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Ecologically based hybrid life cycle analysis of continuously reinforced concrete and hot-mix asphalt pavements

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ABSTRACT

An ecologically-based hybrid life cycle assessment model is used to evaluate the resource consumption and atmospheric emissions of continuously reinforced concrete and a hot-mix asphalt pavements. The cumulative mass and ecological resource consumption values are lower for continuously reinforced concrete, but the median values of cumulative energy and industrial energy consumption were lower for hot-mix asphalt. In addition, the use of reclaimed asphalt pavement results in a higher sensitivity for the ecological resource consumption of hot-mix asphalt compared to that of fly ash when use on the natural capital utilization of continuously reinforced concrete pavement. The cumulative and industrial exergy consumption values are significantly reduced with increases in reclaimed asphalt pavement and fly ash, and the use of low fuel transportation modes.

1. Introduction

Roads have a significant impact on the environment, economy and society, and the selection of pavement type thus has wide ranging implications. All phases of road development, from construction to operations, consume large amounts of ecosystem goods and services, and generate waste and emissions. Life cycle assessments (LCA) in various forms, have been used to study the effects of pavements on the environment but there is been little focus on concentrated on ecosystem goods and services. Most studies on have utilized process-based (P-LCA), economic input–output (EIO-LCA), or hybrid LCA models to estimate the environmental impacts by quantifying energy consumption, atmospheric emissions, and waste generation. Direct and indirect roles of ecological resource consumption have, however, generally been excluded in these studies. Due to the large consumption of natural resources during the production of pavements, there is a need to account for the natural capital of pavement designs. Thus an ecologically-based LCA (Eco-LCA) model is used here to account for ecological good and services used by continuously reinforced concrete (CRCP) and hot-mix asphalt (HMA) pavement by enlarging the system boundary to include not only the national economy, but also ecological good and services.

2. Methodology

The developed hybrid Eco-LCA model evaluates pavement designs on the basis of materials extraction and processing, transportation of pavement materials to mixing plant, mixing plant operations, transportation of mixtures to the construction site, and placement of the pavements. Materials and energy used are quantified, and then a hybrid LCA model developed. The emissions during material transportation and mixing plant operation are calculated by the P-LCA model, and are augmented to the results of the Eco-LCA model to account for direct process-based analysis and indirect economic and ecological analysis.

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We utilize Eco-LCA; a thermodynamic input–output analysis approach to account for the contribution of natural capital (Ukidwe and Bakshi, 2007; Zhang et al., 2010). The model focuses mainly on the consumption of ecosystem goods and services, and aggregates based on various levels such as mass, energy, and industrial and ecological exergy.[1] These metrics are:

- *Cumulative mass consumption (Mass)*; the material consumption of a product; a metrics that have been utilized in material flow analysis (Low, 2005); here only mass is taken into account in terms of kilogram (kg).
- *Cumulative energy consumption (Energy)* captures the energy consumed in the life cycle and is calculated joule (j).
- *Industrial cumulative exergy consumption (ICEC)* expands the system boundary including all industrial processes utilized to convert natural resources into products and is calculated in terms of joule (j).
- *Ecological Cumulative Exergy Consumption (ECEC)* includes the exergy consumed by ecological processes for raw material production, emissions dissipation, and functioning of industrial processes is calculated in terms of solar equivalent joule (sej). It embraces the amount of exergy required by ecological systems to make goods and services used in the industrial system.

Several sustainability metrics are utilized to gain more insights; the ECEC/ICEC ratio or efficiency ratio that takes into account the magnitude of ecological links that missed by ICEC analysis. A high value for the ration account means a pavement design utilizes a greater proportion of non-renewable resources (Ukidwe and Bakshi, 2004). In addition, a renewability ratio is the ratio of renewable to ecological resources consumed and offers an indication of renewable resources depletion. Similarly, the loading ratio of the cumulative consumption of non-renewable resources to those from renewable resources, indicates the relative dependence of a product on non-renewable resources (Ukidwe and Bakshi, 2007); a higher ratio for a pavement indicating relatively more consumption of non-renewable resources.

Life cycle inventory was collected for 1 km of CRCP and HMA with equivalent performance designs based on American Association of State Highway and Transportation Officials ; which is utilized by several previous studies (Horvath and Hendrickson, 1998; Rajendran and Gambatese, 2007; Zapata and Gambatese, 2005).[2]

The main industrial inputs for CRCP, are virgin aggregates and foundry sand, cement, reinforcing steels, and water provided by the sand, gravel, clay, and refractory mining, cement manufacturing, iron and steel mills, and water, sewage, and other systems sectors. Energy required for material transportation, plant operations, mixture transportation to the construction site, and pavement placement is provided by diesel, which is produced by the petroleum refineries sector. For HMA, virgin aggregate and bitumen are the main industrial inputs. These materials are provided by the sectors of sand, gravel, clay, and refractory mining, and petroleum refineries. Diesel, which is mainly consumed during transportation of HMA materials to mixing plant, plant operations, transportation of mixture to construction site, and pavement placement, is provided by the petroleum refineries sector. Electricity, which is provided by the power generation and supply sector, is primarily consumed during HMA mixing plant operations.

Plant energy consumption data associated with per ton CRCP and HMA processing is obtained from Zapata and Gambatese (2005). These values are multiplied by the weight of CRCP and HMA mixes to arrive at energy consumption for 1 km pavement sections. Energy consumption during CRCP processing is based on the diesel fuel amount necessary to mix the total amount of concrete. Energy consumption during HMA manufacturing is based on the diesel and electricity consumption during the asphalt plant operation.

Transportation emissions, which are measured in kilograms of pollutants per ton-km transportation of pavement materials, are also quantified. Emission factors provided by the National Renewable Energy Laboratory life cycle inventory database for single-unit truck are utilized (National Renewable Energy Laboratory, 2010). The analysis includes the carbon dioxide (CO_2), nitrogen oxide (NO_x), particulate matter (PM), carbon monoxide (CO), methane (CH_4), and sulfur dioxide (SO_2) emissions associated with each ton-km of the pavement materials transported. The distance between pavement materials and mixing plant is assumed to be 100 km for each pavement system with 50 km assumed for transporting CRCP and HMA mixtures from plant to construction site. In addition, CRCP and HMA emit atmospheric pollutants during their mixing processes and estimates of these are taken from US Environmental Protection Agency (EPA) (1995; 2000) with aggregated emissions calculated by multiplying the quantity of raw materials with the emission factor.

3. Results

3.1. Deterministic analysis

As can be seen from Fig. 1, CRCP is found to involve a larger resource consumption of energy and industrial exergy than HMA, although the latter has slightly higher values total mass and ecological exergy consumptions. Looking at the resource consumption by life cycle, the material production phase uses the largest overall amount of resources provably because of

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[1] The amount of energy that can used to produce work (Dewulf and Van Langenhove, 2005).

[2] CRCP design includes 12% cement, 17% water, 28% foundry sand, and 43% virgin aggregates, by weight, while HMA design consists of 5% bitumen and 95% virgin aggregates, by weight. The volume of 1 km long pavements is multiplied with corresponding densities to calculate mass and the values allocated for each component such as cement, water, foundry sand, and virgin aggregates to determine the inventory required for pavements. HMA design is 30 cm thick and requires 5791.61 tons of asphalt, whereas CRCP design is 22 cm thick and requires 4205.74 tons of concrete and 86.7 tons of steel reinforcing bars.