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A life cycle based environmental impacts assessment of construction materials used in road construction

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ABSTRACT

Industrial byproducts such as coal fly ash, coal bottom ash, and recycled concrete pavement (RCP) are being used in considerable amounts as a full or partial replacement of natural aggregates. Studies comparing road construction byproduct materials with natural aggregates are limited. In the present study, a comparison of these byproducts with natural aggregates was carried out with respect to cost, environmental pollutants generated, and energy consumption. Pollutant emission data were aggregated to express results in terms of global warming potential (GWP), acidification potential and various toxicity potentials. For assessment of toxicity potentials, all the toxicities were represented with respect to 1,4 dichlorobenzene. Mixed results were found from the Life Cycle Assessment (LCA) and no single material performed superiorly in all categories. Fly ash and bottom ash were found attractive in cost, GWP, and acidification potential categories. RCP had higher GWP and acidification potential compared to natural aggregates. In toxicity categories, in some cases fly ash and bottom ash had higher; and RCP, in all cases, had much lower toxicity compared to natural aggregates.

1. Introduction

Extensive use of natural aggregates in construction projects has been gradually depleting this resource near areas where aggregates are in high demand. The need for resource conservation and lengthened transportation distances has increased the demand to introduce substitute materials for natural aggregates. At the same time, industry, construction and other similar activities produce large quantities of industrial byproducts such as coal combustion byproducts, foundry sand, construction and demolition waste, and steel slags that cause a heavy burden on landfills. These byproducts can and have been beneficially reused mainly as road construction materials (Ahmed, 1993).

Industrial byproducts can contain trace concentrations of various pollutants that may potentially leach and contaminate the underlying soil and groundwater. Currently there are no universal specifications for addressing the environmental impact of byproduct reuse in road construction. Faced with this challenge, each state has a different approach for decision making on byproduct reuse. The Recycled Materials Resource Center has developed and made available online (RMRC, 2008) a framework for screening the industrial byproducts for beneficial uses. The framework consists of lab scale leaching tests followed by field scale long term monitoring of groundwater, surface water and soil quality surrounding the area where the byproduct is used. An industrial byproduct can be used for a beneficial purpose if the byproduct passes these screening tests.

Lab scale leaching tests have been a topic of research for many years. Different types of leaching tests have been developed to assess the extent of long term pollution from subsurface use of byproducts for conditions where environmentally relevant parameters such as pH, redox potential, and liquid to solid ratios may change (Kosson et al., 2002; prEN 14405, 2001; prEN 14429, 2001). The leaching test protocols did not always simulate the proper environmental conditions and thus underestimated or overestimated the mobility of a pollutant from an industrial byproduct (Ghosh et al., 2006). While much emphasis has been placed on leaching test protocols and risks of contaminant leaching, little attention has been paid to other kinds of impact, such as energy consumption and emissions that do not directly originate from the road materials. To evaluate the use of energy consumption and environmental impact from a broader perspective, a life cycle analysis (LCA) approach can be used.

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An LCA is a method of accounting for the environmental impacts associated with a product or a service. The method takes into account various upstream processes and emissions generated during the lifetime of a product. Therefore, the primary task in an LCA study is the estimation of emission factors (emissions generated from the production of unit mass of product) from various upstream processes directly and indirectly linked to the manufacturing of the products. The processes one would include to calculate emissions depend on the system boundary of the project, which needs to be determined upfront.

There are several published examples of the use of LCA for evaluation of different materials in road construction. Rajendran and Gambatese (2007) and Zapata and Gambatese (2005) presented a comparative analysis of energy consumption and solid waste generation associated with traditional reinforced concrete and asphalt pavements. In Denmark, a model for LCA of road construction and disposal of waste generated from municipal solid waste incinerator was developed (Birgisdottir, 2005). In Finland, Mroueh et al. (2001) used an LCA model for road construction to assess the environmental impact from several alternative materials such as fly ash, steel slag and crushed concrete. They found that the use of the industrial byproducts as a substitute for natural aggregate could reduce the environmental impact for some of the impact categories. However, except for the Danish model, none of these studies have included an extensive toxicity assessment approach. In the U.S., PALATE (2008), an extensive tool for pavement life cycle analysis has been developed. PALATE does include a relatively more detailed toxicity assessment approach compared to other studies. However, learning and use of the model requires a significant time investment and it is also not practical to easily compare two or more materials using PALATE. In addition, PALATE is based on an economic input output analysis through use of EIO-LCA model; this approach while powerful and well accepted may yield different results compared to a process based LCA approach (Junnila, 2007). The goal of this research was to develop a complementary, easy to use, web based tool for comparing materials used in road construction. We used a process based LCA approach, and developed a web based model, BenReMod (http://benremod.eng.utoledo.edu/BenReMod/). In this paper, we report on BenReMod-LCA model results regarding the environmental impacts associated with use of natural aggregates in comparison to industrial byproducts such as coal fly ash, coal bottom ash, and recycled concrete pavement (RCP). Coal fly ash can also be used in cement manufacturing, however this study focused on direct replacement of the natural aggregate with byproduct materials and evaluation of other beneficial uses of the industrial byproducts are not discussed in this paper.

2. Methods

2.1. Overview

The life cycle analysis approach was taken to compare environmental impacts of natural aggregate, fly ash, and RCP when they are used in road construction. (The focus of this research was on impacts of diverting byproducts from their placement in landfills and on resource conservation, thus the life cycle analysis focused on direct comparison of natural aggregates with the industrial byproducts.) Construction activities such as excavation and compaction as well as maintenance were not considered since we assumed that environmental emissions and cost associated would be similar for maintenance work. The toxicities generated from materials during life time of a road were taken into account by various time horizons of the toxicity categories. Olsson et al. (2006) excluded the landfill metal leachate concentrations in their analysis with the assumption that if a byproduct is placed in the landfill and metals leached from it, the leachate would be treated and there would not be any major emissions to the environment. We followed the same logic in this paper and accounted for the concentrations leached from the materials into the environment only when they are placed in the road.

The thickness, width and length of the section were taken as 600 mm, 2.5 m and 1000 m respectively, resulting in a volume of 1500 m^3. We assumed that industrial byproducts and natural aggregates were transported from source to site by 32 ton trucks for 50 km and 100 km, respectively. Cost of transportation was taken as $0.13/ton/km (Wilburn and Goonan, 1998).

2.2. System boundary

System boundary is one of the most important parameters that affect the results of an LCA (Suh et al., 2004). System boundary of a material in this study included the production and transportation of the material and associated electricity and oil consumption (Fig. 1(a and b)). In production of the material (and refining the oil) electricity is needed. In this work, only coal combusted electric generation was taken into consideration. Approximately 49% of the electricity in the US comes from coal plants (EIA, 2008a). Energy information administration data (EIA, 2008b) show that coal is the primary power source for electricity production in some states (e.g. Ohio, Indiana, Kentucky). In addition, production of construction materials does not follow the US energy profile. For example, for cement industry 70% of the energy come from coal based power (Huntzinger and Eatmon, 2009). Therefore, while the use of coal as an electricity power source is a simplification, an analysis of the effect of different energy sources was beyond the scope of this study especially considering that the energy mix changes in time, from region to region, and from sector to sector.

Most of the time, fly ash and bottom ash are readily used or need very few processes to modify them for use in road construction. Environmental loading data from these processes is almost nonexistent. For these reasons, environmental loadings of their production processes were not included in the present study. However, their disposal cost at a landfill was considered.

Oil is necessary for transportation. The production of the fuel from crude oil extraction via refining to distribution was taken into account in this study. However, the manufacturing of production plants was not included in the system boundary. As far as vehicles are concerned, the production of the vehicles themselves have not been taken into account, but we did take into account the operation

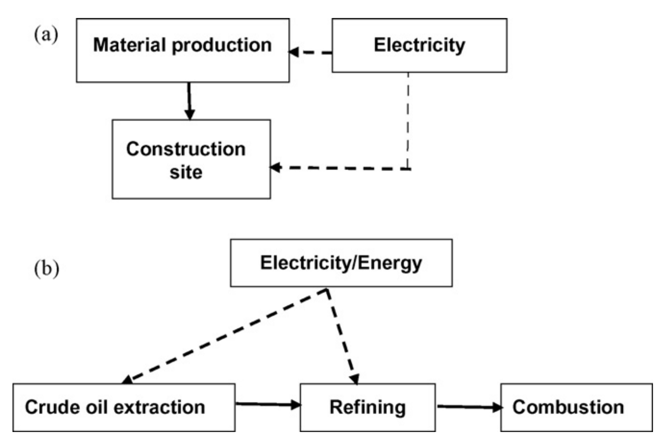

Fig. 1. A schematic representation of the system boundary in the present study. (a) System boundary for a material production and (b) system boundary for the transportation. (Note: dashed arrows indicate no transportation is required to proceed from one process to the other).