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Quantifying the environmental burdens of the hot mix asphalt (HMA) pavements and the production of warm mix asphalt (WMA)

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Abstract

Asphalt pavement has significant environmental burdens throughout its life cycle. A life cycle assessment (LCA) model is used to quantify the environmental burdens for material, construction, maintenance and use phases of hot mix asphalt (HMA) pavement. Two peer reviewed journals have been used to collect all of the inventory loadings as an input for the LCA model and ten impact categories have been evaluated as output. The result of the inventory analysis is a summary of all inflows and outflows related to the "functional unit". The result of each impact category is the total of all the individually characterized inventory loadings in each category. Each life cycle phase of HMA pavement has been quantified on these ten impact categories and a comparison provided among the phases to understand the percentage contribution to the environment. Human and eco toxicity values are higher for the material phase, whereas the rest of the impact categories are significant in the use phase. The material phase contributes 97% of the overall human toxicity in water from standpoint of asphalt pavements, whereas in the material phase the production of bitumen is responsible for 90% human and eco toxicity in terms of air based burden. As a solution, the life cycle inventory of WMA has been estimated and reduction only done in HMA production. From analysis, it was estimated that WMA provides a reduction of 29% on the acidification impact and 25% reduction on both fossil fuel consumption and photo oxidant formation impact of HMA.

Keywords: Life cycle analysis; Environmental burdens; Inventories; HMA; Impacts; WMA

1. Introduction

Highway networks cover over eight million lane-miles while supporting three million vehicle-miles each year in the United States [20]. Asphalt and cement concrete are the two most common materials used for pavement construction. Approximately 83% of all pavements and streets in the United States are made of flexible type (asphalt wearing surface), 7% are rigid type (Portland cement concrete roadway with or without an asphalt wearing surface), and nearly 10% are of composite type like asphalt surface on Portland cement concrete base [25]. According to National Asphalt Pavement Association (NAPA), asphalt materials currently cover more than 94% of the paved roads in the United States. For building an asphalt pavement consideration of the environmental consequences through all phases of its development, from material extraction to construction, from construction to operation and service is important. Lately researchers and engineers have been considering the environment impacts of engineering decisions. Life cycle assessment (LCA) can be used as a method to assess the environmental effects of an asphalt pavement system over its entire life period [10,14]. It is being accepted and applied by the

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pavement industry, to quantify and compare the environmental effects of asphalt products and processes.

Several researchers have studied the effects on the environment due to materials, construction, maintenance, recycling, use and end of life phase of asphalt pavement in terms of energy and air emissions [2,3,7,23,24,4,22,19,6,21,13]. Also, some other studies have focused on not all but few life cycle phases of asphalt pavement in terms of energy, air emission or raw materials [9,15,16,25,1,5,10]. Among the aforementioned studies few also compare the environmental impact between asphalt and concrete pavement. Most studies have utilized LCA models to estimate the environmental impacts by quantifying energy consumption, atmospheric emissions and waste generation. However, ecological impacts or emissions in water in terms of toxicity for human and ecosystem generally been excluded from these studies. One study has performed the ecological impact for materials (extraction, manufacturing, transportation) and construction phase of asphalt pavement in terms of inventory loadings [12].

The aim of this study is to quantify the environmental burdens of four phases (material, construction, maintenance and use) of hot mix asphalt (HMA) pavement in terms of energy, air emissions and water emissions using the LCA model and to compare the impacts among those phases. It is hypothesized that material and use phase should generate more emissions as compared to the other two phases of HMA pavement. To achieve this objective, a life cycle inventory that quantifies the energy, material phase inputs (emissions during aggregate extraction, bitumen production and HMA production), construction phase inputs, maintenance phase inputs and use phase inputs (normal traffic, traffic disruption and lighting), were developed. Based on this inventory loading, impact assessments were evaluated on ten categories. In addition, the percentage improvement that would result by implementing warm mix asphalt (WMA) technology instead of HMA has been evaluated on four impact categories.

2. Asphalt pavement

Asphalt or flexible pavements have low or negligible flexural strength or are rather flexible in their structural action under the loads. The mechanism of an asphalt pavement is to transmit the vertical or compressive stresses to the lower layers by grain to grain transfer through the points of contact in the granular structure. A typical asphalt pavement consists of four components: (i) soil subgrade, (ii) sub-base course, (iii) base course, and (iv) surface course.

The subgrade should provide adequate stiffness because it provides resistance to deflection, allowing rollers to produce a firm compaction of all layers. The soil subgrade is critical to the overall performance of an asphalt pavement. It essentially provides for a strong foundation and serves as a working platform for dump trucks and supports traffic loads. Proper design and construction of the foundation are keys in preventing volume changes due to wet-dry cycles in expansive clays and freeze-thaw cycles in frost susceptible soils. Lime, cement or fly ash is frequently used to stabilize the sub grade if additional support is necessary. Base and sub-base courses are constructed using asphalt concrete, crushed stones or granular materials or gravels. The surface course is usually composed of HMA because this layer is directly subjected to traffic loads.

HMA is a combination of approximately 95% stone, sand, or gravel bound together by asphalt cement. Asphalt cement is heated and mixed with the aggregate at a HMA facility. After mixing, the HMA is loaded into trucks and transported to the worksite. The trucks dump the HMA at the site and in front of paving machines. HMA is placed and compacted using a heavy roller.

Asphalt is the residual fraction obtained from the fractional distillation of crude oil. It can also be found from natural resources. It is the heaviest residue separated from crude oil. It is highly viscous, black, sticky and entirely soluble in carbon disulfide and composed primarily of highly condensed polycyclic aromatic hydrocarbons. It is primarily used for paving roads because of its good waterproofing and adhesion properties.

3. Life cycle phases of asphalt pavement

Asphalt pavement has five life cycle phases. These are

(i) Material phase (bitumen, aggregate and HMA production)
(ii) Paving or construction phase
(iii) Maintenance phase
(iv) Use phase
(v) End of life phase

The life cycle begins with bitumen being processed from the crude oil or natural sources. Aggregate is collected from the natural sources. Collected bitumen and aggregate are transported to the HMA plant. Subsequently, HMA is manufactured at 150–190 °C. From the HMA plant, HMA is transported to the construction site. HMA is placed on the selected site and the paver machine is used to compact it. Pavement is opened to the traffic when the construction of asphalt pavement is done. Depending on the type and crack on the pavement, routine maintenance takes place after a certain interval of time. Generally there is no end of life for asphalt pavement because it is 100% recyclable [2]. It can be reused for the maintenance purpose or for new asphalt pavement construction.

4. Goal and scope of the study

The main purpose of the study is to assess the environmental impact of an asphalt pavement. The aim is to identify and quantify the environmental impact of each life phase of an asphalt pavement and to make a comparison among these phases. Generally, the environmental impact caused by asphalt pavements is due to the cumulative contributions from the raw material extraction, production, road construction, transportation, use, deposition or reuse phases. These potential impacts are characterized by the use of energy, materials, and emission from combustion and procurement of energy and other process emission. Also, the components of a road based transportation system vary depending on the existing soil characteristics, the route, estimated traffic flow, types of pavements and other technical parameters. To make the calculations possible, a fundamental and simplified composition of HMA pavement has been assumed. In addition to the main goal, other important sub-goals for the study are to come up with a methodology for life cycle assessment of HMA pavements and to observe the trends in the impact areas for each phase of HMA pavement.

5. Functional unit

The functional unit studied is (a) 1 km of asphalt pavement with, (b) maximum grain size of asphalt being 20 mm, (c) road width being 8.5 m (traffic lanes 2 × 3.75 m + inner shoulder 1 m) (d) the maintenance strategy used as being 80 mm overlay (e) a time scale 50 years and (f) 20,000 vehicles/day.

6. Scope and system boundary

Environmental effects were quantified on four life cycle phases of HMA pavements. As mentioned earlier there is no end of life for asphalt pavement. It can be recycled and used as reclaimed asphalt pavement. However, due to aging and repeated recycling, bitumen may not be efficient enough as a binder material for the pavement surface. Hence, the asphalt mixture at this phase is known as waste. In such case, it is a common practice to place the inefficient material in the sub-structure of the pavement. Also, this waste has embodied energy because used bitumen is a residue from the crude oil. In future, researchers may come up with a cheap process which may allow asphalt material to serve as fuel. But in reality, today such energy conversion process has not yet been accomplished. Table 1 represents the scope and system boundary of the study.

7. Methodology for LCA

To achieve the goal of the study, a life cycle inventory (LCI) that quantifies the energy, material inputs, and emission during aggregate extraction, asphalt binder production, HMA production, paving, maintenance and traffic, was developed. A wide range of published reports and databases were reviewed to quantify the energy and emission data for each process and activity defined as part of the system. Then the inventory data for each specific phase of HMA pavement were collected from the peer reviewed journals. Inventory data for emissions during bitumen, aggregate and HMA production were collected from a pilot study report [21] and paving, maintenance and use phase were adopted from another research study [6]. The result of the inventory analysis is a summary of all inflows and outflows related to the “functional unit”. All LCI loadings except energy and materials were transformed from grams to kilograms per kilometer. The inventory loadings were characterized for estimating impact assessment. The result of each impact category is the total of all the individually characterized inventory loadings in each category. For example, all types of emissions (CO_2, CH_4, N_2O) that could contribute to global warming were grouped under the impact category “Global warming”. Based on the findings from the literature review 10 impact categories were selected for LCA. Table 2 represents those impact categories along with their unit.

It is worth noting that one assumption has been made for the calculation of material phase. It was assumed that for the construction of one kilometer HMA pavement 1000 tons of HMA were required. This represents a combination of 60 tons of bitumen and 940 tons of

Table 1
Scope and system boundary.

Life cycle phases	Area	Environmental impacts included in this study
Phase I: material	Production	Energy, greenhouse gas (GHG) emissions, acidification, photo oxidant formation, human toxicity (air and water), eco toxicity (air and water), eutrophication, dust and depletion of landfill waste during production of bitumen, aggregate and hot mix asphalt.
	Transportation	Energy, GHG emissions, acidification, photo oxidant formation, human toxicity (air and water), eco toxicity (air and water), eutrophication and dust during the transportation of bitumen and aggregates.
Phase II: construction		Energy, GHG emissions, acidification, photo oxidant formation, human toxicity (air and water), eco toxicity (air and water), eutrophication and dust during the construction of asphalt pavement.
Phase III: Maintenance		Energy consumed and required for the materials used during maintenance GHG emissions, acidification, photo oxidant formation, human toxicity (air and water), eco toxicity (air and water) and eutrophication during maintenance
Phase IV: Use	Lighting Traffic Traffic disruption	Energy, GHG emissions, acidification, photo oxidant formation, human toxicity (air and water), eco toxicity (air and water), eutrophication and dust during the use (lighting, normal traffic and traffic distribution) phase of asphalt pavement

Table 2
Classification and characterization [10].

Life cycle phases	Inventory loading	Impact category	Impact category area	Unit of characterization factor	Value of characterization factor
Material	Aggregate, Bitumen	Depletion of minerals		ton minerals	1
	Energy (GJ)	Depletion of fossil fuels		GJ	1
	CO_2	Global warming		kg CO_2-eq. (100 years)	1
	CH_4				23
	N_2O				296
	SO_2	Acidification		kg SO_2-eq.	1
	NO_2				0.7
	NH_3				1.88
Construction	SO_2	Photo oxidant formation		kg C_2H_4-eq.	0.048
	NO_2				0.028
	CO				0.027
	CH_4				0.006
	NMVOC				1
	SO_2	Human toxicity	Emission to air	kg 1,4-dichlorobenzene-eq.	0.096
	NO_2				1.2
	CO				2.4
	HC				5.7E + 05
	NMVOC				0.64
	PM				0.82
	NH_3				0.1
	Heavy Metals				5.1E+05
Maintenance	HC	Human toxicity	Emission to fresh water	kg 1,4-dichlorobenzene-eq.	2.8E+05
	As				950.6
	Cd				22.9
	Pb				12.3
	Hg				1426
	NMVOC	Eco toxicity	Emission to air	kg 1,4-dichlorobenzene-eq.	3.20E−11
	HC				1480
	As				7.8E+04
	Cd				3.7E+05
	Pb				2.4E+03
	Hg				4.1E+05
Use	HC	Eco toxicity	Emission to fresh water	kg 1,4-dichlorobenzene-eq.	1.1E+04
	As				4.0E+04
	Cd				7.4E+04
	Pb				3.7E+02
	Hg				7.2E+04
End of life	NO_2	Eutrophication		kg PO_4-eq.	0.13
	NH_3				0.35
	COD				0.022
	PO_4				1
	Nitrate				0.1
	P				3.07
	N				0.42

aggregate. All inventory loading for material phase (bitumen, aggregate, HMA) were collected per ton and multiplied with the individual factor for transforming the loadings to that equivalent for one kilometer of pavement. Energy consumption was divided in terms of the type of fossil fuel used (i.e., heating oil, diesel, electricity, biomass fuel, peat, coal, natural gas, uranium, hydropower). Water emissions and air emissions in the environment were differentiated in terms of inventory loadings for different life cycle phases. Inventory loadings which are responsible for these two emissions were listed separately. It may seem like some inventory loadings and characterization unit considered for both emissions were similar but the value of characterization factor is different for calculating the environmental impacts. Hydrocarbons (HC) were considered as a part of volatile organic compounds (VOC). In the inventory loadings where HC and VOC data were available separately, they were characterized as separate items. However, where only one component, HC or VOC was available, it was calculated as one substance (as VOC). Arsenic (As), cadmium (Cd), mercury (Hg) and lead (Pb) were considered as heavy metals. Table 3 illustrates a sample calculation.

8. Impact category results and tables

On the basis of calculations, summary tables for each life cycle phase of HMA pavements have been provided in this section. Tables 4–6 represent the environmental impacts of three sub-phases of material phase, which are the production of asphalt, aggregate and HMA. Table 7 illustrates the results of the material phase which is a summation of these three sub-phases. Tables 8–10 show the results for the paving, maintenance and use phases of HMA pavements. All of these life cycle phases of HMA pavements were evaluated with respect to the ten impact categories.

9. Interpretation

9.1. Environmental burdens from material phase (bitumen, aggregate, HMA)

Fig. 1 represents the contributions of the three sub phase processes (bitumen production, aggregate production and HMA production) of the material phase to the environmental impact. The environmental burdens from material phase are significantly dependent on the production of HMA. In addition, the manufacture of bitumen and drying of aggregate has harmful effects on some impact category. Production of bitumen has adverse environmental effects in

Table 3
Calculation of global warming.

	Total per tonne produced material (kg)	Unit factor	kg CO_2-eq.	Total per km (kg CO_2-eq.)
Bitumen production				
CO_2	173	1	173	
CH_4	3.53E−05	23	8.12E−04	
N_2O	1.06E−04	296	0.0314	
Total			173.032	$173.032 \times 60 = 10381.92$
Aggregate production				
CO_2	1.42	1	1.42	
CH_4	3.82E−06	23	8.765E−05	
N_2O	3.61E−05	296	0.0107	
Total			1.431	$1.431 \times 940 = 1345.14$
HMA production				
CO_2	34.4	1	34.4	
CH_4	1.07E−05	23	2.461E−04	
N_2O	5.18E−05	296	0.015	
Total			34.42	$34.42 \times 1000 = 34420$
Total				46147

Table 4
Impact results from life cycle inventory for bitumen production.

Impact category	Impact category area	Unit of characterization factor	Total (per km)
Depletion of minerals	Bitumen	ton minerals	60
Depletion of fossil fuels		GJ	218.1318
Global warming		kg CO_2-eq. (100 years)	10381.92
Acidification		kg SO_2-eq.	79.56
Photo oxidant formation		kg C_2H_4-eq.	15.66
Human toxicity	Emission to air Emission to fresh water	kg 1,4-dichlorobenzene-eq. kg 1,4-dichlorobenzene-eq.	10533660 33600
Eco toxicity	Emission to air Emission to fresh water	kg 1,4-dichlorobenzene-eq. kg 1,4-dichlorobenzene-eq.	27528 1320
Eutrophication		kg PO_4-eq.	9
Dust		kg/ton	0.48
Depletion of landfill waste		m^3	0.023

Table 5
Impact results from life cycle inventory for aggregate production.

Impact category	Impact category area	Unit of characterization factor	Total (per km)
Depletion of minerals	Aggregate	ton minerals	940
Depletion of fossil fuels		GJ	61.993
Global warming		kg CO_2-eq. (100 years)	1345.14
Acidification		kg SO_2-eq.	0.822
Photo oxidant formation		kg C_2H_4-eq.	0.914
Human toxicity	Emission to air	kg 1,4-dichlorobenzene-eq.	4.11
	Emission to fresh water	kg 1,4-dichlorobenzene-eq.	–
Eco toxicity	Emission to air	kg 1,4-dichlorobenzene-eq.	2.68E−11
	Emission to fresh water	kg 1,4-dichlorobenzene-eq.	–
Eutrophication		kg PO_4-eq.	0.017
Dust		kg/ton	0.45
Depletion of landfill waste		m^3	6.26E−04

Table 6
Impact results from life cycle inventory for HMA production.

Impact category	Impact category area	Unit of characterization factor	Total (per km)
Depletion of minerals	Bitumen and aggregate	ton minerals	1000
Depletion of fossil fuels		GJ	730.5
Global warming		kg CO_2-eq. (100 years)	34420
Acidification		kg SO_2-eq.	135.30
Photo oxidant formation		kg C_2H_4-eq.	19.04
Human toxicity	Emission to air	kg 1,4-dichlorobenzene-eq.	1054684
	Emission to fresh water	kg 1,4-dichlorobenzene-eq.	33600
Eco toxicity	Emission to air	kg 1,4-dichlorobenzene-eq.	2738
	Emission to fresh water	kg 1,4-dichlorobenzene-eq.	1320
Eutrophication		kg PO_4-eq.	16.4
Dust		kg/ton	0.0038
Depletion of landfill waste		m^3	2.24E−06

Table 7
Impact results from life cycle inventory for material phase.

Impact category	Impact category area	Unit of characterization factor	Total (per km)
Depletion of minerals	Bitumen and aggregate	ton minerals	1000
Depletion of fossil fuels		GJ	1010.62
Global warming		kg CO_2-eq. (100 years)	46147
Acidification		kg SO_2-eq.	215.68
Photo oxidant formation		kg C_2H_4-eq.	35.614
Human toxicity	Emission to air	kg 1,4-dichlorobenzene-eq.	11588348
	Emission to fresh water	kg 1,4-dichlorobenzene-eq.	67200
Eco toxicity	Emission to air	kg 1,4-dichlorobenzene-eq.	30266
	Emission to fresh water	kg 1,4-dichlorobenzene-eq.	2640
Eutrophication		kg PO_4-eq.	25.4
Dust		kg/ton	0.94
Depletion of landfill waste		m^3	0.024

Table 8
Impact results from life cycle inventory for construction phase.

Impact category	Impact category area	Unit of characterization factor	Total (per km)
Depletion of minerals		ton minerals	–
Depletion of fossil fuels		GJ	69
Global warming		kg CO_2-eq. (100 years)	5117.30
Acidification		kg SO_2-eq.	23.40
Photo oxidant formation		kg C_2H_4-eq.	8
Human toxicity	Emission to air	kg 1,4-dichlorobenzene-eq.	1932
	Emission to fresh water	kg 1,4-dichlorobenzene-eq.	560.143
Eco toxicity	Emission to air	kg 1,4-dichlorobenzene-eq.	24
	Emission to fresh water	kg 1,4-dichlorobenzene-eq.	29.2
Eutrophication		kg PO_4-eq.	3.76
Dust		kg/km	8.1
Depletion of landfill waste		m^3	–

Table 9
Impact results from life cycle inventory for maintenance phase.

Impact category	Impact category area	Unit of characterization factor	Total (per km)
Depletion of minerals		ton minerals	–
Depletion of fossil fuels		GJ	470
Global warming		kg CO_2-eq. (100 years)	27450
Acidification		kg SO_2-eq.	72.90
Photo oxidant formation		kg C_2H_4-eq.	154.22
Human toxicity	Emission to air	kg 1,4-dichlorobenzene-eq.	597.25
	Emission to fresh water	kg 1,4-dichlorobenzene-eq.	0.07
Eco toxicity	Emission to air	kg 1,4-dichlorobenzene-eq.	10
	Emission to fresh water	kg 1,4-dichlorobenzene-eq.	3.41
Eutrophication		kg PO_4-eq.	13
Salting		kg/km	150004.7
Depletion of landfill waste		m^3	–

Table 10
Impact results from life cycle inventory for use phase.*

Impact category	Impact category area	Unit of characterization factor	Total (per km)
Depletion of minerals		ton minerals	–
Depletion of fossil fuels		GJ	1514046
Global warming		kg CO_2-eq. (100 years)	102592869
Acidification		kg SO_2-eq.	1723074
Photo oxidant formation		kg C_2H_4-eq.	320932.14
Human toxicity	Emission to air	kg 1,4-dichlorobenzene-eq.	4544748
	Emission to fresh water	kg 1,4-dichlorobenzene-eq.	135
Eco toxicity	Emission to air	kg 1,4-dichlorobenzene-eq.	17703
	Emission to fresh water	kg 1,4-dichlorobenzene-eq.	6294
Eutrophication		kg PO_4-eq.	299217
Dust		kg/km	130224
Depletion of landfill waste		m^3	–

* Use phase is the result of the influence of pavement material on lighting, fuel consumption of traffic and traffic disturbance.

terms of toxicity. It is responsible for 90% human and eco toxicity in terms of air based burden. Also, production of bitumen and HMA appeared to contribute equally to the toxicity of water. This phase has equal contribution of 38% on both acidification and eutrophication impact categories. On the other hand, it has more significant effect on the photo oxidant formation after the human and eco toxicity.

Production of aggregate has a significant effect on two impact categories which are depletion of minerals and depletion of fossil fuels. HMA production alone contributes more than 50% in five impact categories which are depletion of fossil fuel, global warming, acidification, photo oxidant formation and eutrophication. It has a significant effect also on toxicity in terms of air, but less than that due to the production of bitumen.

9.2. Comparison of the life cycle phases of HMA pavement in terms of environmental burdens

Fig. 2 presents the percentage contribution to the overall environmental impact and Fig. 3 illustrates the quantitative data for each life cycle phase of HMA pavement.

Among these four life cycle phases, material phase is the main source of harmful pollutants in terms of human toxicity and eco toxicity. This phase is responsible for

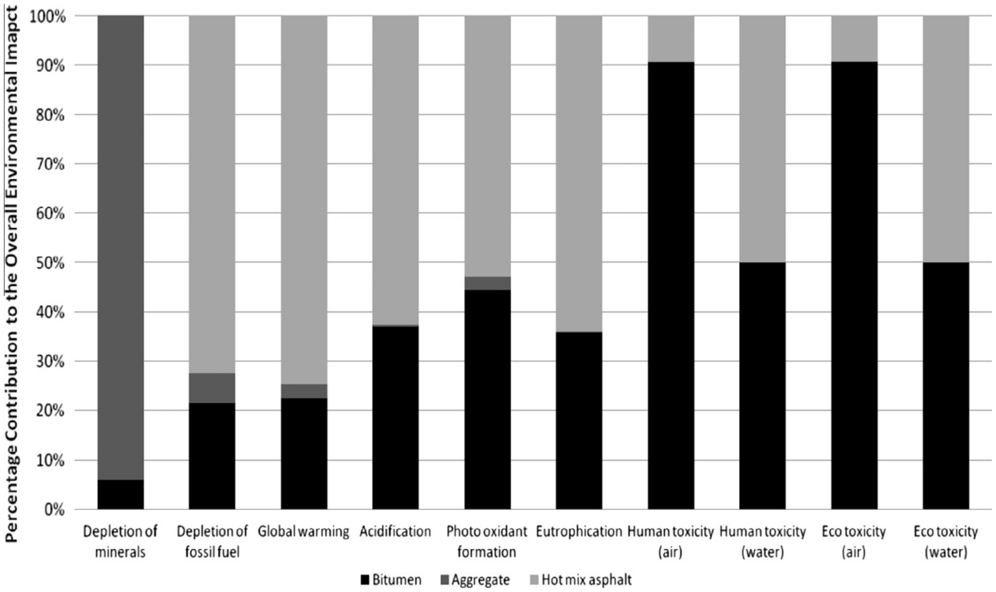

Fig. 1. Contribution of main processes of material phase to the environment impact.

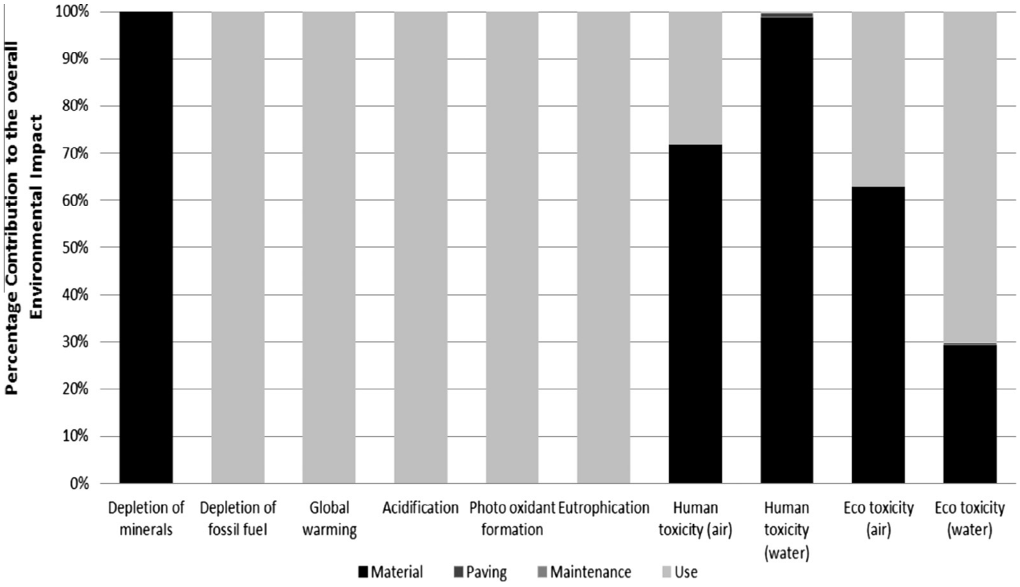

Fig. 2. Contribution of main processes of HMA pavement to the environment impact.

approximately 97% human toxicity in water, 72% human toxicity in air and more than 60% eco toxicity in air. However, it has low emission of eco toxicity in water compared to use phase. This result may be due to the lack of inventory loading data availability in terms of HC and heavy metals in aggregate and HMA production. Otherwise, it can be expected that material phase could have a higher contribution toward eco toxicity in water. In addition to that, this phase consumes the highest amount of raw materials causing the depletion of minerals.

Use phase is a combination of three areas which are normal traffic, traffic disruption and lighting. Based on the overall impact assessment it appears that use phase has the most significant environmental impact in terms of depletion of fossil fuel, global warming, acidification, photo oxidant formation and eutrophication. This phase is responsible for approximately 27% human toxicity in air and 36% eco toxicity in air. This phase has less significant effect in terms of human toxicity in water. Paving and maintenance together are responsible for approximately more than 2% of environmental burdens in terms of human toxicity in water. Both construction and maintenance phases have very low environmental emission compared to the material and use phases. However, the maintenance phase has a high emission rate in five impact categories compared to construction phase which are acidification, depletion of fossil fuel, photo oxidant formation, global warming and eutrophication.

10. Recommendations or alternatives

As expected, it appears that the use and material phases of HMA pavement place a greater burden on the environment. In the developed countries (i.e. United States) it is very difficult to control the emission from use phase as it is a combination of normal traffic, traffic disruption and lighting. In the US for example, almost everybody has their own individual car. This is unlike the situation in Asia where most of the people travel by public transportation. Fig. 4 represents the concerned facts from the emission of HMA pavement. Categories like human toxicity, fossil fuel depletion and global warming are most impactful. Global warming and fossil fuel depletion are due to use phase whereas material phase is solely responsible for human and eco toxicity.

So, the need is to control the emissions from the use phase by implementing more public transportation and bringing awareness among people. On the other hand, it is possible to reduce the emissions from material phase by implementing new material production and pavement design technology. WMA technology has the potential to reduce the emissions that are typically associated with the production of HMA.

11. Warm mix asphalt (WMA)

WMA is generally produced and spread at lower temperatures in comparison with HMA. HMA is manufactured at

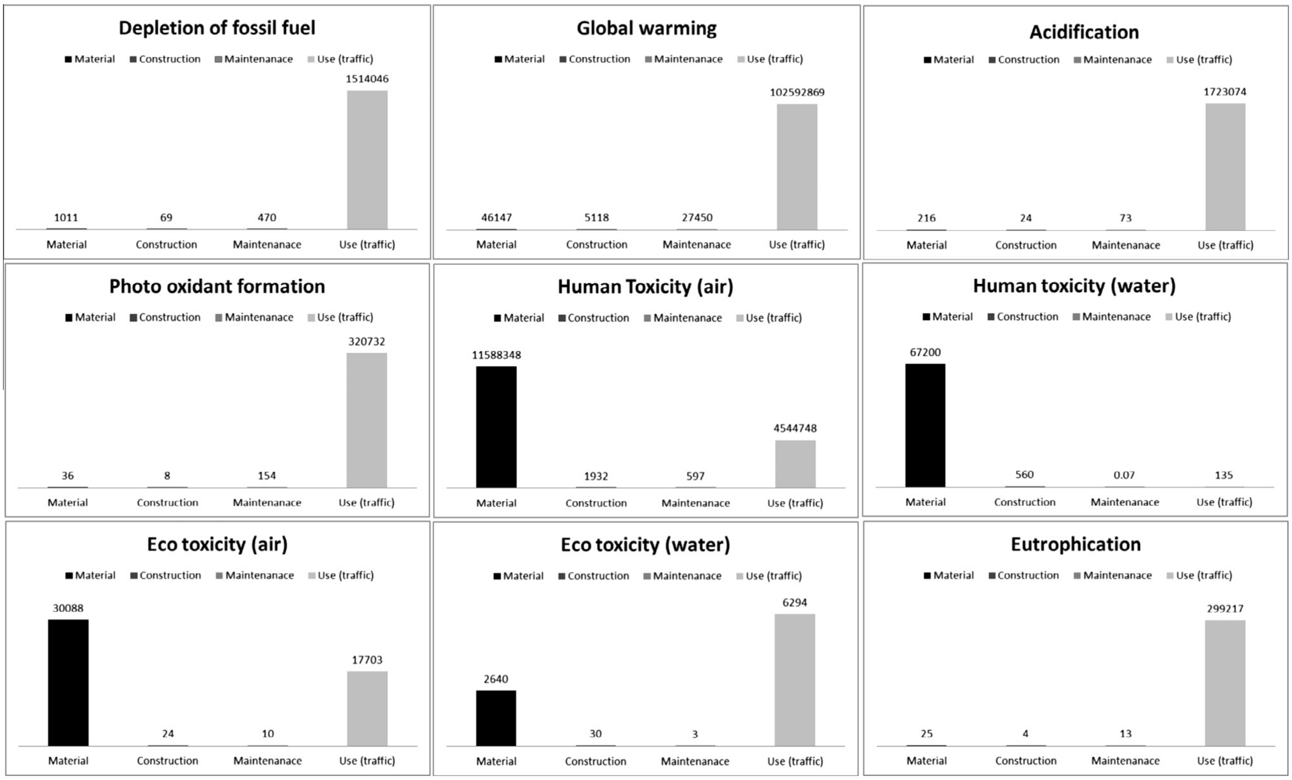

Fig. 3. Quantification of all the impact categories for each life cycle of HMA pavements.

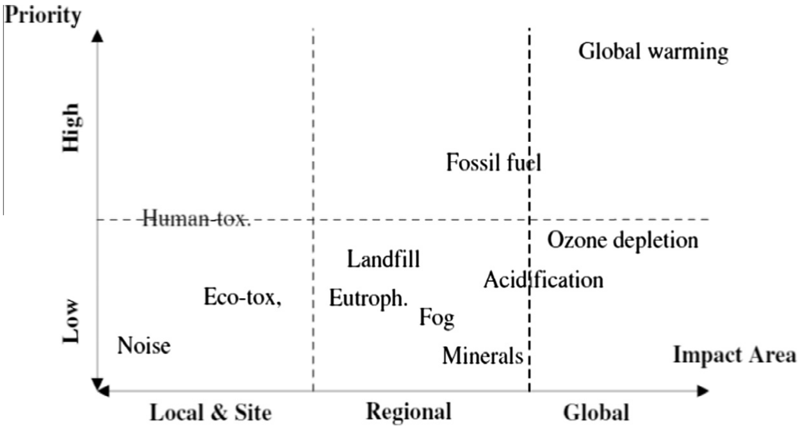

Fig. 4. Concerned impact area of asphalt pavement [10].

150–190 °C whereas WMA and half WMA are produced at 100–140 °C and 60–100 °C respectively [11,17]. This lowering of temperature is the result of adding organic additives, chemical additives and water based or water containing foaming agents. These additives are categorized into three parts (i) foaming processes (divided into water-containing and water based process); (ii) addition of organic additives (Fischer–Tropsch synthesis wax, fatty acid amides, and Montan wax); (iii) addition of chemical additives (usually emulsification agents or polymers).

There are significant environmental benefits to the use of WMA. It reduces the asphalt plant emission, fumes and energy consumption which are all beneficial for the environment as well as for the human employees. Also, the addition of recycled scrap tires to WMA is possible. This way it is possible to produce rubberized asphalt mixtures which can reduce the mixing and compaction temperature as well as extend the performance of the pavement.

Table 11
Unit characterization factor for WMA inventory data [8,11,18].

Emission components from HMA	Reduction due to use of WMA (%)	LCI for WMA (LCI for HMA × unit factor)
CO	8	×0.92
NO_x	60	×0.40
CO_2	35	×0.65
SO_2	25	×0.75
VOC	50	×0.50

11.1. Methodology to calculate inventory and impact data for WMA

The same methodology as was outlined earlier in regard to HMA, was applied to find the impact category data for WMA. WAM-Foam technology was adopted in this study. The environmental impacts of the WMA additives were neglected due to their small masses as compared to the functional unit considered in the analysis. It was evident from the literature review that for estimating the life cycle inventory for WMA, we need to adjust the quantities of the life cycle inventory data of HMA production, as illustrated in Table 11. Reduction is only done in HMA production. Based upon the data availability and unit characterization factor, the benefit of using WMA over HMA was evaluated on four impact categories: depletion of fossil fuel, global warming, acidification and photo oxidant formation. Table 11 presents the unit characterization factor for converting HMA inventory data to WMA inventory data.

11.2. Results and analysis

As expected, WMA has a better environmental performance compared to HMA in all these four categories. Table 12 presents the difference between HMA and WMA in terms of environmental impact.

Fig. 5 illustrates the percentage improvement due to the use of WMA on these four impact categories. WMA provides a reduction of 26% on the global warming impact of HMA and a reduction of 29% on acidification. The

Table 12
Difference between HMA and WMA.

Impact category	Unit of characterization factor	HMA	WMA
Depletion of fossil fuels	GJ	1010.62	754.95
Global warming	Kg CO_2-eq. (100 years)	46147	34102
Acidification	Kg SO_2-eq.	215.68	152.70
Photo oxidant formation	Kg C_2H_4-eq.	35.61	26.57

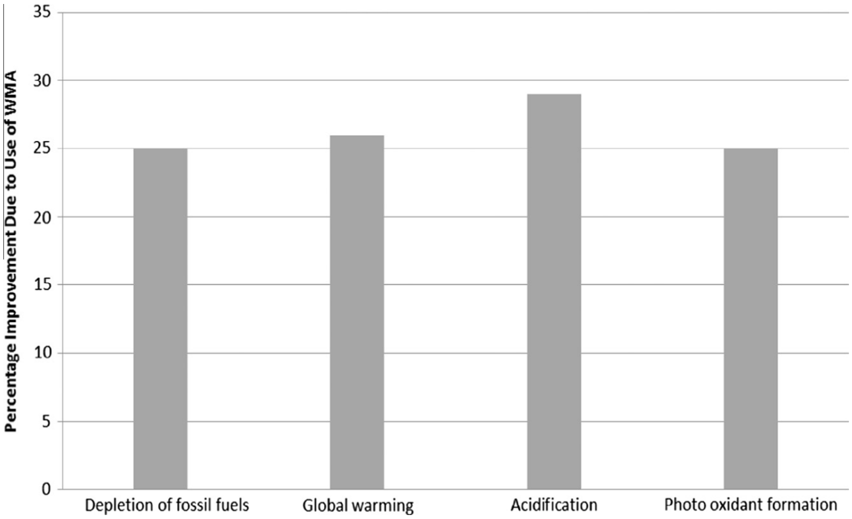

Fig. 5. Percentage improvement due to the use of WMA.

other two impact categories, fossil fuel consumption and photo oxidant formation decreased by 25%. The fossil fuel consumption is less due to lower temperature requirement during the production of WMA. Also, the emission of other inventory loadings responsible for photo oxidant formation, acidification and global warming are less due to the use of WMA.

12. Summary and conclusions

The objective of the study has been to assess the environmental impact of HMA pavement and to recommend alternatives for reducing the environmental emissions. In order to investigate the environmental burdens of four phases (material, construction, maintenance and use) of HMA pavement in terms of energy, air emissions and water emissions, a comprehensive LCA model was utilized and comparison made among those phases. To accomplish this objective, a life cycle inventory that quantifies the energy, material phase inputs, construction phase inputs, maintenance phase inputs and use phase inputs was adopted from the literature review. All inventory loadings were converted to their respective impact categories using LCA model and impact assessment were evaluated on ten categories. Based on the analysis conducted, the following conclusions may be drawn:

(1) The environmental burdens of HMA pavements significantly depend on the material and use phases. The material phase is mainly responsible for human and eco toxicity whereas the use phase contributes more to the other impact category areas. The material phase contributes 97% of the human toxicity in water, 72% of the human toxicity in air and more than 60% of the eco toxicity in air.

(2) Among the three sub phases of material phase, production of bitumen is responsible for 90% human and eco toxicity in terms of air based burden, whereas, the production of bitumen and HMA appeared to have equal contribution to the toxicity of water.

(3) The use phase has the most adverse effect on global warming, fossil fuel depletion, acidification, photo oxidant formation and eutrophication.

(4) The environmental burden imposed by the construction and maintenance phases is lower compared to the material and use phases. However, between these two phases the maintenance phase is more impactful to the environment.

(5) As it is very difficult to reduce the emissions from the use phase due to the increasing demands placed by the growing population and traffic, there is a strong need to control the environmental impact from material phase by implementing innovative techniques like WMA. The results indicated that WMA has lower environmental emissions compared to HMA in terms of global warming, acidification, fossil fuel depletion and photo oxidant formation. Specifically, WMA provides a reduction of 25% on the depletion of fossil fuel and photo oxidant formation. Likewise, the use of WMA is estimated to provide a reduction of 26% on the global warming and 29% on the acidification impacts of HMA respectively.

(6) A comprehensive LCA model is used to quantify the environmental impact of the HMA pavement and the production of WMA. This evaluation is based upon current data available from a limited number of sources. Further research and data collection is recommended in terms of HC and heavy metals in the field of aggregate and HMA production in order to find out the quantitative contribution of material phase on the eco toxicity in water. As the use of WMA has a positive impact on reducing the environmental impact from HMA production, it is necessary to find out its quantitative improvement on other impact categories. In addition to that, other

technologies such as reclaimed asphalt pavement (RAP) may be investigated for use so as to effect further sustainable improvements in HMA production.

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