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A closed-loop life cycle assessment of recycled aggregate concrete utilization in China

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ABSTRACT

This paper studies the potential environmental impact of recycled coarse aggregate (RCA) for concrete production in China. According to the cradle-to-cradle theory, a closed-loop life cycle assessment (LCA) on recycled aggregate concrete (RAC) utilization in China with entire local life cycle inventory (LCI) is performed, regarding the environmental influence of cement content, aggregate production, transportation and waste landfilling. Special attention is paid on the primary resource and energy conservation, as well as climate protection induced by RAC applications. Environmental impact between natural aggregate concrete (NAC) and RAC are also compared. It is shown that cement proportion and transportation are the top two contributors for carbon dioxide (CO_2) emissions and energy consumption for both NAC and RAC. Sensitivity analysis also proves that long delivery distances for natural coarse aggregate (NCA) leave a possible opportunity for lowering environmental impact of RAC in China.

1. Introduction

Sustainable development is important to the global environment and human development. For the construction industry, concrete is one of the most widely used construction materials around the world. Environmental issues associated with CO_2 emissions play a leading role in the sustainable development of concrete industry in this century (Naik, 2008; Wu et al., 2014). Due to high demand on concrete production, construction industry is responsible for about 7% of global CO_2 emissions (Mora, 2007) and China accounts for about one-quarter of global greenhouse gas in the world (Zhang et al., 2009; Wu et al., 2012). Besides, it is estimated that about 37.5 billion tons of aggregate are consumed annually around the world and China holds almost 40% among them. In China, large amount of construction and demolition (C&D) waste is also generated and occupies nearly 50% of municipal solid waste (Ding and Xiao, 2014).

Nowadays, in order to pursue sustainable development in civil engineering, consensus has been reached that consumption of raw materials and energy should be decreased, C&D waste should also be prevented from landfilling. Recycling has the potential for reducing C&D waste disposed in landfills and preserving natural resources. As a result, recycled coarse aggregate (RCA) as constituent in newly cast concrete has been widely used in the construction industry (Xiao et al., 2012a; Behera et al., 2014).

In fact, since early 1990s, interests in using alternative materials especially employing recycled aggregate concrete (RAC) in construction have continuously been grown (Poon and Chan, 2007; Vandecasteele and van der Sloot, 2011; Xiao et al., 2016). In order to safely apply RAC in civil engineering projects, researchers have been engaged in many investigations on both mechanical and structural behavior of RAC. Achievements summarized by Hansen (1986), ACI 555R-01 (2001), Xiao et al. (2012b) and Kou et al. (2012) have strengthened the confidence for utilizing RAC in engineering projects. However, in addition to technical objectives, environmental issues should also be addressed and balanced. It is because that governments, building designers, manufactures and contractors can use environmental statistics in establishing sustainable construction environment.

Abbreviations: NAC, natural aggregate concrete; RAC, recycled aggregate concrete; NCA, natural coarse aggregate; RCA, recycled coarse aggregate; C&D, construction and demolition; GWP, global warming potential; CED, cumulated energy demand; CMR, consumption of mineral resources; LCA, life cycle assessment; LCI, life cycle inventory; ISO, International Organization for Standardization; CNMLCA, China Centre of National Material Life Cycle Assessment.

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Actually, with the drive towards sustainable development, as a methodological framework, life cycle assessment (LCA) has been well developed in the past three decades. It has become a powerful tool for quantifying, evaluating, comparing and improving products in terms of potential environmental impacts and economic viabilities attributable to products' life cycle (Rebitzer et al., 2004). 1990s had saw a remarkable growth of scientific and coordination LCA activities worldwide. The International Organization for Standardization (ISO) has been involved in LCA since 1994. ISO adopted formal tasks and carried out series for international standards, such as ISO 14001 (2015), ISO 14004 (2004), ISO 14006 (2011), ISO 14040 (2006) and ISO 14044 (2006). ISO has played a leading and coordinating role in bringing LCA practitioners, users and scientists together in collaborating continuous improvement and harmonization on LCA frameworks, terminologies and methodologies (Guinee et al., 2010).

In the area of sustainable evaluation on RAC utilization, LCA has also been an effective tool in meeting municipal decision makers' interest (Salhofer and Diaz, 2007). Results from LCA can be used as indicators for environmental effects in source separation, waste treatment and concrete recycling technologies (Ortiz et al., 2009; Van den Heede and De Belie, 2012).

Marinković et al. (2010) and Tošić et al. (2015) in Serbia performed a comparative LCA program and they found that energy savings in recycling projects are only possible if recycling plants are located close to building sites. In addition, they also determined the multi-criteria optimization for NAC and RAC, based on their local life cycle inventory (LCI).

Hossain et al. (2016a) in Hong Kong conducted LCA studies to assess and compare the environmental consequences of RCA production from C&D waste and wasted glass, and concrete paving eco-blocks (Hossain et al., 2016b) by using case specific and first hand data. They found that compared with natural coarse aggregates (NCA), RCA produced from C&D waste reduce 65% greenhouse gases (GHGs) emission with a saving of 58% non-renewable energy consumption. Dong et al. (2015) in Hong Kong investigated the changes caused by replacing overseas LCI with local data due to the lack of local data. The results indicated that the change of single score increases with the adjustments in the original LCIs and the changes in the localized concrete datasets are mainly attributed to the adjustments of cement and transportation.

From the environmental point of view, Turk et al. (2015) in Slovenia conducted the LCA method to evaluate the RAC and natural aggregate concrete (NAC). According to their results, the environmental impact of recycled concrete is reduced to about 88% (but only to 96% with respect to CO_2 emissions - i.e. global warming) of the corresponding conventional concrete impacts. However, the results also showed that the use of RAC is very sensitive to the delivery distance and long delivery distances (i.e. of 100 km or more, one-way) would result in the outweighing of environmental benefits.

Gayarre et al. (2016) in Spain presented a study to evaluate the life cycle analysis of precast concrete kerbs manufactured with concrete aggregate obtained both in fixed and mobile plants. It was found that a significant energy saving has been promoted together with a relevant decrease in the emissions. According to their results, the possibility of using a mobile plant for waste processing may not be the best option. Globally speaking, the best option would be to perform concrete recycling at a fixed plant.

Furthermore, Coelho and de Brito (2013a, 2013b) in Portugal, Blengini and Garbarino (2010) in Italy, Knoeri et al. (2013) in Switzerland have also taken LCA researches in analyzing the environmental and economic implications of C&D waste recycling chain. Other LCA investigations in Australia (Collins, 2010), United States of America (Chowdhury et al., 2010; Carpenter et al., 2013; Loijos et al., 2013), Canada (Yeheyis et al., 2013) and Germany (Weil et al., 2006; Wittmaier et al., 2009) also provided suggestions on the C&D waste management and their applications. Most of these studies proved that RAC utilization has some advantages with appropriate management or delivery distance in local projects. It can be found from the mentioned LCA studies that the environmental impact of RAC application location varies in different regions due to the unique LCI and its situation.

According to the review research made by Laurent et al. (2014), most LCAs on solid waste management systems have primarily been concentrated in Europe. Very limited LCA recycling applications in developing countries could be found. China holds less than 5% significant LCA studies in solid waste recycling areas, C&D waste management is thus hindered in agendas. However, it is believed that RCA recycling in developing countries is significantly different compared to Europe such as the production and transportation methods for aggregates recycling. There is a genuine opportunity for RAC utilization in China on the aspect of environmental burdens. Serious problems on resource shortage of NCA are currently occurred in China. The NCA sources have become scarce, while the source locations are usually far away from urban areas. Nevertheless, recycling plants are usually located near or in big city areas for economic reasons (De Melo et al., 2011). To what extent does aggregate transportation affect environmental issues should be tackled. Another issue of environmental impacts of RAC in China is arising from the production processes. It is convinced that the quality of RCA from C&D waste deeply affects the mechanical property of RAC and its structural performance (Xiao et al., 2005, 2012b; Eguchi et al., 2007; Rao et al., 2007). However, in China, limited viable and advanced technologies have been applied on the RCA production in engineering projects. This situation is mainly due to the lack of government policies on recycling and landfill ban. The environmental impact of RAC application is still unclear.

As a result, the present study dealing with potential environmental effects of RAC utilization would be a regional analysis, particularly in China. Attention has been paid on the feasibility of aggregate delivery and production. It is also noticed that the cradle-to-cradle (C2C) theory has widely been accepted, as an alternative to the common cradle-to-grave theory (William McDonough architects, 1992; van Dijk et al., 2014) and it has got the attention by several professionals and scholars from the field of sustainability (Braungart et al., 2007; Kumar and Putnam, 2008). However, the current LCA researches on RAC applications mentioned above were exclusive an open-loop analysis. In fact, RCA produced from concrete waste, which can then be used for concrete production in a closed loop cycle, as waste disposal to landfills being avoided. Therefore, based on the cradle-to-cradle theory, the following analysis on the environmental impact of RAC utilization would be a closed-loop LCA research.

2. Methodologies

The description of the following LCA methodology was based on the guideline of ISO 14040 (2006) and ISO 14044 (2006), and consists of four distinct analytical steps: (1) defining goals and scopes; (2) creating life cycle inventory (LCI); (3) assessing impacts; and (4) interpreting results.

2.1. Goal and scope definition

The objectives of this LCA study include: (a) to draw up a regional LCI for NAC and RAC production in China based on available local data, directly collected from own investigations, some researches and enterprises involved in this area; and (b) to