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The environmental impact evaluation on the application of permeable pavement based on life cycle analysis

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ABSTRACT

Conventional pavement, namely concrete and asphalt pavements, usually necessitate considerable energy inputs during construction. Due to increasing road coverage in cities and the impervious feature of conventional pavements, the heat island effect is becoming increasingly severe. Many environmental problems have appeared. Permeable pavements have improved the situation. This study intends to achieve a convincing comparison of the environmental impacts of permeable pavements and conventional pavements. A methodological framework of life cycle assessment is used to quantify the environmental impacts in the study. The results indicated that during the use of the road, pavement roughness will increase and greatly impact the vehicle fuel consumption and road GHG emissions. The maintenance needs to be implemented in time. The cold mixing polymer composite based pavement has the best environmental friendly potential among three different pavement surface materials selected in the present research. Porous asphalt pavement does not show significant advantage in reducing energy consumption and GHG emissions comparing to the normal dense asphalt. This may because asphalt production requires heating, and the permeable feature of pavement is not considered. This study presented a basic evaluation of the environmental characteristics of different pavement materials. It provides a basis for the evaluation of environmental factors in pavement design and construction, which promotes a further research on the quantification of environmental factors in the future.

1. Introduction

The increasing global interest in environment sustainability calls for the impact assessment of all kinds of industries. Transportation infrastructures are an essential component of a city sustainability while pavement construction has a large impact on the environment. In addition to water pollution, conventional air pollution and noise, the environmental impact during a pavement's life cycle also includes greenhouse gas (GHG) emissions, energy consumption and so on. According to the U.S. Energy Information Administration (EIA), the buildings sector, which includes residential and commercial structures,

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accounts for almost 21% of the world's delivered energy consumption in 2015, while the worldwide transportation sector accounts for 55% of total end-use sector liquid fuels consumption in 2015 (EIA, 2017). Between 2000 and 2010, the annual GHG emissions of transport sector have increased from 10% to 14% of global emission of which approximately 72 percent is attributed to road construction, rehabilitation, maintenance, service, and usage (ASTAE, 2009). This quantification of environmental burdens is a significant step in improving pavement design and management strategies.

Nowadays, asphalt and concrete are widely used in pavement projects. However, the sealed area can lead to the heat island effect and undesired flooding when the drainage system capacity cannot satisfy the storm water volume (Zhu et al., 2018; Saadeh et al., 2019). As the sustainability of a city becomes more and more important, an innovative pavement, permeable pavement system (PPS), has become an important component. Traditional drainage systems use sewers and pipes to reintroduce rainwater from sealed areas back into the natural water cycle. For permeable pavement, the storm water will seep through the porous surface instantly instead of accumulating on the highway, causing flooding and damage to the pavement. The general principle of PPS is simply to collect, treat and infiltrate freely any surface runoff to support groundwater recharge (Scholz and Grabowiecki, 2007). The use of permeable pavement, instead of traditional asphalt, has been shown to decrease surface runoff and lower peak discharge significantly (Hunt et al., 2002). Furthermore, permeable pavement can effectively relieve the urban heat island effect. As urban surface temperatures rise, the water stored in the base or underlying soil evaporates and is released into the air from the pavement pores. Despite the enhanced drainage ability of permeable pavements, the environmental impacts should be evaluated.

To evaluate the environmental impacts of pavement, we can use life cycle assessment (LCA) to estimate life cycle energy consumption and green-house gas (GHG) during the life cycle of pavements. LCA is a standardized approach to quantifying the environmental impacts of a product, asset, or service throughout its life cycle (ISO, 2006). It is used to inform decisions on material selection to better understand, measure and reduce environmental impacts, hence it is sometimes referred to as environmental LCA (Glass et al., 2013).

Life cycle assessment (LCA) is a comprehensive approach to evaluating the total environmental burden of a particular product or more complex systems of projects (Li et al., 2016; Kayhanian et al., 2019). Therefore, LCA can be used to examine all the inputs and outputs over its life cycle, from raw material production to the end of the product's life. Besides giving the knowledge of products' environmental impacts, LCA results are also able to help making management strategies. According to the international standard, LCA is consist of four stages: goal and scope definition, inventory analysis, impact assessment and interpretation (ISO, 2006).

A lot of research has worked on the life cycle assessment of pavements. Because of the complexity, most literature focuses on the pavement itself or a specific component without considering all related aspects. System boundaries of existing researches are various. Incorporation of all life-cycle phases and components should be improved, and it is important to understand the relationship among each component (Santero et al., 2011). Maintenance and rehabilitation phase are frequently studied in pavement LCA works. The effects of different indicators are discussed. For instance, rolling resistance of pavement rehabilitation can significantly influence the energy use and GHG emissions under different traffic levels (Wang et al., 2012). A study provided preventive maintenance approach during the pavement service life to reduce the environment burdens (Giustozzi et al., 2012). The allocation of energy used for binder and additives for asphalt pavements is calculated at the project level (Butt et al., 2014).

A relatively detailed methodological framework by integrating the mechanistic-empirical pavement design guide (MEPDG) and pavement LCA (Chong and Wang, 2017). Based on the process of a pavement life cycle, the framework are developed by seven modules: (1) material, (2) construction, (3) maintenance and rehabilitation, (4) use, (5) congestion, (6) transport, (7) end-of-life. In their case, they analyzed the pavement-related energy consumption and GHG emissions under different traffic levels. They also provided the Green Asphalt Calculator (GAC) toolkit in a different piece of research for helping estimate the energy use of different asphalt mixtures under various production conditions (Chong and Wang, 2017). In one study, they develop an LCA model tool based on Microsoft Excel, but it is used for the calculation of construction and maintenance of asphalt pavement (Huang et al., 2009).

Impervious surfaces have a high potential for water pollution while permeable pavements are able to remove suspended solids and nitrogen (Scholz and Grabowiecki, 2007). Permeable pavement surface mainly includes: blocks, permeable asphalt, permeable concrete and Polyurethane. Block pavements are usually used in parking lot and walkways. It also has good infiltration ability, but it can be gradually clogged by fine particles and impurities at the joints (Renken et al., 2015). Permeable polyurethane (PU) bound asphalt pavements are considered as the most effective construction method for environmentally friendly transport infrastructures. The surface corresponds to 65–80% of the total pavement structure's carbon footprint (Vares and Pulakka, 2015). In material production phase, asphalt pavements can be energy intensive due to the essential heating of bitumen and aggregates to produce asphalt mixtures, while concrete and Polyurethane can be paved at ambient temperature. Hence, the energy consumption can be much lower.

In spite of the rapidly growing numbers of literatures on pavement LCA, little work has been done on the LCA of permeable pavements (Wang et al., 2018). The carbon footprint of permeable asphalt and permeable concrete is evaluated in Vares and Pulakka's work (2015). However, they didn't consider energy consumption, and the research only focused on light-load roadways such as walkways and bicycle lanes. Therefore, it is necessary to develop a reliable and systematic approach to evaluate the environment impacts of permeable pavement and to provide a more comprehensive assessment.

The purpose of this study is to (1) develop a reliable and global methodological LCA framework for pavement engineering, (2) apply the framework to estimate the life cycle energy consumption and GHG emissions of different kinds of permeable pavements, and (3) based on the evaluation results, provide suggestions to help make balanced decisions in design and management to improve pavement sustainability.

The framework and analysis will focus on the energy consumption and GHG emissions. The other environment indicators and life cycle cost may be studied in the future.

2. Materials and methodology

2.1. Materials

The present study will mainly assess three typical pavement materials: stone mastic asphalt (SMA-13), porous asphalt (PA) and Polyurethane-bound (PU) porous pavement. The main properties (grain size distribution, nature of grains, etc.) of each material are listed in Table 1.

SMA is a hot mixed pavement material consisting of bitumen, fibre stabilizer, mineral powder and a small amount of fine aggregates of asphalt mastic filled in well-graded coarse aggregates skeleton gap. Typical SMA composition consists of 70–80% coarse aggregate, 8–12% filler, 6.0–7.0% binder, and 0.3 per cent fibre. It provides a deformation-resistant, durable surfacing material, suitable for heavily trafficked roads. In recent years, it has been widely used in expressway and anti-skid surface as a highway.

Porous asphalt (PA) pavement is mainly composed of coarse aggregates of single particle size, with little or no fine aggregates added. Compared with other asphalt mixtures, the most significant feature of PA pavement is that has a large porosity (usually 13−25%). The surface of the aggregate particles is coated with a layer of asphalt binder to form a skeleton-void structure according to the intrusion mechanism. PA adopts intermittent gradation. The pores formed by skeleton inlaying have closed pores, semi-continuous voids and continuous pores. Water flows through the continuous pores in the porous asphalt mixture. Therefore, ensuring the formation of a certain number of well-connected void structures within the porous asphalt mixture is the key to the design of PA pavement.

Polyurethane is used as binder in PU permeable pavement. In recent years, increasing interest from industry concerning polyols derived from renewable sources has been noticed (Schacht et al., 2018), because these natural ingredients can be successfully used to obtain different Polyurethanes including porous composites (Sharma and Kundu, 2008).

Polyurethanes are synthesized using two basic components: isocyanates (A component) and polyols (B component) (Kurańska et al., 2013). To construct PU pavements, the following equipment is needed: a hand-held mixer for mixing A and B components of polyurethane, a vertical mixer for mixing gravel with polyurethane, and a driving trowel for light compaction and recovery after PU paving. Since PU binder doesn't need to be heated before construction, the construction process doesn't include a rotary dryer and bitumen heating and storage system.

2.2. Methodology

According to ISO14040 guidelines, the general framework of LCA is performed in three steps: Goal & Scope Definition, Inventory analysis and impact assessment. The LCA framework developed by the research of Chong and Wang, 2017 is used for calculation in this study. The present study aims to assess an assumed pavement project with different materials, thus to compare the impact of each material. The following assumed pavement conditions (Table 2) will support inventory analysis (Fig. 1).

Table 1
Grain size distribution of different pavement raw materials.

Materials	Grain size (mm)	Mass Percentage (%)		
		SMA-13	PA	PU
Limestone	0–0.063	8	4	2
Diabase	0.063–2	12	4	8
	2–5.6	15	7	41
	5.6–8	55	85	49
	8–11.2	10	0	0

Table 2
Conditions of the pavement.

	Unit	
Lanes		2
Width	m	$3.5 \times 2 = 7$
Length	km	1
Annual average daily truck traffic volume	per lane, per direction	5000

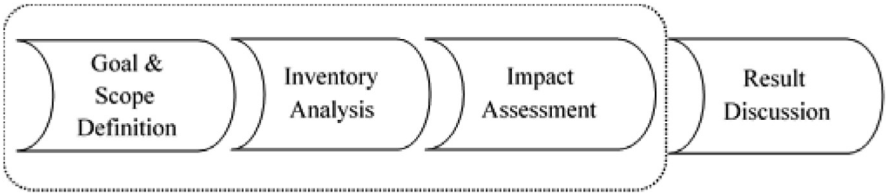

Fig. 1. The methodology framework.

2.2.1. Goal and scope definition

The study aims to assess the energy consumption and GHG emissions of three kinds of pavements with different surface materials in their life cycle. Meanwhile, the result of this study is able to evaluate the environment impacts of permeable pavement, which would provide suggestions to help make balanced decisions in design and management to improve pavement sustainability.

2.2.2. Inventory analysis

Inventory analysis is the most important step in LCA. Although there are varieties of indicators can be performed in inventory analysis, we only chose energy consumption and GHG emissions. The life cycle of pavement is divided into seven modules as shown in Fig. 2.

In material module, the environmental influence of raw material is estimated. After determining the types and quantities of pavement materials, the energy use and GHG emissions of acquiring and producing raw materials can be calculated by using the data of raw pavement materials from World Bank (2014) and others (Zhang et al., 2010).

In the construction module, energy consumption and GHG emissions is determined by equipment fleet, productivity and hourly fuel consumption of each piece of equipment. The total energy use and GHG emissions are the sum of the fuel consumption of each type of equipment and material. By using the Green Asphalt Calculator, we can easily calculate the energy use and GHG emissions during asphalt mixture production.

The types and quantity of vehicle and pavement roughness affect pavement performance, so they are the primary factors of energy use and GHG emissions in the pavement use module. The percentage of different type vehicles is provided by Zaabar and Chatti (2010). In order to compare the environmental impacts of pavements in different pavement roughness value, we calculated the energy use and GHG emissions in different international roughness index (IRI). To calculate the extra fuel consumed for different type of vehicle, the annual average daily traffic volume (AADT) is needed. In this study, the energy use and GHG emissions of three different pavement materials are calculated in different AADT in order to discuss the environmental impacts in different traffic level.

For SMA-13 and PA, patch repair is the most commonly used method in the maintenance and rehabilitation (M&R) module. And the M&R module is similar to the construction module. For the convenience of comparison, the end-of life module is not included. The pavement is assumed to have an infinite life span as long as M&R activities are implemented timely.

3. Results and discussion

As shown in Fig. 3, different pavements show a common pattern: AS IRI >2.76, with IRI value grows, energy consumption and GHG emissions increase rapidly and highly depend on AADT. For lower AADT values, the optimum IRI trigger value is 2.76 m/km. For higher AADT values, the optimum IRI trigger value is 2.56 m/km.

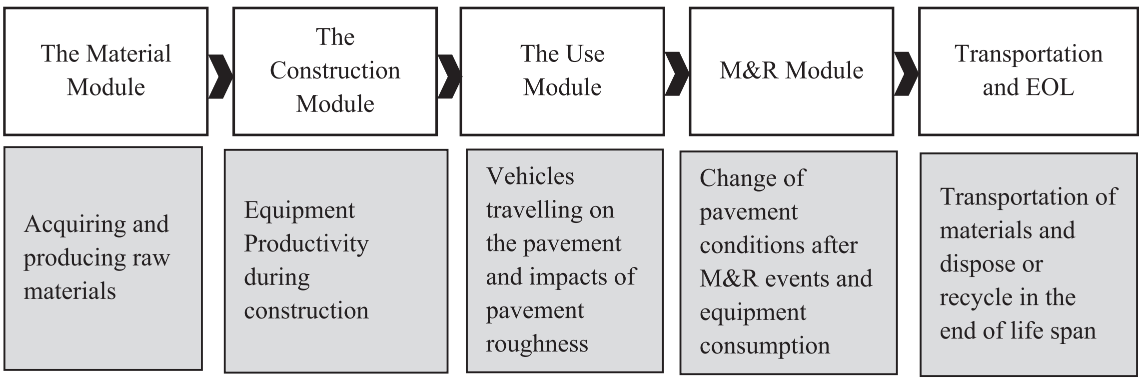

Fig. 2. Inventory Analysis Modules.

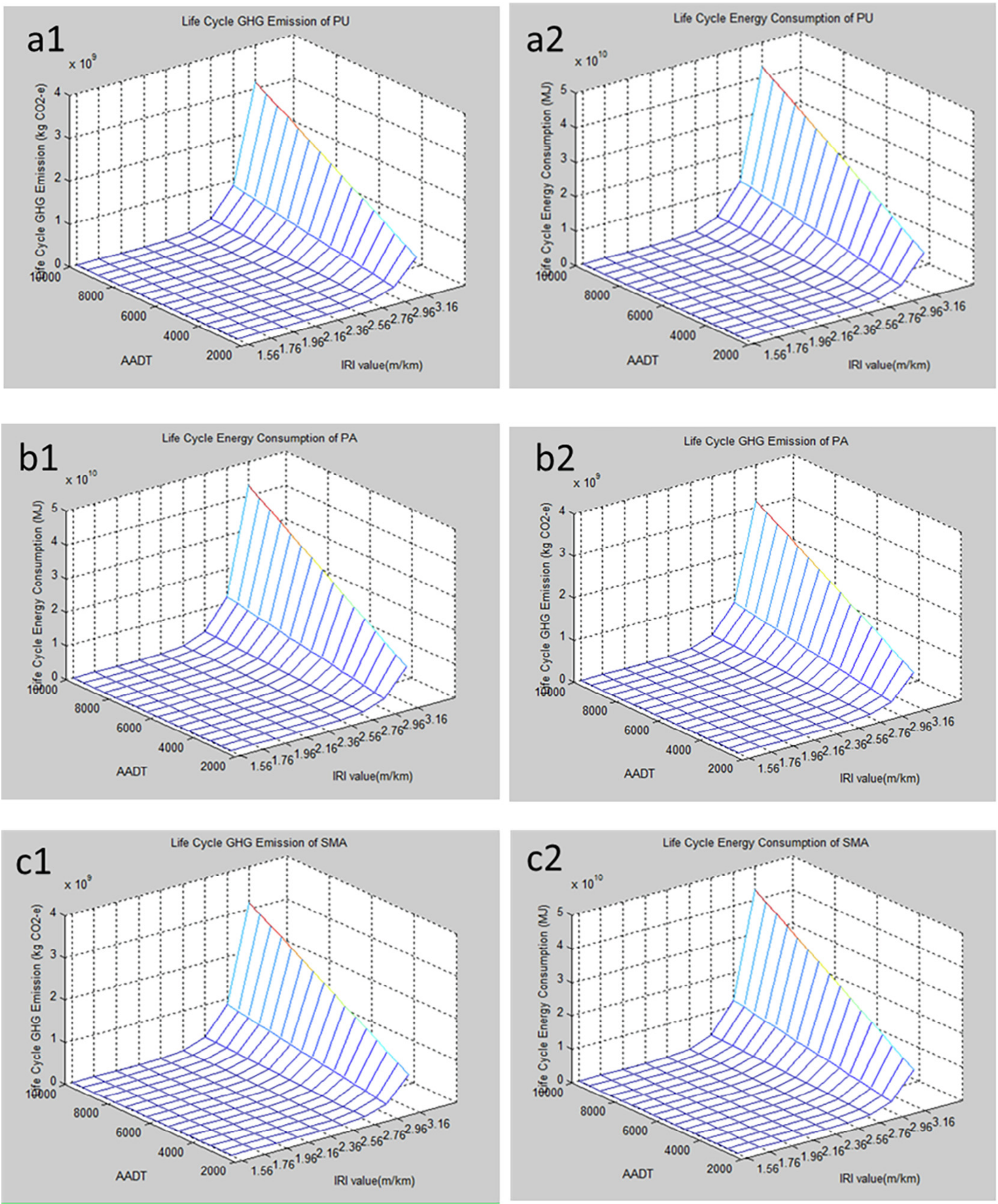

Fig. 3. Life cycle energy consumption and GHG emissions of different pavements: a1) The GHG Emission of PU; a2) The energy consumption of PU; b1) The GHG Emission of PA; b2) The energy consumption of PA; c1) The GHG Emission of SMA; c2) The energy consumption of SMA.

It is better to control the pavement roughness as IRI <2.56, so that traffic volume will not greatly influence the energy consumption and GHG emission, and the environmental impact levels can be kept low.

Comparing the results of different pavements (Figs. 4 and 5), we notice that with relatively low IRI values, SMA-13 contributes the greatest energy consumption and GHG emission while PU pavement explicit the least environmental impact. It is mainly benefited from the cool mixing procedure of PU pavement, in which procedure PU binder can be well-mixed with aggregates without any heating. Especially, at low IRI value (IRI <2.36 m/km), PU shows greater sign of environmental friendly. However, the difference between SMA-13 and PA is inconspicuous, because during the production, only the gradation has the difference while other procedures during paving are mostly similar with SMA.

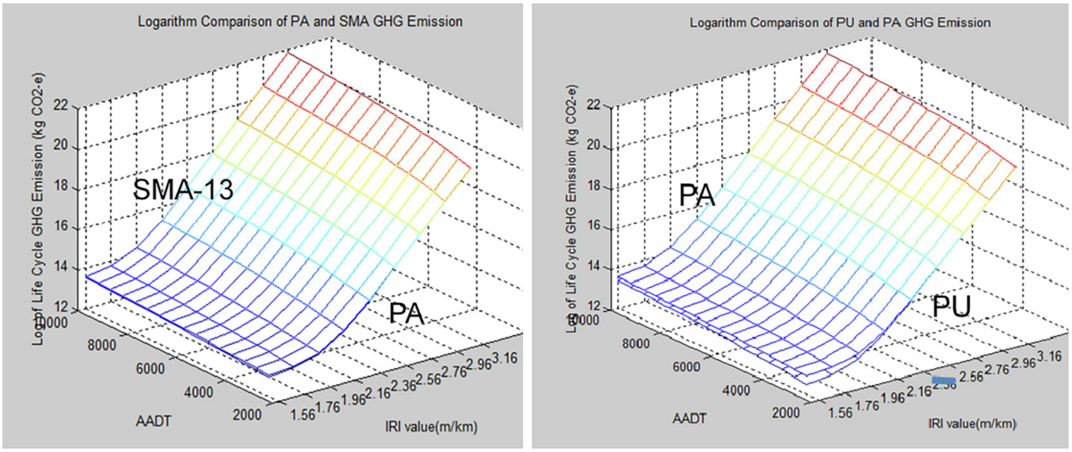

Fig. 4. The comparison of environmental impacts of different pavements.

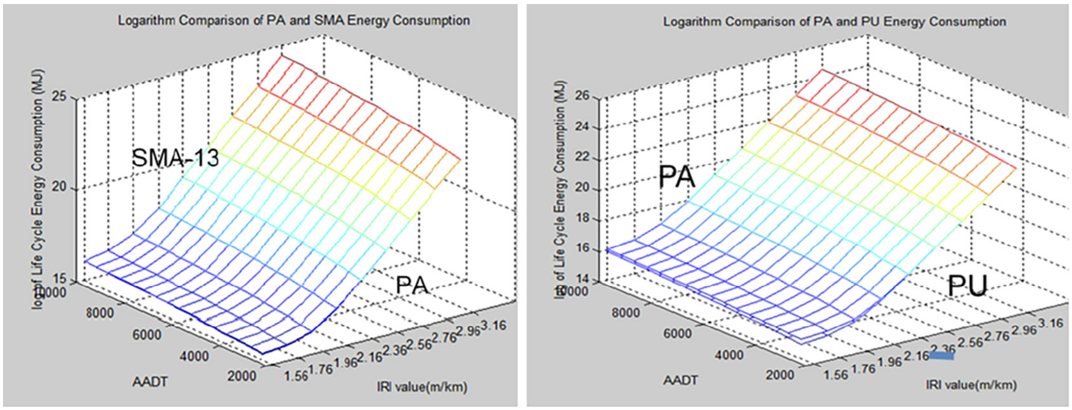

Fig. 5. The comparison of environmental impacts of different pavements.

4. Conclusions

This paper presents a method to estimate the environmental impact of conventional pavement (SMA-13) and permeable pavement (PA and PU) by using an LCA framework. The unique characteristics of PU binder pavement are considered during the assessment. The conclusions are as following: During the use of the road, pavement roughness will increase and greatly impact the vehicle fuel consumption and road GHG emissions. The M&R events needs to be implemented in time. PU binder pavement has the best environmental friendly potential among three different pavement surface materials. PA pavement does not show significant advantage in reducing energy consumption and GHG emissions. This may because asphalt production requires heating, and the permeable feature of pavement is not considered.

This study only discussed the pavement impacts in theory. The environmental impacts of permeable feature of porous pavement will be explored experimentally in the future.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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