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A bi-level environmental impact assessment framework for comparing construction and demolition waste management strategies

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ABSTRACT

Several pioneering life cycle assessment (LCA) studies have been conducted in the past to assess the environmental impact of specific methods for managing mineral construction and demolition waste (MCDW), such as recycling the waste for use in concrete. Those studies focus on comparing the use of recycled MCDW and that of virgin components to produce materials or systems that serve specified functions. Often, the approaches adopted by the studies do not account for the potential environmental consequence of avoiding the existing or alternative waste management practices. The present work focuses on how product systems need to be defined in recycling LCA studies and what processes need to be within the system boundaries. A bi-level LCA framework is presented for modelling alternative waste management approaches in which the impacts are measured and compared at two scales of strategy and decision-making. Different functional units are defined for each level, all of which correspond to the same flow of MCDW in a cascade of product systems. For the sole purpose of demonstrating how the framework is implemented an illustrative example is presented, based on real data and a number of simplifying assumptions, which compares the impacts of a number of potential MCDW management strategies in New York City.

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1. Introduction

Construction and demolition waste (CDW) constitutes a large portion of the solid waste produced by humans. According to the U.S. Environmental Protection Agency (EPA), in 2014, 484 million metric tons of CDW was produced in the United States, which was more than twice the amount of municipal solid waste produced in the same year (EPA, 2016). Therefore, optimizing CDW management techniques can lead to significant economic and environmental benefits. Since concrete is the most widely used construction material (Kosmatka and Wilson, 2016) it constitutes the largest portion of construction and demolition waste (CDW). In addition to concrete, CDW consists of other ceramic mineral components such as tiles, bricks, and masonry stone. In many countries over 60% of CDW are ceramic mineral compounds (DG-ENV, 2011), here referred to as MCDW. MCDW is either landfilled or processed into recycled aggregates (RA). The European standard EN-12620 "Aggregate for Concrete" defines RA as aggregate resulting from the processing of inorganic or mineral material previously used in construction EN-12620 (2013). Based on the aggregate constituents, the standard classifies RA into different categories, according to which the use of RA in different applications is regulated. In the present work, although the concept of RA is used as defined by the standard, distinctions will be made between a number of applications of RA without focusing on the constituents or categories of the aggregate.

Processing MCDW typically includes sorting, crushing, and sieving to achieve the desired particle size distribution. RA has been used as aggregate in concrete production; an application that has been extensively researched in the past decades (de Brito and Saikia, 2013; Hansen, 1992). In the United States MCDW is commonly processed into RA mainly for use as low-value unbound aggregate in applications such as road base course, construction fill, and in drainage systems. The application of RA in structural concrete is mostly limited to concrete pavement rehabilitation in U.S. highways. Nearly 100 concrete paving projects which used RA, from processing the old pavement, in concrete were completed in the U.S. before 1994 (Snyder et al., 1994) and several more after (ACPA, 2010; Gonzalez and Moo-Young, 2004). In such projects no-longer serviceable to-be-replaced concrete pavements are recycled into aggregate onsite with mobile crushers and used in the concrete for the new pavement (Snyder et al., 1994). More recent studies show that the application of RA has not significantly changed since the completion of the above-mentioned reports (Jin and Chen, 2015). The reason for the tendency to use RA in concrete pavement rehabilitation projects is that the source of CDW is one pavement with known and relatively uniform quality of concrete, rather than multiple and ever-changing construction and demolition sites. MCDW has other potential applications that are currently under investigation. For example, MCDW may be used as raw material for producing portland cement clinker (De Schepper et al., 2013).

Numerous environmental life cycle assessment (LCA) studies have been performed on MCDW management (Bovea and Powell, 2016; Coelho and de Brito, 2012; Mercante et al., 2012; Pacheco-Torgal et al., 2013). Those studies pursue different goals, in particular: (1) comparing the environmental impacts of producing RA and natural (virgin) aggregate (NA) (Estanqueiro et al., 2016; Hossain et al., 2016; Korre and Durucan, 2009), (2) comparing the environmental impacts of producing concrete with only NA as aggregate and concrete incorporating RA (Braunschweig et al., 2011; Knoeri et al., 2013; Marinkovic et al., 2010; Yazdanbakhsh et al., 2016, 2017), and (3) comparing the impact of landfilling MCDW with that of processing the waste into RA for use as paving materials in road construction (Butera et al., 2015; Penteado and Rosado, 2016).

In order to make environmentally-conscious decisions on how to manage MCDW, the environmental impacts of all the alternative implementable waste management strategies need to be measured and compared. This goal was not pursued, at least in full, by the above-mentioned types of LCA study. If the results from the first type of study show that the environmental burden of producing RA is lower than that of NA, it does not lead to the conclusion that recycling MCDW to RA has the highest environmental benefit. For example, typically in order to produce concrete with a desired compressive strength more portland cement is required when RA, as opposed to NA, is used as coarse aggregate (de Brito and Saikia, 2013). Since portland cement has the highest environmental burden among concrete components (Marinkovic et al., 2010), recycling MCDW into RA for use in concrete may be an environmentally burdensome waste management solution, as will be demonstrated here in an example study.

The findings from a study of the second type may show that the overall impact of producing concrete incorporating RA is lower than that of producing concrete with the same properties using NA. However, such a finding does not lead to the conclusion that recycling MCDW to RA for use in concrete is an environmentally beneficial strategy. Consider a scenario in which MCDW is recycled into RA for use as unbound aggregate in road construction. In addition, assume that the environmental benefit of using RA as unbound aggregate is higher than using RA in concrete. In such a case, changing the MCDW management strategy from recycling the waste into RA for use as unbound aggregate to recycling the waste into RA for use as concrete aggregate will lead to an environmental burden. Finally, the third type of study compares only the two waste management strategies of landfilling and recycling MCDW into RA for use as unbound aggregate.

This work presents a framework for comparing the environmental impacts of all alternative MCDW management strategies. However, to avoid a very lengthy mathematical representation, the framework will be formulated for the three most common strategies: landfilling, processing MCDW into RA and using it as concrete aggregate, and processing the waste into RA and using it as unbound aggregate. Although the mathematical representation of the framework is based on a number of assumptions and is limited to the above-mentioned strategies, it constitutes a robust model that can be readily modified or expanded to account for different assumptions or waste management strategies. To demonstrate the applicability of the framework, an illustrative example study is presented that compares the environmental impacts of a number of potential MCDW management strategies in New York City. For this purpose, construction and demolition waste data from the city of New York along with a number of commercial life cycle inventory (LCI) datasets were used and a number of simplifying assumptions were made. It should be emphasized that the sole purpose of the example study is to demonstrate how the framework can be implemented, and that the example study does not aim to be conclusive about the optimum MCDW recycling strategy in New York City.

To be consistent with the past research on using recycled aggregate in concrete, a distinction is made between fine and coarse aggregates. Fine aggregate passes the 4.75-mm (No.4) sieve during sieve analysis (ASTM C136, 2014) while coarse aggregate is retained on the same sieve (Mindess et al., 2003). The vast majority of the past studies on fine RA show that replacing natural fine aggregate with fine RA reduces the compressive strength of concrete significantly (Evangelista and de Brito, 2014; Katz and Kulisch, 2017), as fine RA typically contains soil, organic materials, and weak mortar that is easily pulverized during the crushing process. Currently, the regulations in many countries prohibit or limit the use of fine RA in structural concrete. The LCA framework pre-

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