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Hybrid input–output life cycle assessment of warm mix asphalt mixtures

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ABSTRACT

One of the most important challenges facing our society is the efficient and economic use of energy, and with it the corresponding need to reduce greenhouse gas (GHG) emissions. Due to growing concerns over global warming and climate change in recent years, warm mix asphalt (WMA) has become an important new research topic in the field of pavement materials, as it offers a potential solution for the reduction of energy consumption and GHG emissions during the production and placement of asphalt mixtures.

While many studies have been conducted to demonstrate that the mechanical properties of such mixtures are not significantly affected, many questions and concerns regarding the environmental benefits they offer have yet to be addressed. In this study, a comprehensive hybrid life cycle assessment of WMA production was carried out to accurately evaluate and quantify the potential benefits of WMA technology by assessing the environmental impacts of its production associated with energy consumption and GHG emissions.

The results of this study show that, for the WMA mixtures considered here, when the upstream supply chain related to the production of the materials composing such mixtures is taken into account, WMA technology is able to significantly save energy and reduce GHG emissions when compared to the control mixtures. However, it must be noted that in some cases, the manufacturing temperature at the asphalt plant must be reduced before the benefits of reduced emissions and fuel usage can be obtained. The results of a detailed production layer decomposition indicate that the fuel, mining and construction sectors are the main contributors to the environmental impacts of manufacturing the WMA mixtures studied.

1. Introduction

In recent years, environmental protection and sustainable development have become important global themes. The pavement industry is facing, among other challenges, the need to reduce environmental impacts and energy usage. In road construction, a number of new technologies have been actively developed to lower the production and placement temperatures of hot mix asphalt (HMA). Generically, these technologies are referred to as warm mix asphalt (WMA) and can be classified into three groups: those with organic additives, chemical additives and water-based or water-containing foaming processes (D'Angelo et al., 2008; Rubio et al., 2012). Their goal is the same: to reduce bitumen viscosity in order to lower the mixing and placement temperatures. More sustainable production of bituminous mixes can be obtained without significantly affecting their level of mechanical performance. The main benefits of this technology highlighted in the literature are: the reduction of plant emissions (generally expected to be between 30% and 40%); reduced fuel usage (typically ranging from 11% to 35%); paving benefits (it is possible to construct the pavement at cooler temperatures and to transport the mix over greater distances); and less exposure of workers to harmful gases (a 30%–50% reduction) (D'Angelo et al., 2008).

The recycling of scrap tyres has also been of interest to the asphalt industry throughout the world for over 40 years as pavements containing crumb-rubber modified (CRM) binders save energy and natural resources by making use of waste products.

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Asphalt pavements with rubberized binders offer improved resistance to rutting, fatigue and thermal cracking; they also reduce traffic noise and maintenance costs and prolong pavement life (Ruth and Roque, 1995; Liang, 1996; Huang et al., 2002; Shen et al., 2005). These mixtures, however, present one major drawback: the manufacturing temperature must be increased from 165 °C to 180 °C as the rubber lends greater viscosity to the binder and thus larger amounts of greenhouse gas (GHG) emissions are produced during their production than in the case of conventional bituminous mixtures (CEDEX, 2007; Akisetty et al., 2011). WMA technology offers promising solutions to the drawbacks of CRM asphalt thanks to the use of fluidifying additives which are able to guarantee lower viscosity of the bitumen at typical production temperatures without affecting bitumen performance at pavement service temperatures.

To evaluate the potential benefits of WMA, a number of field trials and studies have been conducted in Europe and the United States; these have shown that the manufacturing and placement of WMA produces fewer emissions when compared to HMA (Barthel et al., 2004; Button et al., 2007; D'Angelo et al., 2008). In these studies, however, the upstream supply chain related to the production of the bitumen, aggregates and additives was not included. Life cycle assessment (LCA) is the methodology most commonly applied to assess the environmental impacts associated with the stages of a product's life from cradle to grave. LCA is a comprehensive methodology for examining the net environmental performance of products and services. There are three methods: process, input–output and hybrid, the most common of which is the process-based approach; only a few studies have used input-output-based or hybrid LCA (Santero et al., 2011).

For this study, a hybrid input-output-based life cycle assessment (hLCA) was chosen. This methodology represents the union of two methods: process and input–output analysis (IOA). Process analysis (PA) is specific and detailed, but it is affected by a systematic truncation error caused by the finite system boundary. IOA, on the other hand, includes all indirect supply-chain impacts and thus avoids truncation errors. Input-output (IO) sectors, however, are aggregated and IOA can therefore not be specific and detailed (Lenzen, 2000; Moskowitz and Rowe, 1985; Suh et al., 2004). The shortcomings of both methods have led researchers to combine their strengths into a hLCA method (Bullard et al., 1978; Heijungs and Suh, 2002; Suh, 2004; Suh and Nakamura, 2007). hLCA is able to assess the energy consumption and environmental impacts of products and services by taking advantage of a country's economic IO tables; these were originally developed to describe industry sectors' economic transactions and have since become an effective tool for use by LCA studies.

In this study, a comprehensive hLCA of the production of WMA with and without CRM binders was carried out in order to determine and compare the environmental impacts associated with energy consumption and emissions. Carbon dioxide is the GHG which most contributes to global warming and is produced when energy is consumed during the mixing process. Optimizing energy consumption and fuel requirements is of vital importance, especially as energy costs rise due to the depletion of crude oil brought on by the increasing demand for energy. Australia is a country that needs to import crude oil. Indeed, in recent years, there has been a dramatic increase in the demand for and price of oil and imports are expected to increase to 76% of total consumption by 2030 (de Vries et al., 2007; Geoscience Australia and ABARE, 2010). Knowing that Australia produced 8.8 million tonnes of HMA and WMA in 2012 and Spain, 19.5 million, and given a global annual investment of $400 billion in construction and maintenance of pavements, there is reason to believe that the pavement industry represents an opportunity for significant improvements in environmental impacts (EAPA, 2012; IRF, 2010). The production phase of asphalt mixtures consumes the largest amount of resources (Tatari et al., 2012); therefore, the main benefits of using WMA technology will come from reducing the manufacturing temperature at the asphalt plant. This temperature reduction leads to a significant decrease in fuel consumption and, consequently, to a reduction of energy usage and CO_2 emissions as well. At the asphalt plant, heat is used to dry aggregates and to reduce the viscosity of the bitumen during the mixing process. When the viscosity of the mixture is lowered, its workability improves and the bitumen can adequately coat the aggregates.

The asphalt mixtures selected for this study consist of WMA mixtures with and without CRM binder (15% and 20% content of rubber powder) using 2% and 4% of a Fischer Tropsch (F-T) wax as the additive to reduce the viscosity. Most of the existing literature has focused on conventional asphalt pavements and WMA mixtures with CRM binders have yet to be studied in detail. This is one of the contributions of this study. The WMA additive chosen is a F-T wax, as this is one of the most extensively studied WMA additives, considered in more than 100 leading studies – including scientific papers, technical reports and theses – and is widely used around the world (Jamshidi et al., 2013). Asphalt mixtures containing this additive have reported good engineering properties (Hurley and Prowell, 2005). For this study, the wax was added to the mixtures in the amount of 2% and 4% by total weight of the bitumen, as previous studies have shown that these dosages are able to achieve a lower viscosity (Rodríguez-Alloza et al., 2013, 2014). Although some studies have quantified the potential environmental impacts of WMA in terms of emissions and resource consumption, the role of the upstream supply chains of the different materials used to produce the asphalt mixtures have generally not been included. One of the contributions of this study is to take into account the emissions and energy usage associated with WMA additives, as these can offset to some degree the reduction of energy and GHG emissions obtained when the mixture is produced at a lower temperature.

The main objective of this study is to accurately evaluate and quantify the potential benefits of WMA technology by assessing the environmental impacts of the production of different WMA mixtures and comparing them with their corresponding control mixtures to determine the embodied energy consumption and GHG emissions in the supply chain.

The scope of this LCA was the production of different asphalt mixtures and the purpose to assess the environmental impacts associated with energy consumption and GHG emissions. There are no upstream system boundaries in input-output-assisted hybrid LCA and the functional unit was one tonne of asphalt.

2. Methodology and data

2.1. Input-output-based life cycle assessment

IOA is an economic technique that was established by Wassily Leontief in the 1930s. This technique is based on the complex interdependencies of industries and uses monetary transactions that describe the structure of an economy. These transactions can be represented by an $n \times n$ direct requirements matrix $\mathbf{A}$, where n is the number of economic sectors. The $\mathbf{A}$ matrix represents the proportion of inputs required for the production of a unit of output. An introduction of the basic IO model and its applications is described in the literature (Dixon, 1996; Leontief, 1986; Miller and Blair, 2009).

Input-output-based life cycle assessment, commonly known as hybrid LCA, is a technique that combines the strengths of top-down IOA and bottom-up PA (Bullard et al., 1978). The marriage of these