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A cradle to gate LCA framework for emissions and energy reduction in concrete pavement mixture design

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Abstract

The plurality of life-cycle assessments for concrete pavements have used national or regional data to develop models to aid in decision related processes for designing concrete pavements. The findings of these studies effectively yield information in which global decisions can be made with respect to material selection and implementation. However, construction projects are dependent upon local supply and demand and require different levels of design complexity: freeze–thaw exposure, leaching potential, and alkali-silica reactivity. This paper presents a cradle-to-gate framework for design engineers and concrete ready-mix producers to implement in an effort to optimize mixture designs across economic, environmental, and mechanical performance criteria. The framework was assessed through the examination of a newly constructed highway in South Georgia. The case study proved that through the incorporation of 20% more Class F fly ash compared to the in-situ mixture design used on the pavement project site, all fresh and hardened concrete properties set by the Georgia Department of Transportation could still be exceeded, while the environmental efficiency would also increase by 23% with a total cost savings of 0.67 million dollars for the 11.52 linear miles (18.54 linear km) of pavement. Additionally, updated emission factors for input materials into concrete pavements, ranging from cement to aggregates, are presented using the most up-to-date data and techniques.

Keywords: Life cycle assessment; Life cycle cost assessment; Fly ash concrete; Sustainable concrete; Pavements

1. Introduction

In 2002, the World Business Council for Sustainable Development published a document, *The Cement Sustainability Initiative*, which proved that the cement and concrete industries alone were responsible for 5% of the world's anthropogenic CO_2 emissions (The Cement Sustainability Initiative, 2002). In 2013, the American Society of Civil Engineers updated their infrastructure report card and the United States was given a grade of D^+ with an estimated $3.6 trillion dollars, nearly 20% of the country's 2015 national debt, needed to be invested by 2020 to receive a passing grade. These facts display the urgency for which sustainable, resilient, and cost-effective solutions need to be developed and implemented into modern infrastructure to sustain modern standards of living and the economy. For the last two decades, life-cycle assessments (LCAs) for concrete pavement systems have been developed in an effort to provide intelligent

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decision-making information with respect to mixture design, input material sourcing, and maintenance requirements through the use of industry-reported fuel consumption by the U.S. Census Bureau and gross material production data by the U.S. Geological Survey (Nisbet, 1996; Marceau et al. 2007; Santero et al. 2011; Solis, 2012). Due to the fact that the vast majority of data related to infrastructure is national or global in nature, many previous life-cycle assessments, especially those for roads, have been large in scope and resulted in findings that are large in scale and therefore intangible to decision-makers at local and state levels: municipalities, ready-mix producers, and Departments of Transportation.

The research presented herein utilized the most current and up-to-date practices for a cradle-to-gate life cycle assessment for concrete pavements. The assessment implements project specific data and experimental practices that co-align with the Georgia Department of Transportation's (GDOT) mixture design and selection process. Additionally, this project takes the form of a case study to promote the tangibility of the findings to an 11.52 linear mile concrete highway project that was completed in March 2015 in South Georgia. The project objective was to create a simplistic framework for the Georgia Department of Transportation to achieve the following three goals: (1) develop a pavement that will yield a longer in-place service life; (2) generate a concrete mixture that has lower first costs; and (3) propose an optimized concrete mixture design that yields a reduced embodied energy and associated CO_2 equivalent emissions.

By selecting a newly constructed project located in Dooly County, Georgia, project-specific data were gathered: mixture designs, material quantities, transportation distances, and costs. These data were essential to accurately analyze how different concrete mixtures could be designed to provide increased structural integrity, reduced costs, and reduced environmental emissions. In an effort to design the most optimal concrete mixture across these parameters, the developed LCA was used to inform the mixture design process. Higher percentages of Class F fly ash in conventional concrete pavement mixtures were studied due to the fact the in-situ mixture on the Dooly County project site already contained a 20% Class F fly ash replacement for the total cementitious content. Interestingly, the GDOT replacement percentage for fly ash is restricted to 15% for the entire cementitious content of a pavement mixture and is suggested for use as an additive to improve workability and plasticity alone. Four concrete mixtures were developed and tested across all standard GDOT requirements for Class 1 pavements to ensure their acceptability in the field. The in-situ design, 20% cement replacement with fly ash, provided by the ready-mixed concrete producer for this project was used as the control for comparison against the experimental mixtures. In short, this research displays the structural, economic, and environmental benefit of using higher volumes of fly ash in concrete pavements in Georgia, while developing updated emissions factors and a framework for other states to carry out a project-specific cradle-to-gate LCA.

2. Literature review and research significance

Work by MIT, UC Denver, and the Portland Cement Association (PCA) developed foundational national and state level LCA methodologies for concrete pavement systems in an effort to determine their total amount of embodied energy and related green house gas (GHG) emissions in terms of CO_2 equivalents (CO_2eq). In 2011, Santero et al. published a comprehensive cradle-to-grave LCA for concrete pavements within the United States and analyzed twelve different road types within urban and rural categories. Santero et al.'s work developed the foundational groundwork for a standardized methodology for pavement LCAs to promote a consistent industry-wide approach and presented emission related findings for each of the pavement categories on a national scale. The presented work in this research used the established LCA methodology by Santero et al. but within a cradle-to-gate framework for a specific project in Dooly County, Georgia.

In 2007, Reiner developed a state based LCA for Colorado and developed emission factors using similar techniques to Marceau et al. in 1996 and Gibbs et al. in 2001. Shen et al. validated the cement CO_2eq emission factor developed by Gibbs in a nation-wide cement plant study in 2014. In addition to the establishment of a methodology to develop emission factors for input material into concrete, Reiner displayed the necessity for incorporating local waste stream materials into concrete pavement systems to reduce environmental pollution and the need to reduce virgin material flows as singular constituents in concrete pavement mixture designs.

In 2010, Durham et al. furthered the work of Reiner for the state of Colorado and displayed the beneficial use of higher volumes of Class F fly ash in replacement of ordinary portland cement (OPC). Durham's findings displayed that a 20% increase in the fly ash volume of the Colorado Department of Transportation's (CDOT) ordinary Class P concrete would result in a $4.40 per cubic yard savings, a reduction in 60,000 tons of used OPC in the state of Colorado from 2005 to 2008, and displayed the experimental mixtures with higher fly ash volumes exceeded all mechanical performance criteria set by CDOT for Class P pavements (Durham et al., 2010). The presented findings and methodologies by Reiner and Durham and Rudzeviciute served to inform the presented research and aided in the development of emissions factors with the most up-to-date and well-reported data.

By refining the LCA boundaries from the presented work by MIT, UC Denver, and the PCA, this research analyzed a single project to incite a new design methodology for concrete pavement mixtures in the state of Georgia. The presented work displays the utility with which case-study based LCAs can inform local businesses and engineers to make well-informed design-based decisions