Resources, Conservation and Recycling 104 (2015) 141–151

Contents lists available at ScienceDirect

Resources, Conservation and Recycling

journal homepage: www.elsevier.com/locate/resconrec

Environmental and economic analyses of recycled asphalt concrete mixtures based on material production and potential performance

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ARTICLE INFO

Article history:
Received 8 May 2015
Received in revised form 23 August 2015
Accepted 27 August 2015
Available online 1 October 2015

Keywords:
Life-cycle assessment
Pavement
Road construction
Recycled asphalt pavement
Recycled asphalt shingles
Pavement roughness
Greenhouse gases
Energy consumption

ABSTRACT

As roadway construction is a material and energy intensive activity with potential impacts on the environment, the pavement industry has been seeking for more sustainable construction practices in the past decades. The use of recycled materials such as reclaimed asphalt pavement (RAP) and recycled asphalt shingle (RAS) is widely accepted as among the most commonly used sustainable strategies for asphalt concrete (AC) pavement due to its ability to partially substitute virgin asphalt binder and aggregate in AC mixtures. This study evaluated the environmental and economic benefits and trade-offs of including recycled materials in pavements using a life-cycle approach. Eleven AC mix designs from Illinois with various asphalt binder replacement (ABR) rates were evaluated in terms of environmental and economic impacts using life-cycle assessment (LCA) and an itemized cost analysis. The LCA was conducted in accordance to International Standard Organization ISO 14044:2006 guidelines. The life-cycle impacts of producing the AC mixtures were calculated in terms of energy, global warming potential, and cost. A general trend of reduction in these three sustainability metrics was observed for mix production with increasing ABR. However, without proper modification and engineering of mix designs (e.g. addition of a softer grade virgin asphalt binder), AC mixtures with high ABR can experience reduced fatigue life. Thus, the effect of pavement performance on the environmental impacts of using mixtures with various ABR was also considered, assuming that these mixtures are used in a 4-in. (102-mm) overlay over a four-lane-mile (1.6 km) roadway. A breakeven concept was used to find the decreased service life at which the energy savings from using recycled asphaltic materials in the overlay equal the additional energy consumption incurred from a potential reduced performance in the pavement use phase. The breakeven point was found to be very sensitive to the traffic level of the overlay, with the breakeven service life decreasing rapidly with increased traffic.

1. Introduction

The transportation infrastructure in general and roadways in particular has a significant impact on the environment. According to one recent EPA report (2013), the greenhouse gas (GHG) emissions associated with the transportation economic sector totaled 1829 million metric tons of CO_2, out of a total of 6702 million metric tons of CO_2 in the year 2011. Within the transportation sector, a large amount of GHG emissions, and consequentially energy, is associated with vehicles traveling along the highway system. These emissions are dependent on the total fuels combusted in different types of vehicles, whose quantities are in turn affected by the quality of roadway construction as well as the subsequent condition of the roadway.

Roadway construction is a subsector that requires significant energy consumption due to the total volume of materials used in paved roads every year. The U.S. EPA introduced the concept of emission intensity to provide a means for comparing the relative emissions of GHGs between various industries or economic sectors while taking into account their economic output. Emission intensity is typically calculated as the ratio of the GHG emissions produced per dollar of gross domestic product (GDP). Within the construction sector, the highway construction subsector had the highest emission intensity at 0.54 tons of CO_2 emissions per thousand dollars of GDP (in 2002 dollars), with a total annual emissions of 19.5 million tons CO_2 (Van Dam et al., 2015).

Similar to other construction materials, the use of hot-mix asphalt (HMA) has a significant environmental impact (EPA, 2013). This is further amplified by the fact that HMA is by far the most widely used material in the roadway construction industry. The combination of a relatively high demand for bituminous products coupled with the high environmental footprint of such materials

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http://dx.doi.org/10.1016/j.resconrec.2015.08.014

has paved the way for the emergence of sustainable strategies and practices to meet roadway infrastructure demands while reducing environmental cost.

There are various strategies that have been developed to improve the sustainability of roadways and roadway construction. One common type of such strategies incorporates the use of recycled materials, such as recycled asphalt pavement (RAP), recycled asphalt shingles (RAS), fly ash, and steel slag, among other materials. The use of RAP and RAS in HMA is the focus of this study, and the environmental, functional, and structural performance when using these materials in flexible pavements is discussed in the following sections.

2. Background

2.1. Environmental performance

The use of recycled material in bituminous roadways is not a new concept. Both RAP and RAS are common recycled materials that are used in asphalt mixtures due to the ability of these asphaltic materials to partially substitute the need for virgin aggregates and asphalt binder. For an asphalt concrete (AC) mix, the percentage of virgin asphalt binder that is substituted by recycled asphalt binder from RAP or RAS is known as the asphalt binder replacement (ABR) ratio. Environmental performance of pavements constructed with RAP and RAS is often expressed in terms of energy and GHG savings at the material production stage due to replacement of virgin materials. While energy and GHGs are only two of numerous other environmental impacts (e.g. acidification, smog, and eutrophication), these two environmental burdens are most often reported in pavement construction analyses because of the data availability of processes such as fuel usage for equipment and plant operations.

RAP is increasingly being used in the United States, as the benefits of reduced environmental footprint and lower costs are well understood and applied. According to one study, the amount of RAP used in AC was around 70 million tons in 2013 (Hansen and Copeland, 2013). This represents around 10% of the total AC produced in the US. Asphalt roofing shingles are also an abundant material with 11 million tons being landfilled each year in the U.S. (Goh and You, 2011). In general, RAS comes from two main sources: shingles that are rejected by the manufacturer, called manufacturer waste scrap shingles (MWSS), and shingles removed during reconstruction of building roofs, called tear-off scrap shingles (TOSS). Goh and You (2011) noted that MWSS provide only a small amount (9%) of shingles for recycling and use in AC while TOSS are a more plentiful source. One benefit associated with using RAS is that it contains a high percentage of binder which could partially replace the virgin binder, thus lowering both costs and environmental footprint.

In the state of Illinois, one study by Lippert et al. (2014) noted that in 2013, the Illinois Department of Transportation (IDOT) used about 1.7 million tons of recycled materials in highway construction projects. The study further observed a fourfold increase in the amount of recycled material in 2013 over the amount used in 2009 on a tons-per-mile basis. The study attributed the increase to, among other factors, the expansion of approved RAS processing facilities and tolerances in the specifications.

The environmental benefits of using RAP and RAS are documented in literature, mostly limited to the evaluation of environmental impacts associated with the initial production of asphalt mixtures. Aurangzeb et al. (2014) examined the environmental footprint of asphalt mixtures prepared with high RAP content. The authors observed reductions in energy and GHGs of up to 12.2% with mixtures prepared with 50% recycled RAP material. Another study observed up to 7.5% reduction in energy consumption and 13% reduction in GHGs or global warming potential (GWP) (Meli, 2006). A similar study also reported up to 4% reductions in energy consumption and CO_2 emissions with the incorporation of 25% RAP and 10% bottom ash in bituminous roadways (Huang et al., 2009). In terms of RAS, one study noted up to 16% reduction in GHG emissions with using mixtures prepared with 20% RAP and 7% RAS (Booz Allen Hamilton, 2013). In general, the environmental performance of RAP has been more widely studied than that of RAS. However, environmental footprint studies of pavement construction with RAP and RAS show consistent savings in the energy consumption and GHG emissions, mostly due to reductions in the virgin aggregate and asphalt binder production.

2.2. Functional and structural performance of pavements

One of the major concerns with the use of recycled materials in pavements is whether an equivalent functional and structural performance will be achieved with pavements containing significant percentages of recycled materials. A large volume of research has been dedicated to investigating the performance of AC mixtures containing recycled materials at both a laboratory and field test scale. Williams (2013) conducted both laboratory and field tests using AC mixtures with different ABR contents at various locations in the U.S. In the laboratory testing, the mixes showed good rutting resistance, fatigue cracking resistance, and fracture properties compared to the mixes without RAS. In the field testing, the mixes in the field showed no signs of rutting, fatigue or thermal cracking, but transverse reflective cracking was observed in Missouri, Colorado, Iowa, Indiana, and Minnesota. Another study by Johnson et al. (2010) reported that RAS sections on U.S. Highway 10 in Minnesota were very brittle in appearance and experienced substantial reflective cracking after the first winter. Ozer et al. (2013) conducted a laboratory study on AC mixtures with different RAS contents (2.5, 5.0, and 7.5%) and virgin asphalt binder (PG 58-28 and PG 46-34). Overall, it was found that fatigue potential increased with increasing RAS content. In addition, using the lighter PG 46-34 binder improved fatigue life and fracture energy, suggesting that a properly modified binder grade should be considered at increasing levels of RAS.

In general, there is a consensus that physical and engineering properties of recycled materials are different from those of virgin materials. Such changes or differences in the inherent properties of recycled materials may also result in differences in the performance even if the mix is properly designed and engineered. RAP and RAS are composed of solid (i.e. aggregate, fibers, etc.,) and binder fractions. Characteristics of the solid fraction include source, specific gravity, hardness, and absorption whereas aging level, viscosity, and stiffness constitute major characteristics of the binder fraction. Among these characteristics, properties of the binder fraction of recycled materials have a great influence on the overall strength and fracture behavior of mixes. There are many factors that can affect the performance of pavements, and it does not seem there is a consensus on the performance of AC pavements containing RAP and RAS at this point due to lack of field performance data. However, it is imperative that a scenario-based analysis be conducted to evaluate such benefits and tradeoffs introduced by using more recycled materials in pavements.

2.3. Life-cycle assessment

Life-cycle assessment (LCA) is one method that can be used to evaluate the environmental impacts of pavements and quantify such benefits and tradeoffs introduced by using recycled content. It provides a systematic platform to quantify environmental performance of a pavement throughout its life-cycle. When the potential concerns about the future performance of pavements are considered, life-cycle methods are required. The heightened