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Life cycle assessment of natural and mixed recycled aggregate production in Brazil

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A B S T R A C T

The natural and mixed recycled aggregate production for use as road base and subbase have been compared through an attributional life cycle assessment. The primary data have been collected in a basalt natural aggregate production facility and in a recycling facility of mixed aggregate, both located in Southeast Brazil. The topic is important since there is a local increasing demand for aggregate use in road construction and there are no studies related to the environmental aspects of the production of natural and mixed recycled aggregate, and no suitable, site-specific data are available to develop a reliable life cycle investigation. The potential environmental impacts related to the two production processes have been estimated by using the Impact 2002+ methodology. The results show that the production of recycled aggregates is preferable to that of natural materials for the impact categories of "respiratory inorganics", "terrestrial ecotoxicity", "land occupation", "global warming" and "non-renewable energy". A specific sensitivity analysis suggests that the mixed recycled aggregate is a better option for all the environmentally impact categories if the distance of the recycling facility from the consumer is up to 20 tkm longer than the distance of the natural aggregate production facility from the consumer of this product. These results, and those of the detailed life cycle inventory and impact assessment, may support the decision making process in the same field as well as the development of similar life cycle assessment studies, provided that both be appropriately adapted to the specific conditions of the system under analysis.

1. Introduction

Construction and demolition wastes (CDW) are generated in construction, demolition and renovation of buildings and civil engineering works, and represent a major challenge to the modern society, mainly because their high generation rates and heterogenic composition (Butera et al., 2015a; Dahlbo et al., 2015). In addition to the high consumption of natural resources and energy (up to 40% of the raw materials extracted globally), construction activities generate significant amounts of wastes, corresponding to an average of 35% of the total solid wastes produced worldwide (Construction Materials Recycling Association, 2005; Marzouk and Azab, 2014).

In Brazil, the construction industry accounts for around 14% of the gross domestic product (GDP), and is a major consumer of natural material resources, with about 20%–50% of the total consumption (Paz and Lafayette, 2016). It has been estimated that the Brazilian municipalities collect yearly 45 million tons of CDW from drop off centres and from illegal disposal sites; there are no reliable data available on the CDW produced by large generators, and then, it can be inferred that the total amount produced in the country is even higher (ABRELPE, 2015). In the State of São Paulo, the most populated and economically important of Brazil, a total amount of 24 million tons of CDW is produced yearly, which corresponds to 55% of the municipal solid waste produced in the State (São Paulo, 2014). Despite the focus of the current Brazilian environmental regulation on waste prevention and valorisation, landfilling is still the predominant option for CDW management. Thus, there is a demand for researching technical, regulatory, economic and environmental aspects of CDW management, especially logistics and

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recycling, in order to improve the construction sector sustainability. In particular, it is known that 80.4% of the Brazilian road network is unpaved, corresponding to approximately 1.36×10^6 km of roads (DNIT, 2013). Considering that the construction of 1 km of a 10 m wide road consumes an average of 2.6 t of natural aggregates (MME, 2009), a total amount of 3.57×10^9 t of natural aggregate would be necessary to supply the current demand of paving roads. These data indicate the presence of a huge demand for aggregate use in road construction, and for a developing country, the use of recycled aggregate may be an opportunity to couple economics and environment sustainability.

Brazil has large reserves of minerals for extracting natural aggregates; however, this abundance must be carefully analysed. The cost of transporting natural aggregates from the quarry to the distribution centres or to the final consumer increases its final price, since in Brazil all transportation occurs by road, and in many regions, the quarries are located at distances greater than 100 km from the consumers. In other cases, even if the mineral is economically available, it cannot be extracted due to environmental restrictions, municipal zoning laws, or because the uncontrolled growth of large urban centres ends up invalidating the operation of quarries (MME, 2009).

CDW recycling may potentially reduce both waste landfilling and natural resources extracting (Gayarre et al., 2016; Ding et al., 2016), as it has been confirmed by several studies (Blengini, 2009; Blengini and Garbarino, 2010; Marzouk and Azab, 2014; Duan et al., 2015; Vitale et al., 2017). However, in some cases, the environmental burdens connected to recycling may overtake the benefits (Blengini, 2009). This occurs, for instance, for low energy demand processes of natural aggregates production, such as those of fine recycled aggregate vs natural sand (Blengini and Garbarino, 2010), or when there is a too long distance from the generation source to the recycling facility. For example, a recent life cycle assessment (LCA) study of Penteado and Rosado (2016) shows that for a medium-sized city in Southeast Brazil, recycling is preferable than landfilling only if the distance from the generation source to the recycling facility is within 30 km. The quality of recycled aggregate is another important limiting factor of CDW recycling (Di Maria et al., 2015). Depending on the CDW management practices, mainly those of source segregation phase, the aggregates may be used in roads construction as filling material (low-grade application) or in new construction works (high-grade application). Finally, another important issue is the potential contamination of subsoil and groundwater by the leachate produced during the use of CDW recycled aggregated, especially in road construction applications, as discussed in depth in the studies of Butera et al. (2014, 2015a, 2015b). With reference to this aspect, the Brazilian Standard NBR 15.115 (ABNT, 2004a) classifies CDW recycled aggregates (RA) in concrete recycled aggregate (CRA), a material with a minimum of 90% in weight of cementitious fragments and rocks, and mixed recycled aggregate (MixRA), a mixture of ceramic, bricks, concrete blocks, mortar, concrete and cement. Due to the construction techniques, the CDW management practices in working sites, and the current recycling technologies, the RA produced in Brazil is mostly classified as MixRA, a material that according to many studies (Carneiro et al., 2001; Fernandes, 2004; Motta, 2005; Leite et al., 2011; Agrela et al., 2012; Ossa et al., 2016), is suitable for use in road paving construction. According to the Brazilian Standard NBR 15.116 (ABNT, 2004b), both CRA and MixRA may replace NA in base, subbase and subgrade reinforcement of roads, as long as they meet the standard requirements.

The Life Cycle Thinking approach and the related quantitative and standardised tool of LCA are generally recognised as "an informed and science-based support to a more environmentally sustainable decision-making" in CDW management (JRC-IES, 2011; Bovea and Powell, 2016). In particular, they appear able to provide reliable comparisons of aggregate production processes (Butera et al., 2015a). An analysis of scientific literature indicates that there are LCA studies focused on CDW managements (Blengini, 2009; Blengini and Garbarino, 2010; Vitale et al., 2017); others on recycling facilities for CDW (Ibãnez-Forés et al., 2011; Mercante et al., 2012; Coelho and de Brito, 2013a, 2013b); others on LCA of CDW use as material for road construction (Chowdhury et al., 2010; Butera et al., 2015a), and others on CDW use as aggregate for concrete production (Marinkovic'et al., 2010, 2013, 2014; Knoeri et al., 2013; Ding et al., 2016; Hossain et al., 2016). On the other hand, at the authors knowledge, there is only one LCA study focused on the environmental impact of the production of CDW and natural aggregate (Tošić et al., 2015), where, anyway, a detailed life cycle inventory (LCI) is not reported.

The rationale of this study is the local increasing demand for aggregate use in road construction, and the evidence that a specific scientific study may give an important contribution to improve the sustainability of the Brazilian construction sector. In particular, there are no reported studies in literature evaluating the environmental profile of the production of natural and mixed recycled aggregate, and no suitable, site-specific data are available to develop a reliable LCA investigation on CDW recycling. The study aims first to providing a detailed LCI, based on primary data, which may assist the local decision makers in choosing alternative materials for road paving base and subbase, and preventing environmental impacts. The described results can also be useful to similar studies, if the geographical, temporal and technological conditions will be appropriately considered. Moreover, it wants to propose a reliable and scientific assessment of potential environmental impacts of the alternative productions of aggregates for the specific application of road paving base and subbase material, completed with the quantification of the contributions of each specific stage.

2. Methodology

This methodology used in the study follows the ISO 14040 and ISO 14044 standards (ISO, 2006a; ISO, 2006b), which report the principles and framework of a life cycle assessment. In particular, according to ISO 14040, a LCA comprises four major stages: goal and scope definition, life cycle inventory, life cycle impact assessment and interpretation of the results. The first two of them have been included in this section while the remaining two are in the "Result and Discussion" section.

2.1. Goal and scope definition

An attributional life cycle assessment has been developed in agreement with the ISO standards (ISO, 2006a, 2006b). The goal of the study includes: (a) to draw up a regional LCI for natural aggregate (NA) and mixed recycled aggregate (MixRA) production in Brazil, based on primary data collect in a stationary recycling facility and a basalt quarry, both located in southeast region of Brazil (Fig. 1); and (b) to develop a comparative LCA study on the environmental impacts of NA and MixRA production.

The resulting LCI will be useful to design scenarios for future LCA studies on CDW management, and the life cycle impact assessment (LCIA) will help the local decision makers (public or private) on choosing the most environmentally friendly materials. As already mentioned, MixRA may substitute NA for road base and subbase in a ratio 1:1. This is the reason for which the functional unit is defined as the production of 1 t of aggregate, i.e. 1 t of natural aggregate from basalt or 1 t of mixed recycled aggregate from CDW. The processes for each scenario are presented in Fig. 2.

The estimation of the environmental burdens related to the