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Life cycle assessment of concrete made with high volume of recycled concrete aggregates and fly ash

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ABSTRACT

Since concrete is the most widely used construction material in the world, it is important to improve its environmental performance. A possibility is to use supplementary cementitious materials and recycled aggregates. Therefore, the objective of this work is to compare the environmental impacts (EI) of concrete mixes, which contain different incorporation ratios of fly ash (FA) and recycled concrete aggregates (RCA), with and without Superplasticizer (SP). The Life Cycle Assessment methodology was used for environmental assessment, according to ISO 14040 (2006) and EN 15804 (2012). Contrary to most of the previous studies, this one separately obtained the impact for each life cycle stage in detail (e.g. the impact of raw materials production, transportation, and mixing procedure), and explains the reason behind selecting each dataset. Thus, the results of this study can be used for other case studies. The results show that the EI slightly increased when SP was used. Moreover, the incorporation ratio of fine RCA did not change the results for most of the EI categories. Nevertheless, the EI of most of the categories decreased when coarse NA was fully replaced with coarse RCA. Despite the long transportation distance between the coal power plant and the concrete plant considered in the case study, the EI significantly decreased in most categories with increasing amounts of FA.

1. Introduction

Generally, Life Cycle Assessment (LCA) of materials is obtained according to standards ISO 14040-14044 (2006). Frequently, researchers only complete the LCA from "cradle to gate", and more rarely consider the "Use" and "End of life" stages (Fraile-Garcia et al., 2017, 2015), or optimize the products according to their LCA (Fraile-Garcia et al., 2016). LCA studies usually rely on commercial software tools suitable for any product, process or activity (e.g. GaBi, SimaPro or openLCA software) and where various environmental impacts (EI) assessment methods can be used to characterize EI indicators according to EN 15804 (2012). Each method has a limited range of impact categories and CML "from the Centre of Environmental Science - Leiden University" (Guinée et al., 2002) is the one prescribed in EN 15804 (2012) for Environmental Product Declaration (EPD) development. The majority of the studies are mainly focused on the "cradle to gate" stages, and consider most of the following environmental categories: abiotic depletion (ADP), acidification (AP), eutrophication potential (EP), global warming (GWP), photochemical ozone creation potential (POCP) and non-renewable primary energy resources (PE-NRe). CML baseline method is often used to quantify all the categories except PE-NRe, for which the Cumulative Energy Demand method is used.

The construction sector is one of the major contributors to EI, regarding energy consumption, emissions released into the atmosphere and extracted natural resources. Thus, it is essential that sustainability in construction is promoted, to reduce the ecological footprint during the construction, service, maintenance and end-of-life stages of a structure.

Since concrete is the utmost used construction material worldwide, the annual demand of aggregates (major components of concrete) will increase up to an expected value of 52×10^9 tonnes in 2019 (Freedonia, 2016).

Kurda et al. (2018) combined results of different studies and showed that the demand of cement was 4400 million tonnes and it is expected

Abbreviations: ADP, Abiotic Depletion Potential; AP, acidification potential; CDW, construction and demolition waste; EI, environmental impacts; EP, eutrophication potential; EPD, Environmental Product Declaration; FA, fly ash; GWP, global warming potential; LCA, Life Cycle Assessment; NA, natural aggregates; OPC, Ordinary Portland cement; PE-NRe, non-renewable primary energy resources; POCP, photochemical ozone creation potential; RCA, recycled concrete aggregates; SCM, supplementary cementitious materials; SP, Superplasticizer

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to increase to up to 6000 million tonnes. The impact of cement is considered as a lion share of the total EI of concrete (Kurad et al., 2017), and it is responsible for more than 5% of yearly CO_2 emissions worldwide (CSI, 2017).

One alternative to decrease the EI of concrete is by replacing cement and natural aggregates (NA) with supplementary cementitious materials (SCM) such as fly ash (FA), and recycled aggregates such as recycled concrete aggregates (RCA), respectively. To answer these needs, there are several studies on single effect of high volume of RCA (Marinković et al., 2010; Tošić et al., 2015) and FA (NRMCA, 2014; Tait and Cheung, 2016) on the EI of concrete. However, studies regarding the simultaneous effects of high FA and RCA content on concrete EI are very scarce and limited (Marinković et al., 2016). In addition, previous investigations aggregated all the "Life cycle stages" impacts (e.g. the impact of transportation, raw materials and mixing procedure) for specific case scenarios. This makes it very difficult to separate the impacts of each stage and compare their output data with other studies, or to use them in other case studies. So far, to the best of the authors' knowledge, there is no detailed study to show the impacts of raw materials (e.g. cement, FA, fine and coarse RCA, fine and coarse NA, water, SP), transportation and production procedures individually and jointly, and justifying in detail the selection of the datasets to model concrete containing different amounts of FA and RCA. Since the impacts of raw materials and concrete are presented with and without transportation and mixing procedure impacts, the results of this study can be used in other case studies. Broadly speaking, the objective of this work is to compare the EI of the concrete mixes, which contain different incorporation ratios of FA and RCA, with and without SP, and the LCA methodology based on EN 15804 (2012) and ISO 14040 (2006), was considered for environmental assessment.

2. Materials and methods

2.1. Functional unit

The functional unit of the present study is one cubic meter of concrete with different amount of FA (0%, 30% and 60%), fine RCA (0%, 50% and 100%) and coarse RCA (0% and 100%), with or without SP (1%) (Table 1). The rationale behind these mix compositions and their fresh properties were presented in Kurda et al. (2017). In addition, the compressive strength of these concrete mixes, obtained from 15 mm cubic samples according to specification EN 12390-3 (2009), are detailed in Kurad et al. (2017). For this functional unit, complementary assumptions, limits and conditions are shown in §2.2.

2.2. System boundaries

In this study, the production of the raw materials used in concrete mixes was considered from "cradle to gate". Similarly to raw materials, the life cycle stages considered for concrete was also from "cradle to gate" (A1-A3). A1 is the extraction/production of the raw materials required to produce the concrete mixes. A2 is the impact from transportation of the raw materials to the concrete plant. A3 is the concrete production process at the plant.

As shown in the following points, the validity of this study has some limitations:

- Some EI categories were not considered, particularly those that are not significant or commonly used to access EI of construction activities. Therefore, only 6 EI categories were considered (e.g. a detailed analysis of ODP and PE-Re is not included in the paper because of their lower relevancy);
- Due to the lack of information supplied by the companies, some emissions from different stages for production/extraction of raw materials (e.g. diffuse dust emissions in the processes developed at the quarry and at construction and demolition waste (CDW) recycling plant) could not be accounted for. Nonetheless, in this type of study, these emissions are usually insignificant and disregarded;
- The impacts associated with moving waste inside the CDW recycling plant were not considered;
- The Life Cycle of the concrete mixes was considered from "cradle to gate", without considering their application, maintenance and demolition. However, the durability (e.g. chloride ion penetration resistance) and mechanical (compressive strength) characteristics of the mixes were studied by Kurda et al. (2018) and Kurad et al. (2017), respectively, thus representing the performance during the use stage;
- Some data were collected and estimated by company's technicians. Therefore, some input and consumptions were not recorded separately by production sub-stage;
- The data used to obtain the EI of the RCA, coarse NA and concrete production was collected from Portuguese companies;
- The emissions of some activities (e.g. emissions from raw materials transportation) could not be evaluated by using site-specific data. In those cases, reference databases from SimaPro software (Ecoinvent 3 and ELCD) were used.

2.3. Life cycle inventory (LCI)

Table 2 presents the source and location of the data used in the present study. Ordinary Portland cement (OPC) (CEM I) EPD report developed by European Cement Research Academy (ECRA, 2015) was adopted to obtain the cement production impact. The LCI data for coarse NA and coarse and fine RCA, was registered from Braga et al. (2017) and collected on site (Portuguese companies). Additionally, the EPD report prepared by the Danish Technological Institute (DTI), according to specifications EN 15804 (2012) and EN ISO 14025 (2011), was used to obtain the impacts of FA, based on economic allocation. Regarding the fine NA, the data were obtained from Marinković et al. (2010). In addition, SP data were obtained by the European Federation of Concrete Admixtures Associations (EFCA, 2015) in 2015, and published in an EPD. As for modelling, the SimaPro software was used to calculate the impact of transportation and water soil extraction from ELCD-3.1 and Ecoinvent-3 databases, respectively. Furthermore, the impact of the mixing process to produce 1 m^3 of concrete was obtained based on a database of Braga (2015). The NativeLCA method, developed by Silvestre et al. (2015), was considered to elect some of these environmental datasets as generic data.

2.3.1. Raw materials (A1)

A search was carried out to gather information concerning each raw material manufacturing. As a result, several environmental datasets were collected from different countries. The details of the process of selecting each database are presented in Supplementary Information I, II, III, IV, VI and VII for cement, FA, SP, water, coarse NA, and fine NA and RCA, respectively. Furthermore, in order to select an accurate LCA dataset for FA, to be used as generic data in the current study, the NativeLCA method (Silvestre et al., 2015) was applied to each environmental dataset identified (Chen et al., 2010; DTI, 2013; Teixeira et al., 2016). This method was only applied on FA datasets because the knowledge concerning the EI of FA is still very scarce and it is difficult to select the best source. Native LCA is a method used to select the environmental datasets as generic data for a national context, which was developed by Silvestre et al. (2015) and already applied to construction products (Supplementary Information II). As explained from the mentioned Supplementary Information sections, among different datasets, only the database were adapted to the scenario of the present study were selected (Table 3).

2.3.2. Transportation (A2)

The transportation distance is variable from each supplier of raw material to the concrete plant. Thus, the location of most of the main