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Initial evaluation methodology and case studies for life cycle impact of permeability of permeable pavements

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ABSTRACT

In recent years, urban flooding has occurred frequently in different cities in China. This has caused huge economic and environmental damages. As one of the main elements in the concept of sponge city – a potential solution to this problem – permeable pavements have attracted great attentions. This new technology has the ability to mitigate urban flooding effectively and it also provides other environmental benefits. Life Cycle Assessment (LCA) is a newly developed evaluation approach that can be applied to estimate the environmental impacts of pervious pavements in the entire life cycle.

This study propose a basic model which can be applied to both permeable asphalt pavements and permeable concrete pavements to evaluate their environmental impacts. The impacts of this technology are investigated on urban flooding, water recycling and water purification. Then a comparison between permeable asphalt pavement and dense-graded asphalt pavement is conducted for a typical four-lane secondary road. Results indicate that in 10 km of the modeled road, 49TJ of energy consumption, 6700 t of equivalent carbon dioxide emissions, 0.1 t of lead emissions and 1 t of zinc emissions can be avoided if the permeable pavements is used. Moreover, the most significant reduction in energy consumption, GHG emissions, lead emissions and zinc emissions occurs in the use phase.

1. Introduction

Transportation is one of the most significant contributors to carbon emissions and energy consumption in the whole world. It is reported in 2009 that 24% of carbon dioxide were emitted from transportation in the world, while in China the contribution is estimated to be 7% (Komeil, 2013). In addition, the rapid increase in the number of individual cars and the fast growth of the transportation infrastructures would lead to a new level of the carbon emissions and energy consumption in China (Li et al., 2015).

Road pavements are essential elements of transportation infrastructures and recently great attentions have been paid to their environmental impacts in their entire life cycle. Life Cycle Assessment (LCA) is an efficient and promising approach to quantify the environmental impacts of pavements in the life cycle from the cradle to the grave. The environmental impacts of

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pavements in the extraction of materials, construction of pavement layers and recycling or landfilling the used pavement materials can be quantified and evaluated by LCA.

Santero et al. (2011) provided a comprehensive summary of pavement LCA progress and models for the use phase. The studies have compared the functional unit, system boundaries, data quality and environmental impacts of different approaches on LCA (Muga et al., 2009; Huang et al., 2009; White et al., 2010). It is suggested that inconsistency in the assumptions leads to conflicting results of LCA. Also these studies compared existing and applicable models to include traffic delay in the construction phase, rolling resistance, albedo, concrete carbonation, pavement lighting, leaching in the use phase and recycling at the end-of-life phase. Specifically, Wang et al. (2012) presented an analysis of the effects of rolling resistance on energy consumption and GHG emissions in material production, construction, and vehicle operation during use phase of pavements. Li et al.(2016) presented a comprehensive review on characteristics and environmental impact analysis of the reflective coatings for cool pavements. Akbari et al. (2001) suggested that application of cool surface on a national scale in America could reduce the urban heat island effects and, therefore, energy demand for cooling by 20%, or by 40 TWh per year.

As the growths of the concept of 'sponge city', the Permeable Pavement System (PPS) is applied more vastly and therefore, approaches to evaluate the environmental impacts of permeability of pervious pavements are required. Although the models of rolling resistance and albedo have been investigated, there is still a critical need to develop proper model for permeability and pervious pavements. In the study of Scholz and Grabowiecki (2007), the environmental effects of permeability of pervious pavements are investigated in urban flooding, water recycling and water purification. These three factors can be detailed and quantified as traffic delay caused by urban flooding, the water transportation savings by water recycling and decrease in pollution emission by water purification.

RealCost (FHWA, 1998) and Motor Vehicle Emission Simulator (MOVES, EPA, 2010) tools were considered as evaluation approaches of vehicle operation and traffic delay by studies (Wang et al., 2012). RealCost analysis suggested that the traffic delay is caused by the lane and road closures when the pavement is not accessible due to construction, maintenance or other related activities. RealCost measures the economic cost of traffic delay by the number of cars delayed, amount of the time spent in queues and the value of time. Life cycle cost of traffic delay is estimated with RealCost while the environmental impacts are estimated by MOVES which considers the fuel consumptions due to the traffic jam and its related emissions factors (Changmo et al., 2015).

PPS has a huge water recycling potential which can reuse collected surface runoff water to recharge groundwater and reduce the imposed pressure of growing urban impermeable surface on the scarce water resources. Stormwater capture efficiencies of PPS varies from 40% to nearly 100% due to differences in design and climate conditions (Guo and Zhang, 2015; Jayasuriya and Kadurupokune, 2008; Loimula and Kuosa, 2013). It is suggested that a majority of stormwater is captured by PPS in most cases, and the captured water can be reused for industry, irrigation and everyday life. Nnadi et al. (2013) conducted a heavy metal analysis of the plants and soil as well as soil texture tests for land irrigated by recycled water from PPS. It was suggested that heavy metal level is below toxicity levels and no salinity or soil texture problem is found in the tests. These results further demonstrate the safety of water recycled from PPS and its potential application for irrigation purposes.

Many studies have been established on the pollution removal potential of PPS which proved that PPS is efficient on water filtration and water purification. Niu et al. (2016) carried out experiments to study the relations between eutrophication removal rate and layer thickness for the coarse sand bedding and single-graded base gravel. The results indicated that these relations are not linear. Huang et al. (2016) conducted experiments on eutrophication removal rate in graded gravel layers changing with the thickness of layers and maximum aggregate size, and the results indicated that these relations can be approximated as a linear relation. Myers et al. (2011) studied eutrophication and heavy metals removal rate varying due to different base course materials and duration. Song et al. (2009) presented linear results on the relations between heavy metals removal and permeability rate. Finally it is worth mentioning that pollution removal rates of PPS vary by the climate conditions and design parameters.

A large number of studies has been conducted in this regard, but no consistent conclusions can be drawn yet.

The objective of this study is to develop a new evaluation approach to quantify the life cycle environmental impact of permeability of pervious pavements and to conduct initial case studies using the developed approach. The objective of this study can be achieved by:

- introduce LCA framework;
- review the former studies on the effects of PPS which are used in developing an initial evaluation model for the life cycle environmental impacts of this technology;
- and finally execute a simplified case study using the permeability developed model.

2. LCA framework for permeable pavement

As it is defined by International Standard Organization (ISO) Standard 14040, LCA consists of four steps which are goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation (International Organization for Standardization ISO, 2006). The first two steps are discussed in this study and the latter two steps are left for the future research to be investigated.