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Life cycle assessment of low temperature asphalt mixtures for road pavement surfaces: A comparative analysis

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ABSTRACT

The increasing fuel consumption demand, the accelerated pressure imposed by the depletion of scarce raw materials and the urgent environmental protection requirements are forcing the change of pavement industry and academia community's research endeavours towards the development of low emissions road paving technologies able to significantly reduce mixing and compaction temperature as well as the consumption of virgin raw materials. One of the relatively recent technologies in the field of pavement materials that aims at addressing those concerns is the incorporation of reclaimed asphalt pavement (RAP) in the production of warm mix asphalt (WMA).

It is within this context that this study presents a full process-based comparative life cycle assessment (LCA) looking at understanding the environmental impact of reducing mixing temperature, through the use of warm mix technologies, namely chemical additives-based and foamed-based, and different rate of recycling (0% and 50% RAP). Furthermore, the investigation explores the effect of combining these technologies in the construction, maintenance and rehabilitation (M&R) of wearing courses for flexible road pavements. The results of this study showed that, for the conditions considered and assumptions performed, a pavement construction and M&R scenario in which a foamed-based WMA mixture with a RAP content of 50% is employed in the wearing course throughout the pavement life cycle is the most environmentally friendly alternative among all the competing solutions.

1. Introduction

Considerable amount of Greenhouse gases (GHG) and airborne pollutants are released into the atmosphere during the energy intensive asphalt mixtures production process (Thives and Ghisi, 2017). As GHG and their effect on the climate are increasingly in the spotlight with respect to policy, legislation and general public's concern, the pavement industry and scientific community have been challenged to improve the conventional asphalt mixtures production processes by developing more sustainable technologies and behaviors.

One example of the specific engagement of research institutions and enterprises in developing and delivering multi-faceted and sound solutions meant to mitigate the environmental pressure originated by the sector's activities is the SUP&R ITN (Sustainable Pavement & Rail Initial Training Network) research project (Lo Presti et al., 2017).

The SUP&R ITN is a training-through-research program, which through a multidisciplinary and multi-sectorial network, aims (1) to form a new generation of engineers versed in sustainable technologies for road pavement and railways and (2) to provide, to both academia and industry, design procedures and sustainability assessment methodologies to certify the sustainability of the studied technologies to the benefit of the European community. Some of the promising sustainable technologies commonly mentioned in the literature and studied in the framework of this research project are the asphalt mixtures requiring lower manufacturing temperatures, such as (1) warm mix asphalt (WMA) (Kristjánsdóttir et al., 2007; Hamzah et al., 2010; Tatari et al., 2012; Vidal et al., 2013; Mohammad et al., 2015; Rodríguez-Alloza et al., 2015; Almeida-Costa and Benta, 2016; Stimilli et al., 2017), (2) half-warm mix asphalt (HWMA) (Rubio et al., 2013) and (3) cold mix asphalt technologies (Federal Highway Administration (FHWA, 2016).

WMA is the name used to designate a set of technologies by which the traditional HMA is allowed to be manufactured, transported, placed

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and compacted at lower temperatures. Characteristically, the mixing temperatures of HMA vary from 150 to 180 °C (Jones, 2004), whereas for WMA and HWMA they are comprised between 100 and 140 °C, and between 60 and 100 °C, respectively. In addition to the mixing temperature reduction, the list of potential benefits that come with the use of these technologies is completed with the following items (Rubio et al., 2013): (1) reduced emissions; (2) better working conditions due to the absence of harmful gases; (3) quicker turnover to traffic; (4) longer hauling distances; and (5) extended paving window. Furthermore, the potential sustainability of such solutions may be further broadened through the partial or full replacement of virgin and/or manufactured materials with recycled, co-product, or waste materials (RCWM), from which the reclaimed asphalt pavement (RAP), recycled concrete aggregate (RCA), recycled asphalt shingles (RAS), air-cooled blast furnace slag (ACBFS), steel furnace slag (SFS), foundry sand, etc., (Van Dam et al., 2015) are examples.

In order to prove quantitatively the theoretical environmental benefits to which the aforementioned technologies are associated with, the most significant environmental inputs and outputs over their life cycle, from raw materials production to the end of the technologies' life, should be assessed. This can be accomplished through life cycle assessment (LCA). LCA is a data-driven, systematic methodology, to investigate, estimate, and evaluate the environmental burdens caused by a material, product, process, or service throughout its life span (Matthews et al., 2015). The life cycle begins at the acquisition of raw materials, evolves through several distinct stages (material processing, manufacturing and use), and terminates at the product end-of-life (EOL).

1.1. State-of-the-art of LCA studies on WMA technologies

Several research studies have been performed that apply the LCA methodology to measure the potential life cycle environmental impacts of the processes involving the production and placement of the WMA technologies in lieu of conventional HMA. Tatari et al. (2012) developed a thermodynamic-based hybrid LCA model to evaluate the environmental impacts from an ecological resource accounting perspective of three types of WMA mixtures and compare them to those of a conventional HMA mixture. The following WMA technologies were assessed: Aspha-Min®, Sasobit®, and Evotherm® WMA. Vidal et al. (2013) performed a comprehensive LCA of road pavements including HMA and zeolite-based WMA, both with and without RAP content. The ReCiPe method was used to assess the environmental impacts according to two sets of impact categories: midpoint and endpoint categories. Additionally, the cumulative energy demand indicator was adopted to compare the mixtures in terms of energy consumption. Mohammad et al. (2015) compared the environmental performance of two WMA technologies, namely foaming and Sasobit® additive, to that of a conventional HMA mixture, in terms of energy consumption at the asphalt plant and CO and CO_2 emissions monitored during their production and placement. Rodríguez-Alloza et al. (2015) performed a comprehensive hybrid input-output-based LCA of the production of Fischer Tropsch (F-T) wax-based WMA mixtures with and without crumb-rubber modified (CRM) binders. The potential benefits of that WMA technology in relation to a conventional HMA were quantified by accounting for the embodied energy requirement and GHG emissions in the supply chain. Giani et al. (2015) carried out a process-based LCA in collaboration with an Italian asphalt-producing company with the objective of quantifying the potential environmental benefits resulting from constructing asphalt pavement using an unspecified type of WMA with the incorporation of up to 30% of RAP. Almeida-Costa and Benta (2016) quantified the potential benefits of two WMA technologies, Rediset® and Sasobit® additives, in relation to a conventional HMA mixture, by assessing the energy consumption and GHG emissions associated with their production. In turn, Yang et al. (2017) compared the environmental performance of crumb-rubber modified HMA and Evotherm® WMA to that of a conventional HMA mixture, expressed in terms of energy consumption and hazard emissions associated with their production.

1.2. Aim and purpose of the study

Notwithstanding the merits of the studies listed previously in presenting LCA methodologies, documenting assumptions, disclosing data sources, showing the potential environmental benefits of some WMA technologies, mostly in terms of energy consumption and emissions released during their production, several aspects can be pointed out which underpin the room for further studies, thereby expanding the knowledge in this domain: (1) there is still a wide range of other WMA technologies equally worthy of being thoroughly analyzed; (2) they did not analyse the effects of incorporating RAP into the WMA formulations, or if so, (i) they did not exhaust the percentages of RAP; and/or (ii) they did not exhaust the type of WMA in which the RAP is used; (3) apart from a few exceptions the life cycle impact assessment step of the LCA methodology tends to be constrained to the consideration of energy consumption-related indicators and the climate change impact category; (4) the role of the upstream supply chain related to the production of chemical additives used in WMA mixtures is commonly excluded from the system boundaries; (5) the existing studies tend to narrow the system boundaries by focusing on a few life cycle phases, usually the materials extraction, mixtures production and construction phases, and thus excluding phases (i.e., work zone (WZ) traffic management, usage and EOL), which depending on the technical context, might drive the environmental performance of the system being analysed. Moreover, while the consideration of the last point is not methodologically wrong, provided that a given set of conditions are met, it constraints a more global view of the system and thereby opportunities for eventually more meaningful environmental improvements.

Given the issues abovementioned, this research study aims to perform a comprehensive and methodologically sounded pavement LCA of a road pavement section incorporating several WMA technologies (i.e., chemical additives and foamed-based), both with and without RAP content and designed and produced in laboratory, which covers all the pavement life cycle phases, from raw material acquisition, via production and use phases, to the EOL phase.

The overall purpose is to increase the pavement community stakeholders' capacity to make more strategic and informed decisions regarding the construction, maintenance and rehabilitation (M&R) of road pavement that would ultimately enhance the sustainability of pavement systems.

2. Methodology

A comparative attributional process-based LCA study is performed taking into account, as far as possible and suitable, the ISO 14040 series (International Standard Organization (ISO, 2006a, b) and the Federal Highway Administration's (FHWA's) Pavement LCA Framework (Harvey et al., 2016). It calculates and compares the potential environmental impacts of different asphalt mixtures adopted in the construction and M&R of a road pavement section during its life cycle.

The stages adopted in this study include goal and scope definition, inventory analysis, impact assessment, and interpretation.

2.1. Goal and scope definition

2.1.1. Goal

The main goal of this paper is to quantify the potential life cycle environmental impacts of a flexible road pavement section throughout its life cycle. The road pavement section studied involves the use of conventional and low-temperature asphalt mixtures, with and without RAP content, in the construction and M&R of wearing courses of the flexible road pavements.