COMPARISON OF WARM MIX ASPHALT AND HOT MIX ASPHALT PAVEMENT BASED ON LIFE CYCLE ASSESSMENT

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ABSTRACT

One of the important causes of environmental burdens associated with the construction of transportation infrastructures is the energy consumption and emissions. It is generally believed that warm mix asphalt (WMA) technology has advantages related to the reduction of fuel consumption and emissions because of its lowered mixing temperature in comparison to hot mix asphalt (HMA). Nevertheless, environmental impact due to addition of asphalt emulsion agent in WMA cannot be overlooked. In order to quantitatively analyze and compare the environmental impacts of HMA and WMA, a comprehensive life cycle assessment (LCA) of asphalt pavements was conducted, except for use phase. The LCA analysis suggested that the increased environmental impact of the materials used in WMA pavements, especially the asphalt emulsion agent, is completely offset by reduced impact resulting from lowered manufacturing temperature.

INTRODUCTION

With rapid economic development and urbanization, China's transportation infrastructure is also advancing quickly in the last two decades. By the end of 2012, the total highway mileage of China had reached 4,237,500 km, of which expressway mileage had exceeded 96,200km. The *12th Five-year Plan for National Transportation Development (1)* released by Ministry of Transport of China (MOT) in 2011 suggested that total highway mileage should reach 4.5 million km and the expressway mileage should reach 108,000 km by the end of 2015. Among high grade highway, expressway in particular, asphalt pavement is the major pavement type in China. Asphalt pavement has been widely adopted due to following advantages, such as smooth surface/low noise, joint-less, driving comfort, wearing resistance, fast-track paving and simple maintenance. However, the large-scale construction of asphalt pavement has led to increasingly prominent environmental concerns. When using traditional hot mix asphalt (HMA) technology, the construction of asphalt pavement not only consumes large amounts of energy, but also emits greenhouse gases and other harmful gases, which cause serious air pollution.

In recent years, global energy shortage and climate change have become critical issues commonly concerned by international community, and it has been the common responsibility of each country to save energy, reduce emissions and ensure a sustainable development. As a party of *United Nations Framework Convention on Climate Change (2)*, Chinese government undertakes the international obligations to save energy and reduce emissions, and makes them as binding targets in the long-term plan on national economic and social development. In the *12th Five-year Plan for National Economic and Social Development (3)*, it is stipulated that CO_2 emissions per unit GDP will be reduced 17% by 2015 in comparison to 2010. As a key source of energy consumption, greenhouse gases and air pollution, transportation is one of the industries that were selected by the State Council of China to be more environment-friendly and sustainable. In order to complete the task of energy saving and emissions reduction, it was pointed out in the *12th Five-year Plan for National Transportation Development (1)* that the use of warm mix asphalt (WMA) technology should be promoted due to high potential in energy saving and emission reduction as a result of lower mixing temperature compared with HMA.

Warm mix asphalt is a kind of new pavement material, of which the mixing temperature (100°C to 140°C) is between hot mix asphalt and cold mix asphalt, and the performance is close to HMA. The main mechanism of this technology is to add chemical admixtures or water into asphalt mixture during mixing process, reducing the viscosity of bitumen at lower temperature. In such a way, good workability and reasonable long-term performance of the asphalt mixture may be achieved *(4)*. WMA technologies involve the use of organic additives, chemical additives, water-based foaming processes or water-containing foaming processes. Among them, chemical additives generally include a combination of emulsification agents, surfactants, polymers, and additives to improve coating, mixture workability, and compaction, as well as adhesion promoters. Compared to HMA, WMA has many advantages, such as less energy consumption and less pollution during mixing and paving process, better construction environment, and higher percentage usage of recycled materials. Nevertheless there are also some disadvantages for WMA, for instance, the uncertainty of its long-term performance and higher risk of water damage, which may necessitate more frequent maintenance and therefore heavier environmental burdens. Furthermore, the environmental impacts of upstream supply chain that are used during the asphalt mix production process, for example, various additives, have seldom been taken into account.

While promotion of WMA has been adopted in Chinese national plan due to seemingly obvious short-term environmental benefit, its long term and life cycle performance still needs to be carefully investigated. From the view of environment protection and sustainable development, the question of which construction technology is better between HMA and WMA, can be best addressed by life cycle assessment (LCA) method, since this method is most suitable to assess the environmental impacts associated with all stages of a product's life, starting from the cradle to the grave.

Since the first pavement LCA study published in the mid-1990s *(5)*, the approach has steadily gained attraction as a method to quantify the environmental impacts of pavements. Nearly all early pavement LCA studies offer some comparison between concrete and asphalt-based pavement options, especially comparison between asphalt concrete (AC) and jointed plain concrete pavements (JPCPs). Most literatures have focused on conventional asphalt pavements, whilst WMA pavements have rarely been investigated due to novelty of the technique *(6)*. One exception is the hybrid LCA model developed by Tatari et al. *(7)*, which assesses the environmental impacts of different types of WMA pavements and compares them to those of a conventional HMA pavement. Another exception is the process-based LCA model developed by Vidala et al. *(8)*, which conducts a comprehensive life cycle assessment of asphalt pavements, including HMA and WMA with the addition of synthetic zeolites, and asphalt mixes with reclaimed asphalt pavement (RAP).

Most previous literatures focus on the construction of pavements and neglect or overly simplify subsequent phases of pavement life cycle. Besides, synthetic zeolites are hardly used as warm mix agents in China. Therefore a research with local data and detailed description of HMA and WMA pavements is required. LCA methodology is adopted in this study, targeting to analyze and compare the life cycle environmental impact of HMA and WMA pavements, in order to clarify which pavement is more environment-friendly, and to provide suggestions for the promotion of truly sustainable pavement technologies in transportation industry.

METHODOLOGY

Goal and Scope Definition

In China, chemical additives are widely used in WMA pavements construction. In this study an asphalt emulsion agent was chosen to be the warm mix agent. The goal of the present study was to conduct a LCA of asphalt pavement, incorporating HMA and emulsion-based WMA respectively. The base course and subbase course for both pavements are excluded from the analysis since both pavements are assumed to have the same underlying structures.

System Description and Boundaries

The life cycle of pavements is usually divided in six stages—materials production, transportation, construction, use, maintenance, and end-of-life (EOL) *(9)*. In this study, in order to highlight the influence of asphalt mix production technologies, the production process of asphalt mix is set to be a separate process. According to a series of field trials conducted by NCAT *(10-12)*, the WMA technology performs statistically equal to or better than the HMA. Considering the difficulty of quantifying the difference of performance between WMA and HMA, they are assumed to be the same in this study. The major environmental burden of the use phase comes from the fuel consumption and corresponding emissions to air, which depends on the operation of vehicle engines and the friction between pavement and tires. In the case of the same performance for HMA and WMA pavements and the same traffic condition, just as assumed, their resulting environmental burdens also become equal. Assuming the environmental burdens of use phase have no significant difference for both HMA and WMA, the scope of this study is focused on following aspects, including the production and transportation of raw materials, production and transportation of asphalt mix, pavement construction, maintenance, and EOL, whereas use phase is excluded from the study.

Materials - The life cycle of pavements begins with the extraction of raw materials. Asphalt mix mainly consists of natural aggregates such as sand and gravel, bitumen binder, and some chemical agents. The environmental impacts of this stage come from minerals extraction, raw materials production, and the transportation of raw materials to asphalt mixing plant.

Asphalt mix production - In asphalt mixing plant, aggregate screening, drying and final mixing of all raw materials is involved in this stage. The environmental impacts associated with this stage come from the energy consumption of screening, drying and mixing processes, and emissions during asphalt mixing. The construction of asphalt mixing plant, land occupation, and the manufacture of equipment are excluded from this stage.

Asphalt mix transportation - Prepared asphalt mix are poured into hauling vehicles, usually large dump trucks, transported to paving site, and unloaded into asphalt pavers. The environmental impacts of this stage are from the energy consumption and emissions of transport vehicles. The manufacture of these transport vehicles are excluded from this stage.

Construction - In this study, pavements construction stage consists of following processes, such as cleaning of bearing layer, paving of asphalt mix, leveling and rolling. The environmental impacts of this stage mainly come from the energy consumption and emissions from the equipment. The manufacture of this construction equipment is excluded from this stage.

Maintenance - After a period of use, pavements need to be maintained under the influence of environmental and traffic loads. The maintenance of pavements includes the replacement of the wearing course. The environmental impacts of this stage come from dismantling of the damaged asphalt layers and placement of a new layer of asphalt. The impact of traffic delay caused by maintenance is not included in this study yet and will be conducted in the future.

End of life - When pavements reach their end of service life, they will be dismantled and the resulting wastes will be either land-filled or recycled. If the wastes are land-filled, the energy consumption and emissions of dismantling, transport and landfill equipment will be considered. Otherwise, only the energy consumption and emissions of dismantling and transport equipment will be considered. This study therefore assumes there is zero environmental impact during recycling process.

Functional Unit

The functional unit is a reference unit to which the results of the LCA are related, and which should represent the function of the analyzed system. In order to compare different pavements, it is important to use the same functional unit for all the systems compared. The functional unit for road pavements is defined herein by their geometry, service life, and levels of traffic supported. In the case study presented later, the section of road concerned is 1 km long with a width of 16.5 m and three asphalt layers of 0.18 m total thick; the service life of the road is 15 years; and the average daily traffic is 20,000 vehicles per day with 8% of heavy vehicles.

Inventory Data Collection

Materials

Production and transportation of raw materials includes extraction and transportation of sand and gravel, production of bitumen, fiber stabilizers, slag, stone chips, fuels and electricity used by the various equipment. Based on related data providing by *Highway Engineering Budget Quota (13)* and *Highway Engineering Machinery Quota (14)*, which were both published by Traffic and Highway Engineering Quota Agency of China (THEQA) in 2007, the amount of raw materials and energy needed per functional unit is calculated.

The life cycle inventory (LCI) of sand, gravel, fiber stabilizers, slag, stone chips is taken from China LCA Core Database (CLCD), which covers a large amount of basic Chinese LCI data. The LCI of bitumen comes from European Bitumen Association *(15)*, since the process of bitumen production in China is similar to that in Europe. Due to lack of life cycle inventory data on warm mix agent, relevant data of similar materials available in aforementioned databases are adopted.

Asphalt Mix Production

The process of asphalt mix production usually includes de-dusting, heating and drying of mineral aggregates, adding mineral powder and bitumen, mixing, and temporary storage.

According to the two documents published by THEQA *(13,14)*, the consumption of heavy oil and electricity needed per functional unit of HMA pavements can be calculated. Considering the lack of related data, the corresponding emissions per functional unit of HMA pavements are obtained based on the emission factors provided by US Environmental Protection Agency (USEPA) *(16)*.

As to WMA pavements, since the addition of warm mix agent does not increase the mixing time, the amount of electricity consumed per functional unit is considered equal to that of HMA pavements. The amount of heavy oil consumed can be calculated by heat balance method as explained below. Firstly, an energy balance is performed on the HMA asphalt production process to estimate the heat loss from this process. The heat loss coefficients associated with burners and boiler are obtained as a function of the heated mass and the heating temperature. In addition, air pollutant emissions from burners and boiler are estimated as a function of fuel consumption. Secondly, a new energy balance is performed by using the heat loss coefficients mentioned above, taking into account the composition of WMA and the lower final temperature for the mixes. In this way, fuel consumption by burners and boiler for WMA production is estimated, which form the basis for air pollutant emissions calculation.

Asphalt Mix Transportation

The transportation of asphalt mix generally uses large dump trucks. According to the two documents published by THEQA *(13,14)*, the diesel consumption of these large dump trucks for transporting asphalt mix needed per functional unit can be calculated. Considering the representativeness and extensiveness of data, the corresponding emissions per functional unit of both HMA and WMA pavements are obtained based on *EMEP/EEA air pollutant emission inventory guidebook 2013 (17)*, which was published by European Environment Agency (EEA) in 2013.

Construction

The equipment used for paving and compaction mainly consumes diesel and gasoline. With the help of the two documents published by THEQA *(13,14)*, the amount of these diesel and gasoline needed per functional unit can be calculated. The environmental emissions during asphalt pavement construction stage are produced by the combustion of fuels of the operating equipment. In this paper, these values are calculated based on the *Limits and measurement methods for exhaust pollutants from diesel engines of non-road mobile machinery (18)*, which was released by National Environment Protection Administration of China (NEPA) in 2007.

Maintenance

Under the joint action of traffic and environmental loads, the condition of asphalt pavements deteriorates continually. A timely maintenance is therefore required in order to maintain high serviceability for asphalt pavements. In the stage of asphalt pavement maintenance, repair materials and equipment are needed, with associated fuel consumption and emissions. Daily maintenance and minor repairs are excluded in this study as they are difficult to calculate and also considered having negligible environmental impact.

Two types of major maintenance activity are adopted in practice, including medium repairs and overhaul, depending on the pavement damage degrees. Medium repairs, such as overlay, are generally conducted in the event of functional damage, while overhauls are generally used for structural damage.

Taking into account that overhauls usually destroy the whole structure of existing pavements, which effectively ends pavement life cycle, overlay is therefore considered to be the only maintenance method in this study.

The frequency of overlay is derived based on the pavement condition index (PCI) decay model built by Sun *(19)* and decision values provided by *Highway Asphalt Pavement Maintenance Technical Specifications (20)*, which was published by MOT in 2001.

Once the overlay frequency is known, the amount of fuel needed by pavement repairing equipment can be calculated according to *Instruction for Budget Preparation and Quato of Highway Maintenance Project (21)*, which was published by Quota Agency of Department of Transport of Jiangsu Province in 2010. Subsequently, the related emissions can be obtained using similar method as described above.

End-of-Life

When roads reach the end-of-life stage, the general procedure is to dismantle and then dispose of it in landfill sites or recycle the pavement materials. In this study, all pavements are assumed to be dismantled and then land-filled.

According to the two documents published by THEQA *(13,14)*, the fuel consumption for dismantling and transportation equipment can be calculated. The corresponding emissions can be calculated with the help of the guidebook published by NEPA *(18)*. The LCI of the disposal of pavements in a landfill site was taken from the *Ecoinvent* database *(22)*.

LCA-Based Tool

A LCA-based software *eBalance* is used in this study to facilitate the calculation of the environmental impact of the road pavement. The CLCD database is an integral part of the software while *Ecoinvent* database are provided to Southeast University free of charge for research purpose.

Case Study

A newly built six-lane highway in Jiangsu Province is selected for case study. The asphalt surface layer is divided into three sub-layers, with a total thickness of 180mm. Among them, top sub-layer is 40mm thick Stone Mastic Asphalt (SMA-13), using basalt aggregate with nominal maximum size (NMS) of 13mm and SBS modified bitumen; middle sub-layer is 60mm thick asphalt concrete (AC-20), using limestone aggregate with NMS of 20mm and SBS modified bitumen; bottom sub-layer is 80mm thick AC-25, using limestone aggregate with NMS of 25mm and 70# heavy traffic bitumen. The dosage of warm mix agent in this study equals to 5% of bitumen by mass.

RESULTS AND DISCUSSION

In this study, acidification potential (AP), respirable inorganic (RI), and global warming potential (GWP) are selected as indicators to compare the environmental impact of WMA and HMA pavements during their life cycle. The overall results are presented in Table 1, whereas the Figures 1-3 show the acidification potential, respirable inorganic, global warming potential of the various life cycle stages of asphalt pavements.

Table 1: Life Cycle Environmental Impacts of the HMA and WMA Pavements

Life cycle stages of asphalt pavements	HMA			WMA		
	AP/ kg SO_2 eq.	RI/ kg $PM_{2.5}$ eq.	GWP/ kg CO_2 eq.	AP/ kg SO_2 eq.	RI/ kg $PM_{2.5}$ eq.	GWP/ kg CO_2 eq.
Materials	3.219E+03	5.567E+02	7.137E+05	3.480E+03	6.139E+02	7.779E+05
Asphalt mix production	8.816E+02	1.748E+02	1.910E+05	5.365E+02	1.010E+02	1.018E+05
Asphalt mix transportation	1.081E+02	2.127E+01	1.606E+04	1.081E+02	2.127E+01	1.606E+04
Construction	1.612E+02	3.386E+01	1.684E+03	1.612E+02	3.386E+01	1.684E+03
Maintenance	1.015E+03	1.918E+02	2.026E+03	9.482E+02	1.678E+02	1.879E+03
End of life	1.004E+02	4.523E+01	2.014E+03	1.004E+02	4.523E+01	2.014E+03
Total	5.485E+03	1.024E+03	9.265E+05	5.334E+03	9.831E+02	9.013E+05

The totals of AP, RI and GWP of WMA pavements are all slightly less than those of HMA pavements, which means that WMA pavements are probably more environment-friendly and sustainable than HMA pavements. Although WMA pavements show more environmental impacts during materials stage than HMA pavements, mainly due to the production of warm mix agent, these differences are completely offset during asphalt mix production stage and maintenance stage due to lowered mixing temperature.

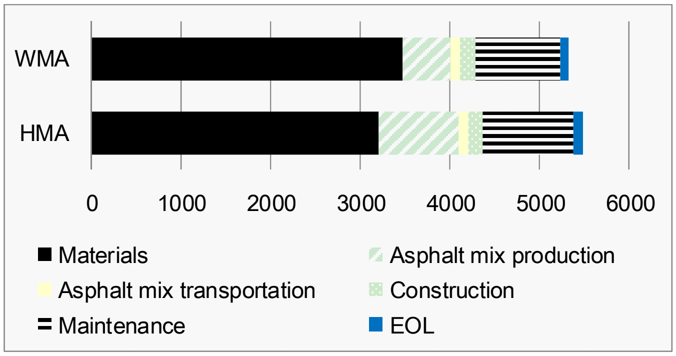

Figure 1: Acidification potential of HMA and WMA pavements.

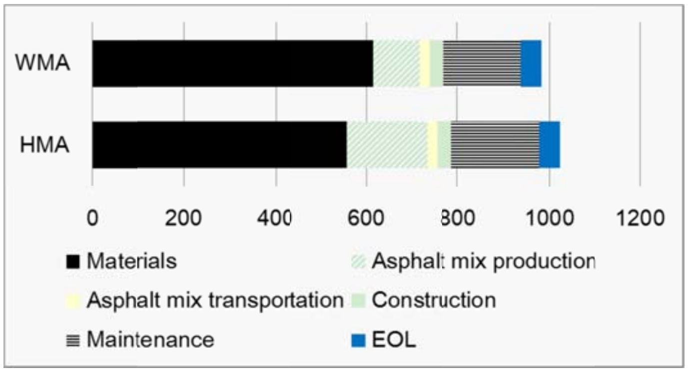

Figure 2: Respirable inorganic of HMA and WMA pavements.

Based on Figures 1-3, it seems that the material stage contributes most to the environmental impacts in AP, RI and GWP. The asphalt mix production and maintenance stages are also critical to the life cycle environmental burdens of asphalt pavements. From Figure 3, the GWP of both HMA and WMA pavements during construction and EOL stages cover little proportion of the whole life cycle of asphalt pavements, the possible reason of which is that, the environmental impacts during the two stages are only associated with the equipment operating.

Figure 3: Global warming potential of HMA and WMA pavements.

As mentioned in the introduction, one of the main advantages of WMA is potentially greater use of RAP as a result of the increased workability compared to HMA. Considering the large proportion of environmental impacts contributed by materials in above figures and the minimal environmental impacts of RAP, the addition of large amounts of RAP in WMA will very likely turn them into a good alternative to HMA. This investigation will be conducted in near future as a follow-up study.

CONCLUSIONS

Life cycle assessment constitutes an important part of the life cycle approach as a tool to support decision making. This paper introduced the concept of LCA briefly, reviewed the existing relevant LCA literature and conducted a life cycle assessment on HMA and emulsion-based WMA pavement.

The results show that WMA pavements produce less environmental impact than those from HMA pavements during the life cycle of asphalt pavements. The increased environmental impacts of the materials used by WMA pavements, especially the impacts of the asphalt emulsion agent, are completely offset by the greater impacts resulting from lowered manufacturing temperature. The use phase difference was ignored due to lack of data, but could potentially impact the results significantly if reliable data are available.

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