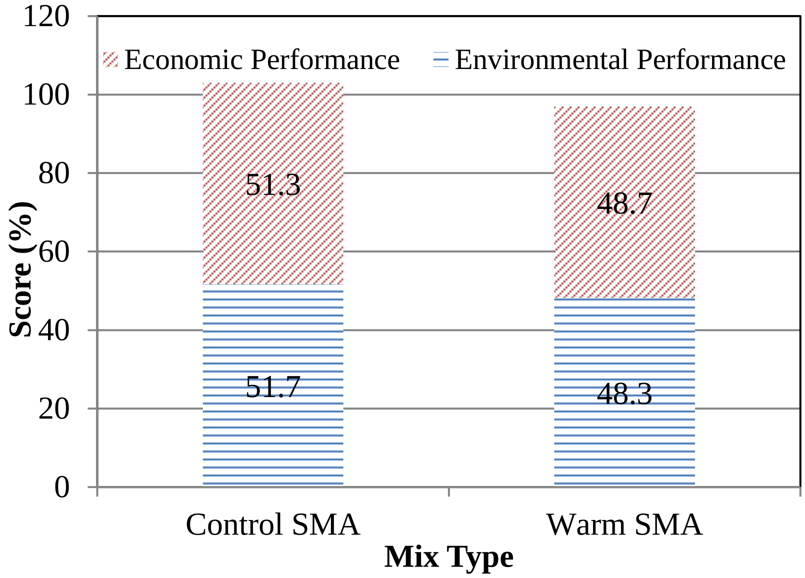

Figure 7. Environmental and economic performance scores of control and warm SMA.

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 value 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.

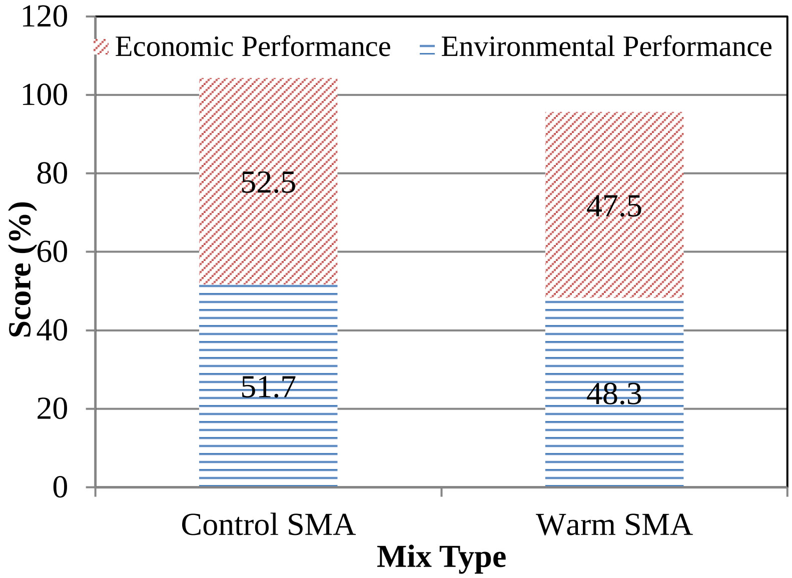

Figure 8. Environmental and economic performance sores of control SMA and warm SMA with 10% more RAP.

5. Conclusions

This study conducted the life-cycle assessment and life-cycle cost analysis for a conventional hot SMA and a warm SMA with a chemical additive. The followings summarize the outcome of this study:

- Warm SMA provides significant environmental benefits compared with the conventional 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, 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 reduced.
- Using warm-mix additive slightly increases the initial construction cost of SMA pavement. However, because warm SMA allows for earlier pavement opening to traffic when used as an overlay, which reduces user cost caused by traffic delay, the

total economic cost of the warm SMA could be lower than that of the conventional hot SMA. In addition, the warm SMA may allow 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 conventional hot SMA.

- The warm SMA is more environmentally friendly while at the same is economically competitive compared with the conventional hot SMA.

It is worth noting that this study did not include the cost benefits of the warm SMA due to an extended paving season and its ability for longer hauling distance, because these benefits are region specific. In addition, the warm SMA may reduce the risk of poor compaction during construction, which ensures long-term pavement performance and, therefore, results in maintenance and rehabilitation cost savings.

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