Estimation of Cumulative Energy Demand and Green House Gas Emissions of Ethanol Foamed WMA using Life Cycle Assessment Analysis

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Abstract: The purpose of this project is to evaluate the possibility of using ethanol as a foaming agent for low emission asphalt technology via Life Cycle Assessment (LCA) analysis. LCA analysis was conducted at two different stages. Firstly, the analysis was performed to estimate the energy consumption and CO₂ emission in the cradle to gate stages incorporating the effects of various foaming agent contents. In the second assessment, the analysis attempts to incorporate the required information based on the available published papers to get a clear idea about the energy consumption and GHG emission involved in all stages from the raw materials production to the end of life of asphalt pavement. The scope and boundaries of this analysis have been set based on several assumptions made prior to performing the analysis. LCA software, SimaPro 7.3, was used to estimate the cumulative energy demand and global warming potential (GWP) of Ethanol-foamed Warm Mix Asphalt (EWMA) and compare these to the results of Hot Mix

Asphalt (HMA) and Water-foamed Warm Mix Asphalt (WWMA). Eco-Indicator 95 analysis was also conducted to establish the weighting factors for the various environmental effects of each asphalt mixture. Based on the results, it was found that the EWMA performed better in terms of energy demand, and lowered GHG emissions compared to HMA and WWMA. EWMA has high potential to reduce the detrimental impacts from the asphalt pavement industry based on Eco-Indicator 95 analysis, which has a lower impact in terms of GHG emissions, ozone layer depletion, acidification, eutrophication, summer smog, and winter smog, as well as energy resources.

Keywords: Low emission asphalt, energy consumption, environmental benefits, human health, sustainable asphalt pavement

1. Introduction

Energy consumption is one of the key elements in pavement construction that significantly contributes to the entire construction cost. In conjunction with that, it is important to control the entire construction cost, and to meet increasingly stringent environmental regulations using a green and energy saving technology, which is known as warm mix asphalt (WMA). Formerly, this technology was discovered by Professor Csanyi at Iowa State University in 1956 [1]. In his study, the foaming asphalt was found to have great potential to use as a soil binder. Then, his invention was altered by incorporating cold water instead of steam into the asphalt, and later licensed to Conoco Inc. to promote foamed asphalt technology in the United States [2, 3]. In general, the foaming effect can be achieved by introducing a small amount of water into the asphalt binder prior to mixing with aggregates during the asphalt concrete production process [4]. The water creates a volume expansion of the binder that results in foamed asphalt, as well as improved the workability, and aggregate coating at lower temperature [5]. Currently, there are two techniques typically used in producing foamed WMA, which are foaming admixture, and the free water system [6, 7]. The energy savings and emissions reductions introduced by current foaming WMA technology could be enhanced if the production process is conducted at still lower temperature settings, through application of ethanol-foamed WMA (EWMA). Generally, ethanol can function in the same manner as water (in water-foamed WMA (WWMA)) and requires less energy to foam, due to its lower boiling temperature, 78 °C. Numerous bubbles will be generated by the vaporized ethanol, which significantly increases the volume of foamed asphalt, hence lowering the asphalt binder viscosity and improving the coating process of aggregates.

WMA using water as a foaming agent is one of the most commonly used WMA technologies in the United States due to its cost-effectiveness. Generally, no extra additives are required and the water is easier to handle and obtain [8]. The concept behind the foamed WMA is that the water turns into steam

and disperses throughout the asphalt, and then the steam expands the volume of the binder. Currently, numerous research projects are still going on prior to improving the performance of the foamed WMA pavement. The list of currently available foamed WMA technologies is presented in Table 1 [9].

The life cycle assessment (LCA) is being accepted and used by the engineers and road industry to assess environmental impacts based on the inventory of relevant energies, resource inputs and environmental outputs [10, 11]. The concept of LCA is not new and extensively applied to measure the impacts of the entire process or production to the environment that linked to any activities from the initial assembly of raw materials to the end-of-life of the product, which all residuals are returned to the earth (landfill). This concept is referred as “cradle to grave” [11]. Based on Horvath and Hendrickson [12] the phases in the LCA analysis can be categorized into five different stages for the entire life cycle of a product:

- i. Materials extraction phase
- ii. Materials processing stage
- iii. Product manufacturing stage
- iv. Use phase
- v. Disposal stage of the product, also referred as end-of-life

2. Goals and Scopes

The purpose of this project is to evaluate the possibility of using ethanol as a foaming agent to reduce the production temperature of asphaltic concrete. Through application of LCA, the overall life cycle performance of EWMA could be understood and compared to two other types of asphalt concretes. Application of ethanol in foamed WMA is believed to be able to greatly reduce the energy

47 required and CO₂ emission during the production and construction of the pavement, due to lower
48 temperatures during the production and construction processes. Analyses have been conducted at two
49 different conditions: 1) cradle to gate analysis for the foamed asphalt mixture prepared at different
50 temperatures and foaming agent contents, and 2) cradle to grave analysis to understand the overall
51 performance of each mixture type. The phases that involved in the cradle to gate analysis are the
52 materials extraction phase, materials processing stage, transportations of raw materials from producers
53 to the asphalt plant and production of the asphalt mixtures. In the cradle to grave analysis, evaluations
54 were only conducted on HMA that prepared at 160°C, WWMA that was prepared at 110°C with 1wt%
55 water, and EWMA produced at 80°C with 1wt% ethanol. The percentages of foaming agents were
56 computed based on the mass of asphalt binder. Several assumptions have been made prior to conducting
57 the LCA, such as:

- 58 1. All the pavement systems have a comparable service life of about 10 years.
- 59 2. The machineries that are used for the construction are the same.
- 60 3. The maintenance procedure and the performance of all systems are the same, without
61 consideration on the climate effects and volume of traffic.
- 62 4. The detailed information about all the systems has been selected based on the field evaluations
63 and experimental works as well as literature review from previous studies.

64 Through LCA analysis, the results for the different asphalt pavements could be compared
65 between each other in order to decide the best alternatives based on energy consumption, carbon
66 footprint, as well as impacts to the environment.

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68 3. Methodologies and Data Inventories

69 This analysis attempts to incorporate the required information as much as possible to get a clear
70 idea about the energy consumption and GHG emission involved in: 1) production (cradle to gate) stages,
71 2) and in the entire (cradle to grave) stages from the raw materials production to the end of life of
72 asphalt pavement. Fig. 1 shows the general LCA scope and boundaries that were considered in the
73 analysis of HMA pavement. Meanwhile, Fig. 2 presents the boundaries that were involved in conducting
74 the assessment on EWMA and WWMA. However, the LCA analysis in this study only takes into
75 consideration the surface (top) layer of the asphalt pavement structure and setting the rest of the
76 pavement structural (sub-grade, base, sub-base, road base) as consistent throughout the analysis. In
77 addition, the type of aggregate and binder grade used in the analyses were the same. Basically, in the
78 foamed WMA concrete, the water and ethanol were used to improve the ability of asphalt binders to coat
79 the aggregate particles at a lower temperature compared to the temperature that is used in the production
80 of conventional HMA. Most of the data involved in the analysis were based on a paper that was
81 published by Chehovits and Galehouse [13] and data which was available in the SimaPro 7.3.

82 In the case of this study, the functional unit is based on one kilometer length of road (two-way
83 road with one lane each direction) and a lifetime of ten years for all three systems. Prior to calculating
84 the volume of asphalt content required for the production of each pavement types, the total width and
85 thickness of the pavement surface layer has been set at 7.5 m and 100 mm, respectively. In addition, the
86 bulk specific gravity of pavement was assumed equal to 2.45.

87
88 Tables 2 to 4 show the input that was incorporated in the LCA analysis of HMA, WWMA and
89 EWMA. The mass of materials adopted in the analysis is based on the Michigan Department of
90 Transportation (MDOT) design, which is about 93 wt% of aggregate, 5.5 wt% of asphalt binder and 1.5
91 wt% filler material. All materials' masses were calculated based on total mass of asphalt concrete. The

raw materials were transported from the nearest available sources in order to reduce the amount of energy consumed and GHG gas emitted while transporting the material from the selected locations to the asphalt concrete production plant in Hancock, Michigan. The locations and total distances required in transporting all the materials are as shown in Fig. 3 and Table 2. Table 3 presents the energy consumed during the production of asphalt concrete and energy required by the pumping system for supplying the foaming agent to the mixing drum. Chehovits and Galehouse [13] mentioned that the manufacturing process covers all steps including handling, storing, drying, mixing and preparation of materials for installation. The manufacturing of HMA consumed about 275 MJ/t (160°C), followed by WWMA with 234 MJ/t (130°C) and 161.6 MJ/t (110°C), while the energy consumptions for the EWMA are 138.2 MJ/t and 95.8 MJ/t for the specimen prepared at 100 and 80°C, respectively. Those adopted energies were based on the interpolations of data referred from Chehovits and Galehouse [13]. When producing the WMA using the asphalt foaming system, a separate device consisting of a storage tank and high pressure pump is required to supply the foaming agent into the heated asphalt [9]. The energy required in operating the high pressure pump is assumed to be approximately 4.94kW/t and 6.35kW/t for the water and ethanol, respectively based on the available pump in the market. The input required for the cradle to grave analysis, involving transporting asphalt mixture to the construction site, pavement rehabilitation and waste scenario are presented in Table 4. The chip seal or seal coat has been used for pavement rehabilitation, which is typically applied in the fourth and eighth years.

4. Results and Discussions

4.1 Energy Consumptions and CO₂ Emissions during Production Stage

114 The cumulative energy demand V1.08 results are shown in Figs. 4 to 6. Based on Fig. 4, the
115 applications of 1wt% and 3wt% of ethanol have increased the energy consumption of EWMA
116 production, which is associated with the delivery process of ethanol to asphalt production plant by
117 approximately 0.18%. Meanwhile, about 0.36% higher energy is required for transporting raw material
118 prior to using 5wt% ethanol as a foaming agent at both production temperatures, 80°C and 100°C. The
119 applications of foaming WMA have lowered the cumulative energy demand for preparing asphalt
120 mixture as presented in Fig. 5. Based on the results, EWMA has a high potential to reduce the energy
121 consumption via lowering the manufacturing temperature. However, excessive amounts of ethanol
122 should be avoided to limit the total energy demand in the overall manufacturing process that is
123 contributed by the ethanol production. This involves cultivation of corn and manufacturing of ethanol
124 liquid. Prior to this, the application of 5% ethanol should be avoided due to excessive amount of energy
125 consumption compared to HMA. However, to select an adequate temperature for EWMA mixture
126 production, it should be based on the sample performance either from the experimental works or field
127 trials. According to WWMA mixtures' energy consumption at both production temperatures (110°C and
128 130°C), higher amounts of foaming agents (water) do not considerably effect the amount of energy
129 required for the manufacturing process. Overall, each pavement presents a similar trend, whereas more
130 than 90% of energy was consumed during the manufacturing process of asphalt mixtures in the early life
131 of asphalt pavement. Fig. 6 shows the total energy demand for each asphalt mixture. It is found that
132 WMA technique can be applied to help support the sustainable development by lowering the energy
133 consumption in the asphalt pavement industry. Besides lowering the required energy for the heating and
134 mixing processes, WMA technology also results in lower aging factor that has significantly improved
135 the fatigue resistance of asphalt pavement [9], especially for the pavement that is placed in the hot

climate regions. However, attention should be taken into account to avoid premature permanent deformation especially in the beginning of service life [9].

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The global warming impacts of different asphalt pavements were assessed using IPCC 2007 GWP 100a to compare the GHG emissions of HMA, WWMA and EWMA. The application of foaming WMA technologies has reduced the total CO₂ emissions during preparation of asphalt mixture. The total GHG emissions resulted from each pavement type are shown in Fig. 7. Based on the figure, it is found that the amount of CO₂ released from WWMA mixtures is constant even when a higher amount of water is used. However, the CO₂ emission of the specimen prepared using ethanol in EWMA is proportionally increased when a higher amount of ethanol is used. This trend can be seen from the EWMA mixture prepared at 80°C and 100°C. The emission was generated during the ethanol's production in the factory and while transporting it to asphalt plant was automatically considered in the SimaPro 7.3. Meanwhile, the constant CO₂ emission from WWMA mixtures is due to the application of water as foaming agent, since water does not require transportation as tap water was used in the case of this study. Asphalt mixture manufactured using foaming WMA technique and ethanol as foaming agent emit a significantly lower amount of GHG, especially for the specimen prepared at 1% and 3% ethanol (based on the mass of asphalt binder).

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Fig. 8 shows that the EWMA has the lowest CO₂ emission compared to WWMA and HMA, especially during asphalt mixture production stage. However, there are no considerable differences of CO₂ emissions in all pavements during the transportation of raw materials to the asphalt plant. About 0.26% (100 kg CO₂ eq) additional GHG has been released for transporting ethanol from the factory to the asphalt plant. This result was observed from the EWMA mixtures prepared using 3% and 5%

159 ethanol at both production temperatures, 80°C and 100°C. The CO₂ emissions during transportation of
160 raw materials only represent less than 10% of the total CO₂ emitted from the asphalt production in the
161 asphalt pavement industry.

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164 4.2 *Cumulative Energy Demand in the Entire Life Cycle Period*

165 The total cumulative energy demand results are shown in Figs. 9 to 11. In general, HMA results
166 in the highest energy demand, followed by WWMA and EWMA as presented in Fig. 9. The application
167 of WMA technology has reduced the energy consumed during production of HMA, which are about
168 1.96% and 2.93% using WWMA and EWMA respectively. Based on Fig. 10, each pavement presents a
169 similar trend, with more than 95% of energy consumed during the lifetime of the pavements. From Fig.
170 11, it is clearly shown that the highest energy demand during the service life of asphalt pavement is
171 dominated by the manufacturing/placement of pavement. Based on the cumulative energy demand, the
172 WMA technique can be applied to support sustainable development by lowering the energy
173 consumption in asphalt pavement industry. Besides lowering the required energy for the heating and
174 mixing processes, WMA technology also results in lower aging factors that had significantly improved
175 the fatigue resistance of asphalt pavement [9], especially for the pavement placed in the hot climate
176 regions. However, additional attention should be factored in to avoid premature permanent deformation
177 especially at the beginning of service life [9].

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179 4.3 *Global Warming Potential in the Entire Life Cycle Period*

180 The global warming impacts of different asphalt pavements were assessed using IPCC 2007
181 GWP 100a to compare the GHG emissions of HMA, WWMA and EWMA. The application of foamed

WMA technologies has reduced the total CO₂ emissions of HMA, which are about 5.65% and 9.13% using WWMA and EWMA, respectively. The total GHG emissions result of each pavement type is shown in Fig. 12.

From Fig. 13, it can be seen that the EWMA has the lowest CO₂ emission compared to WWMA and HMA. However, there is no different in CO₂ emissions in all pavements during the waste disposal stage. Overall, the CO₂ emissions during the waste disposal stage only represent about 10% of the total CO₂ emitted from “cradle” to “grave” in pavement industry. Fig. 14 further shows that the use of EWMA results in the smallest environmental footprint compared to the application of HMA and WWMA. Based on the amount of CO₂ emissions during manufacturing and placement of asphalt concrete, EWMA released about 8,000 and 21,000 kgCO₂ less than WWMA and HMA respectively, during the manufacturing/construction process.

At the end of service life, the asphalt pavements are typically milled from the road and can be either disposed in the sanitary landfill or reused as Reclaimed Asphalt Pavement (RAP). However, in this study all materials were assumed to be disposed into the sanitary landfill. The life cycle inventory of the disposal waste was selected from the Eco-invent database which was available in the SimaPro 7.3. Doka [14] stated that the inventory includes the environmental burdens, machinery and transportation, landfill leachate, emissions to air through landfill gas incineration, long term emission from landfill to groundwater and treatment of leachate in wastewater treatment plants. Based on the result of this study (Fig. 15), it was found that the highest amount of CO₂ has been released by bitumen in the waste disposal stage, about 64.47%. This is due to the presence of a high amount of carbon molecules in the asphalt binder compared to the other materials. Application of RAP material had significantly lowered

the CO₂ emissions, and also enhanced the performance of asphalt pavement. However, the disposal process of aggregate has consumed the highest energy compared to asphalt binder and filler materials. This is due to 93% of asphalt pavement being dominated by aggregate.

4.4 *Eco-Indicator 95 Analysis*

The environmental impacts of HMA, WWMA, and EWMA were evaluated using Eco-Indicator 95 as tabulated in Table 5. This method is categorized as a technical, quantitative and / or qualitative process to characterize the effects of environmental burdens identified in the LCA inventory. Vidal et al. [15] mentioned that the contributions of every stage of the life cycle and waste disposal stages to the overall impact varies depending on the types of asphalt pavement. Based on the overall results, the impacts of EWMA are lower compared to WWMA and HMA pavements. This is due to the reduction of manufacturing and construction temperatures, which are 30°C and 80°C lower compared to WWMA and HMA, respectively. The major reduction can be seen through a significant reduction of GHG emissions, acidification, eutrophication, and winter smog as well as energy resources. Besides that, WWMA had performed better in term of heavy metals and carcinogen impacts; however the differences compared to other pavement types are less than 2%.

5. **Conclusions**

Based on the cradle to gate analysis, several conclusions can be made:

1. The cumulative energy demand and GHG emission of each asphalt pavement is primarily affected by the type and the quantity of material that is incorporated in the asphalt concrete. Smaller energy consumption and GHG emission were noted when the EWMA manufactured at a lower temperature.

2. The transportation of raw materials only consumed less than 10% of the energy compared to asphalt mixture production which dominated at least 90% of the total energy consumption from the cradle to gate stages. Meanwhile, more than 70% of GHG has been released during the manufacturing of raw material and asphalt mixture.
3. EWMA is a good alternative in replacing HMA and WWMA. However, from the result, the amount of ethanol should be limited to 3% to ensure the energy consumption is lower than the production of HMA.

Based on the cradle to grave analysis, several conclusions can be made:

1. Even though this study is not definitive, with regard to environmental performance, EWMA has performed better compared to WWMA and HMA.
2. Cumulative energy demand and GHG emissions for different asphalt pavements are primarily depending on the production temperature. Asphalt pavement manufactured at lower temperature requires a smaller amount of energy and lower GHG emission as shown by EWMA. The results indicate that more than 98% of energy was consumed during the pavement service life. Meanwhile, about 88% of GHG has been released during the pavement lifetime.
4. EWMA has a high potential to reduce the detrimental impacts from the asphalt industry based on Eco-Indicator 95 analysis, whereas it can lower the greenhouse gas emissions, ozone layer depletions, acidification, eutrophication, summer smog, winter smog and energy resources.
5. EWMA is a good alternative in replacing HMA and WMA using water as a foaming agent. However further study on the laboratory prepared and field trial samples should be carried out to understand the long term performance and durability of EWMA.

251 **6. Recommendations for Future Works**

- 252 1. The energy consumptions used in heating/drying the materials also could be affected by the
253 properties of those materials, including specific heat capacity and specific gravity. Prior to
254 getting a better result, it is important to incorporate those criteria especially for the asphalt
255 mixing plant that uses a combination of different aggregate types that were purchased from
256 different sources.
- 257 2. Commonly used asphalt binder grades differ depending on the highest and lowest temperature
258 experienced by the asphalt pavement in a specific area. Different performance grades of asphalt
259 binders typically have different properties in terms of chemical composition, as well as ideal
260 viscosity for mixing and the compaction process. The credit regarding this property should be
261 taken into consideration in order to get an optimum result. On the other hand, different
262 pavement rehabilitation methods and life extension periods also should be considered in order to
263 improve the accuracy of the analysis.
- 264 3. It is also suggested to incorporate different types of ethanol and the energy allocation, as well as
265 strictly considering the type of machines involved in the manufacturing and construction process
266 of asphalt pavement.
- 267 4. The overall performance through assimilation of long term performance, and additional cost due
268 to incorporation of ethanol also should be evaluated in future works prior to providing the best
269 asphalt pavement option in supporting sustainable development.

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1 **Table 1.** List of foamed WMA technologies

Foaming Additives or Technologies	Company	Recommended Dosage
Aspha-min®	Eurovia and MHI	0.3 wt% of asphalt concrete
ADVERA® WMA	PQ Corporation	0.25 wt% of asphalt concrete
WAM-Foam®	KoloVeidekke Shell Bitumen	No additive required. Incorporating soft and hard foamed binder
LEA®	LEA-CO	0.2-0.5 wt% of asphalt binder
LEAB®	BAM	0.1% wt% of asphalt binder

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1 **Table 2.** Transportation of raw material and mass of material required inputs

Process	Item	Pavement Type		
		HMA	WWMA	EWMA
Transportation of raw material to asphalt plant	Aggregate	21422 km	21422 km	21422 km
	Bitumen	6207.9 km	6207.9 km	6207.9 km
	Filler (Cement)	172 km	172 km	172 km
	Foaming Agent			1%: 25.7 km
	($M_n\% / \sum M$) x Total Distance	-	Tap water	3%: 77.1 km 5%: 129 km
Mass of materials required	Aggregate	1708.88 t	1708.88 t	1708.88 t
	Binder PG58-28	101.06 t	101.06 t	101.06 t
	Filler (Cement)	27.56 t	27.56 t	27.56 t
	Foaming Agent	-	1%: 1.01 t	1%: 1.01 t
			3%: 3.03 t	3%: 3.03 t
			5%: 5.05 t	5%: 5.05 t

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1 **Table 3.** Energy required for asphalt mixtures production processes and foaming agent pump

Foaming Agents	Production Temperature (°C)	Composition (Based on Mass of Asphalt Binder)	Energy Required for Production Process (GJ)	Energy Required for Foaming Agent Pump (kwh)
Water	110	1%	297.10	2.49
		3%	297.43	7.48
		5%	297.76	12.48
	130	1%	430.21	2.49
		3%	430.68	7.48
		5%	431.16	12.48
Ethanol	80	1%	176.13	3.21
		3%	176.32	9.63
		5%	176.52	16.04
	100	1%	254.08	3.21
		3%	254.36	9.63
		5%	254.64	16.04

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1 **Table 4.** Input required for the cradle to grave analysis

Process	Item	Input
Total Distance for Transporting material to site	Asphalt Mixture	656.3 km
Placement of Pavement	HMA	16.54 GJ
	WWMA	15.99 GJ
	EWMA	13.78 GJ
Pavement rehabilitation	Aggregate	315 t
	Emulsion	34.5 t
	Energy for the machineries	133.5 GJ
Waste scenario	Aggregate	92.5%
	Asphalt Binder	6.2 %
	Filler (Cement)	1.3 %

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1 **Table 5.** Eco-indicator 95 analysis results

Impact category	Unit	Type of Asphalt Concrete		
		HMA	WWMA	EWMA
Greenhouse	kg CO ₂	210015.4	192858.3	188651.8
Ozone layer	kg CFC ₁₁	0.152169	0.149301	0.148481
Acidification	kg SO ₂	1513.263	1282.78	1215.08
Eutrophication	kg PO ₄	1076.221	1036.607	1036.002
Heavy metals	kg Pb	8.905603	8.842814	8.849174
Carcinogens	kg B(a)P	0.010013	0.009844	0.009928
Summer smog	kg C ₂ H ₄	259.9898	249.3126	245.8918
Winter smog	kg SPM	634.2758	567.1177	546.9637
Energy resources	MJ LHV	9203450	8948158	8933112

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Figureg

Fig. 1. HMA system

Fig. 2. Foamed WMA system made with water or ethanol

Fig. 3. Location of material production companies and asphalt mixing plant

Fig. 4. Energy demand from raw material transportation

Fig. 5. Energy demand based on pavement types during production process

Fig. 6. Energy demand during raw material transportation and manufacturing of asphalt mixtures

Fig. 7. Total GHG emissions of each pavement types

Fig. 8. Comparison of CO₂ emission during raw material transportation and manufacturing processes

Fig. 9. Energy demand based on pavement types

Fig. 10. Energy Demand during lifetime and waste disposal stage

Fig. 11. Energy demand categorized under transportation, manufacturing and maintenance processes

Fig. 12. Total GHG emissions of each pavement types

Fig. 13. Comparison of CO₂ emission during lifetime and waste disposal stage

Fig. 14. CO₂ emission observed in the transportation, construction and maintenance stages

(a) Greenhouse Gas Emission

(b) Energy Demand

Fig. 15. GHG emission and energy demand during waste disposal stage