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Carbon footprint of block prepared with recycled aggregate: a case study in China

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Abstract. This study aims to evaluate the carbon footprint of concrete blocks prepared with local recycled waste materials derived from Changsha using life cycle assessment (LCA) technique. The local life cycle inventory was developed for conducting case-specific assessment of concrete blocks prepared with recycled aggregates (RA) sourced from a local construction and demolition (C&D) waste. The result is also compared with concrete blocks made by natural aggregates (NA). The results show that greenhouse gases (GHGs) emissions related to the production of RA were 3 kg CO₂ eq., which is 57% lower than the production of NA. However, the adoption of RA in concrete blocks production induced higher GHGs emissions than NA concrete blocks due to higher amount of cement was needed to achieve a same required mechanical strength. Guidelines to further design and develop sustainable green concrete blocks prepared with RA to meet the mechanical requirements based on the current situation in Changsha city has also been highlighted.

1. Introduction

As the threat of climate change becomes more acute, intensive attention has been given globally [1]. Among the industries, construction industry induces a significant environmental impact and is particular obvious in fast growing country like China. Since 2007, China has become one of the largest carbon emitter in the world, accounting for about one-quarter of global GHGs emissions [2,3]. In addition, China's CO₂ emissions from cement production is around 10.85% of the total emissions in China [4]. Concrete block as a kind of commonly used cement-based construction product, therefore can be perceived as one of the main sources for the generation of GHGs emissions [5].

Changsha is a capital city of Hunan province, located at the middle of China has constructed about 100 million m² of building area in 2016, which recorded as one of the highest in China according to National Bureau of Statistics of China [6]. This subsequently generated a substantial amount of C&D waste and GHGs emissions. Therefore, sustainable management of C&D waste and the production of low-carbon construction products in Changsha has becomes essential. However, one of the challenge facing in C&D waste management is running out of disposal sites for the wastes generated in Changsha. In order to pursue sustainable development, the local government of Changsha city has launched a series of policies to recycle and reuse of waste (instead of landfilling) for minimizing the environmental



pollution impacts. Many studies have demonstrated that C&D waste can be recycle and reuse in producing construction products such as concrete blocks [7-9].

For assessing GHGs emissions, LCA method is considered as a promising tool to obtain a comprehensive understanding of potential energy consumption, GHGs emissions and environmental impact by defining a scope of analysis for a given product through its life cycle [10-12]. Several studies have been focused on the environmental assessment of RA production, use in concrete block, kerb and road sub-bases construction by LCA [13-18].

Case specific variations of environmental impacts are clearly observed among the studies due to different management scenarios and considerations in different regions. Thus case-specific study using local data is suggested by scientific studies. Therefore, this study was conducted to quantify the GHGs emissions of concrete block produced with RA based on available local data, and then compared with its counterparts in Changsha. In addition, suggestions are given for the sustainable management of RA production and its utilization in concrete block products.

2. Materials

In Changsha, NA used for the production of concrete blocks are transported from a distance of about 100 km. In terms of RA, the aggregates are obtained from local demolition sites within the city of Changsha. The main composition of the RA derived from the C&D waste are red brick, concrete and mortar. The current attempt is to compare concrete blocks produced with RA and having a similar mechanical strength with that of concrete blocks made by NA. The mix proportion sourced from a local concrete block producer in Changsha for concrete blocks of 1 tonne (per units) are given in Table 1.

Table 1. Mix proportioning of concrete blocks prepared with NA and RA (1tonne blocks).

Types of block	Cement (kg)	NA (kg)	RA (kg)	Water (kg)	Compressive strength (MPa)
NA concrete block	99	821	0	84	21.51
RA concrete block	162	0	714	130	22.50

3. Methodology

For assessing GHGs emissions as carbon footprint, the ISO 14067 standards was used in this study to capture the environmental impacts of concrete products by considering the use of local recycled aggregate derived from C&D waste [19].

3.1 Goal and scope definition

The goals of this study are: (a) to develop a regional LCI for concrete blocks made with RA based on available local data, (b) to assess and compare the GHGs emissions of concrete blocks made with both RA and NA, and (c) to suggest the development of low-carbon concrete block based on the current situation in Changsha. The scope of the study includes the NA and RA production (including both transportation), cement production, concrete block manufacture and waste disposal. It is represented the sequence of actual processes in the life cycle of both types of concrete block production.

3.2 Functional unit and boundary

Different types of raw materials were used for the production of concrete blocks. In order to keep the inventory data consistently, it is important to use the same amount and functional unit (1 tonne) as materials mix proportion. Therefore, each material has been used in the production of 1 t of concrete blocks according to their mix-proportion, and thus 1 t of blocks is considered as functional unit in this study. According to the guidelines of ISO 14067, “cradle-to-site” system boundary was selected (Figure 1), and the system boundaries are indicated with dashed lines.

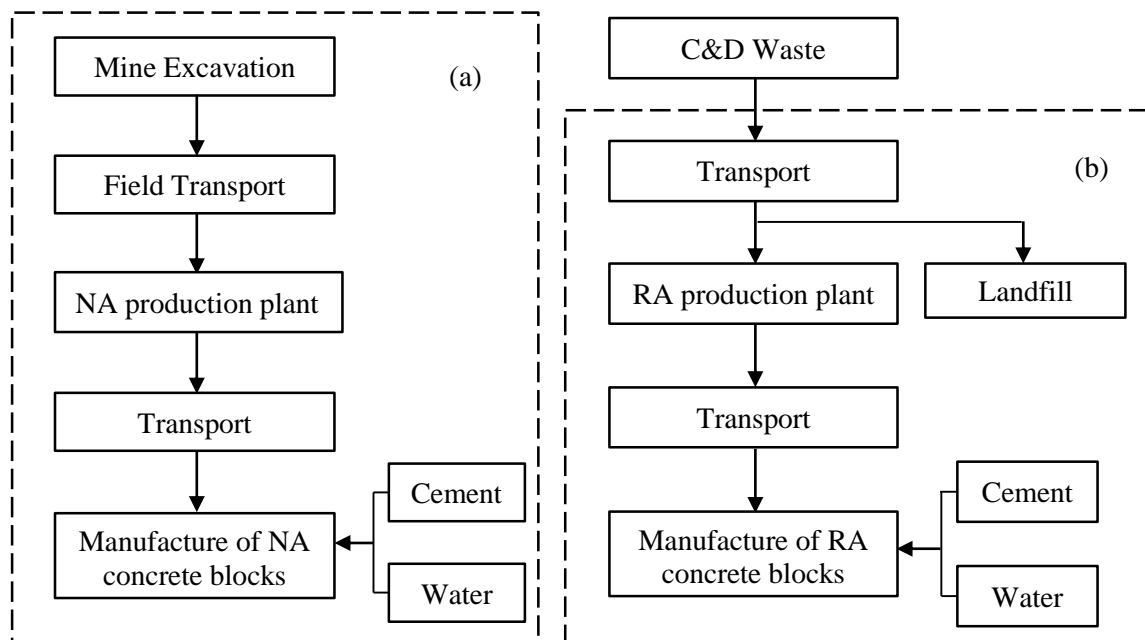


Figure 1. System boundary: Cradle-to-site. (a) NA concrete block production. (b) RA concrete block production (with landfill disposal).

3.3 Life cycle inventory (LCI) data

LCA includes the collection and calculation of data to quantify the input of materials and the output of solids, liquids and gases at selected system boundaries [20]. In this study, case-specific downstream data was collected and used for RA concrete block production in Changsha from a respective manufacturer, while CLCD database was used for the upstream data for energy production and consumption and transport in this study. References and LCI databases were also used for some materials and processes missing in the CLCD database.

In the process of inventory analysis, new data may be added, or the original limitations may be found. Therefore, the data collection program was modified in repeated calculations to meet research purposes. Table 2 shows the information of the raw materials for manufacturing concrete blocks and their type of transport with a given specific transport distance. Table 3 shows the energy requirement for both NA and RA production.

Table 2. Materials and transport for concrete block production in Changsha.

Materials	Locations	Transport type(t)	Distance (km)
NA	Extraction site to NA production plant	Trucks (12)	1
NA	NA production plant to block production plant	Trucks (30)	100
Recycled C&D waste	Recycled C&D waste generation sites to RA production plant	Trucks (12)	20
C&D waste	C&D waste generation sites to landfill	Trucks (12)	25

Table 3. Energy requirements for materials/processes.

Materials/processes	Energy consumption per tonne	Fuel type
NA production	9 MJ	Electricity
	14 MJ	Diesel
RA production	12 MJ	Electricity
	6 MJ	Diesel
Landfill of C&D waste	R ^a	R ^a
Cement production	R ^b	R ^b
Concrete block production	11 MJ	Electricity

^a Referring to [21].

^b Referring to [22,23].

3.4 Impacts assessment

The details of concrete block production were modelled in SimaPro 8.3 software, and the GHGs emissions were assessed by using the IMPACT 2002+ method in terms of GHGs in kilograms of CO₂ equivalent (kg CO₂ eq.).

4. Results and discussion

Based on the chosen functional unit, system boundary and the collected data, carbon footprint of (1 tonne) concrete block production using NA and RA in Changsha is reported.

4.1 Life cycle impact assessment

Table 4 shows the cumulative GHGs emissions of concrete block production using NA and RA. Apparently, the total GHGs emissions related to the production process of concrete blocks produced with NA and RA were 97 kg CO₂ eq. and 138 kg CO₂ eq., respectively. The results implied that RA concrete blocks had higher GHGs emissions than that of NA concrete blocks, mainly due to the amount of cement used in RA concrete blocks was higher to obtain a similar mechanical strength. This is understandable by the fact that the weak quality of RA (hardened old mortar adhered to the aggregate surface) directly affect the mechanical properties of the concrete blocks.

Table 4. Comparison of cumulative GHGs emissions of NA and RA concrete block production.

Processes	GHGs emissions (kg CO ₂ eq./t of block)	
	NA concrete block	RA concrete block
Cement production	90	146
NA production	7	-
RA production	-	3
Avoided landfill	-	-11
Total	97	138

Figure 2 presents the share of the raw materials in concrete blocks on total GHGs emissions. For both types of concrete block, cement production was the highest contributor to the concrete block life cycle (more than 90% of the total GHGs emissions). This is because a large quantity of GHGs are produced during the coal burning and calcination process for limestone [24,25].

As expected, the second most contributor for the total GHGs emissions was NA production (Figure 4). The high emissions are related to the use of electricity and diesel fuel for NA production (i.e. extraction, crushing, sieving, etc.), and a comparatively long transportation distance from the NA production plant to the local concrete block manufacturer. On contrary, RA from C&D waste had a positive value in terms of environment impacts due to the shorter transportation distance (the RA were

obtained from the city area) and saving of disposal landfill. For example, about 7 kg CO₂ eq. GHGs were emitted for producing NA from crushed stone, whereas only about 3 kg CO₂ eq. GHGs were emitted for the case of RA production. Moreover, other environmental benefits of using RA instead of NA (extracted from natural resources) include the less impacts of the carcinogens, ionizing radiation, aquatic ecotoxicity, terrestrial ecotoxicity and aquatic acidification [26-28]. The GHGs emissions of water in both NA and RA concrete blocks was insignificant as compared to cement and aggregate, and thus was excluded from this study.

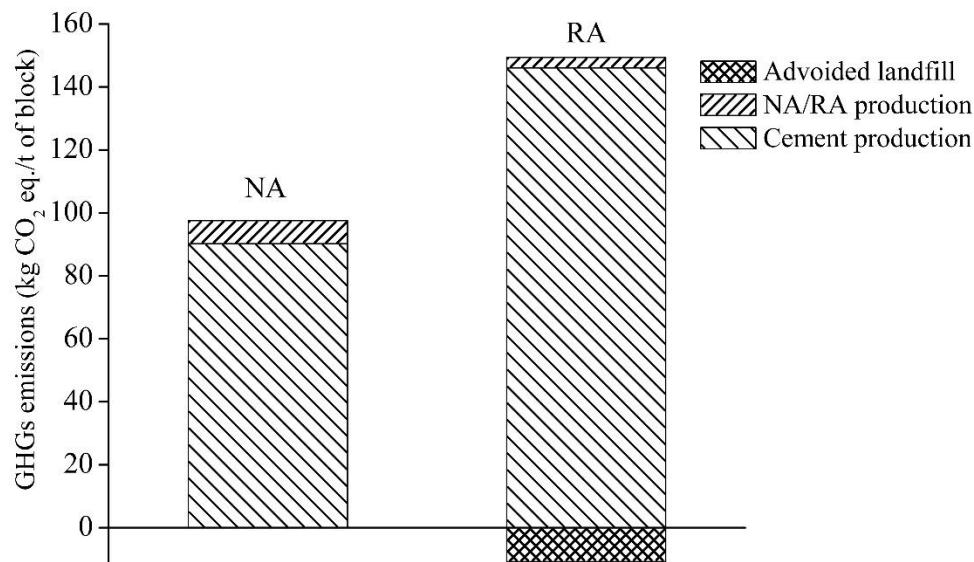


Figure 2. Comparison of GHGs emissions of NA and RA concrete blocks.

4.2 Interpretation

According to the carbon footprint analysis (a case study in Changsha city), the utilization of RA in concrete block production was not beneficial in terms of environmental benefits. The design and manufacturing process of RA concrete blocks in Changsha failed meeting the requirements of low-carbon concrete blocks prepared with RA derived from local C&D waste. This is due to the higher amount of cement was required in RA concrete blocks (for a same mechanical strength), owing to the inferior properties of RA. In addition, due to the 71% of the electricity in China comes from the combustion of fossil fuels [29], the use of high electricity in the cement production process could also contribute to a significant increase of total GHGs emissions in the whole life cycle process.

In summary, without improving the recycling methods of C&D waste and the quality of the RA used, concrete block containing RA may need higher amount of cement to achieve same mechanical strength as with NA concrete blocks [30], thereby induce higher environmental impacts.

5. Suggestions

Due to increasing of GHGs emissions in China, the Chinese government has been committed to reduce GHGs emissions by 40-50 % by the year of 2020 [31]. In addition, increase in urban populations and boosting of construction activities in Changsha, a considerable amount of C&D wastes generation is expected to increase in coming years. To accommodate these issues, promoting a sustainable management of C&D waste generation is essential. Based on the findings of this paper, following steps are suggested to better utilize the local C&D waste (from Changsha) in the production of low environmental impact concrete block:

- (i) improve the quality of RA by adopting high-tech demolition machines or using post-treatment methods to remove the old mortar adhered on the surface of RA.
- (ii) use of supplementary cementitious materials (e.g. fly ash, ground granulated blast-furnace slag, etc.) to replace part of the cement for the production of RA concrete block.

- (iii) adopt of clean energy (e.g., bio-fuel) instead of burning steam coal in the cement production process.
- (iv) assess the environmental impacts and benefits of RA concrete blocks by considering the whole life cycle.

6. Conclusion

In this study, the carbon footprint of concrete blocks produced with NA and RA in Changsha was studied and compared. Based on the primary data collected from the local manufacturers, a regionally based life cycle inventory was developed. The results demonstrated that about 30% lower GHGs emissions can be achieved for the production of NA concrete blocks when comparing with corresponding concrete blocks made with RA. This is because an extra 64% of cement was required for RA concrete blocks to achieve a same mechanical strength of NA concrete blocks. It should be noted that for the concrete block production, the highest GHGs emissions were coming from the use of cement, responsible for more than 90% of the total GHGs emissions during concrete blocks production. Therefore, ways to minimize the use of cement could be significant contribute to the lower GHGs emission.

Although RA concrete blocks currently impose higher GHGs emission than NA concrete blocks in in Changsha, the use of RA in concrete blocks could help in minimizing the C&D waste disposal problem and encourage use of less natural aggregates. Furthermore, the current data of RA production (GHGs emissions) in Changsha is about 57% lower than that of NA required. Therefore, effective design to reduce the cement content or finding alternative low-carbon cementitious materials to further improve the overall performance of concrete blocks is important for sustainable construction industry in China.

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