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Life cycle assessment of geopolymer concrete

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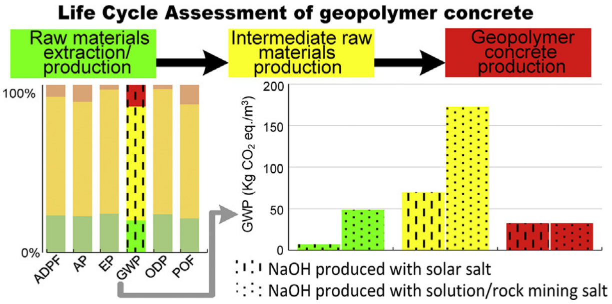
HIGHLIGHTS

- An LCI of geopolymer concrete was scaled-up from laboratory to industrial scale.
- The source of NaOH for geopolymer concrete production influences LCA results.
- Using NaOH made from solar salt is favorable in terms of environmental impacts.
- The energy mix affects geopolymer concrete LCA results.

GRAPHICAL ABSTRACT



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ABSTRACT

The Life Cycle Assessment (LCA) of a Geopolymer Concrete (GC) was elaborated after scaling up the Life Cycle Inventory (LCI) from laboratory scale to industrial scale. The most relevant raw materials and processes contributing to its environmental performance were identified. Besides, the influence in the environmental impacts of both, the electricity generation mix considered (2012 and 2018 energy mix for Ecuador), and the source of alkali activators (produced in Ecuador and imported from Europe), was demonstrated. The production of sodium hydroxide is the most relevant process in all life cycle impact categories. An energy mix with a higher contribution of hydroelectricity (2018 energy mix: 85% hydroelectricity) entails favorable results. The differences between locally produced and imported sodium hydroxide are the energy mix considered (Ecuadorian vs. average European), and the type of sodium chloride used as raw material (obtained through seawater evaporation in Ecuador vs. solution and rock mining in Europe). GC entails an environmental performance advantage compared to a conventional concrete (CC) if the following two conditions are applied: sodium hydroxide is produced using local solar salt, and the electricity mix is the expected energy mix for 2018 in Ecuador. Under this condition, Global Warming Potential (GWP) characterization for GC is 64% lower than CC.

1. Introduction

Concrete is one of the most widely used man-made materials in the world [1]. It is a composite material resulting from the mixture of cement, aggregates, water, and chemical admixtures in different proportions depending on its intended performance. The environmental impacts related to cement production are the main issue regarding the sustainability of its use, as cement represents the highest CO_2 emissions contribution to concrete [2–5].

Approaches aiming at improving the sustainability of the building and construction sector involve the use of cement with reduced environmental burden (e.g., blended cement, cement with clinker replacement with industrial by-products, or less emission intense clinker), and replacement of virgin materials with recycled or reclaimed substitutes [6,7]. However, a technological shift towards

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the use of new low CO_2 binders, and the application of new construction techniques are necessary as well [7].

Life Cycle Assessment (LCA) is an analytical tool for assessing the environmental performance of products during their lifespan. Several LCA studies have been elaborated for estimating environmental impacts of cement [4,8–15], and some for concrete [2,3,5,16–22]. LCA has also been applied to geopolymer cement/-concrete products [23–33].

Geopolymers, are made by activating amorphous aluminosilicate materials, such as Fly Ash (FA), Blast Furnace Slag (BFS), or natural zeolites; with alkali-based chemicals, such as hydroxides and silicates [34]. The use of natural zeolites as a raw material in synthesizing geopolymeric materials is not so common, but recently zeolites have been used more often as the raw materials in geopolymer preparation [35–41]. Sodium hydroxide is the most widely used alkali activator [34]. There is an abundance of natural zeolite sources in Ecuadorian coastal region, which are suitable for geopolymer synthesis [42–45].

Geopolymer technology applied to the construction industry presents an environmental performance improvement potential at the building material level. Previous research has shown environmental performance advantages of Geopolymer Concrete (GC) over Conventional Concrete (CC), when used as alternative cementitious material [18–20,22,24,26,28,29,31,32,46]. LCA has already been used to assess the environmental impacts of GC. Main environmental burdens within GC life cycle has been associated with the use of alkali activators [19,21,22,24,26,29,31–33]. Using alkali activators such as sodium silicate based on rice husk ash has shown great potential in reducing the environmental impacts of GC [21].

The influence on the environmental impacts of the process of obtaining the alkali activators and the type of electricity generation technology considered at every production process has not been addressed in previous research. It has been recognized that methodological LCA choices may influence GC environmental impact results and research conclusions [19,20,22,24,26]. The present study analyses a novel GC (GC), which contains the following raw materials: natural zeolites, sodium hydroxide (NaOH), sodium silicate (Na_2SiO_3), and sand. The aim of the present study is to scale up the Life Cycle Inventory (LCI), developed at laboratory scale, to industrial scale in order to evaluate the environmental performance of a GC developed by Ulloa et al. [41], and to assess its potential benefits to improve the sustainability of the building sector when compared to a conventional concrete (CC) mix. The circumstances under which environmental performance improvement is more likely to occur are addressed using scenario analysis.

2. Materials and methods

The LCI of GC production was developed at laboratory scale [41,47]. However, this study aims to estimate the potential environmental impacts of its production at an industrial scale. Thus, a scale up from laboratory to industrial scale is modeled.

This LCA study follows the ISO 14,040 and ISO 14,044 methodology [48,49]. Calculations were performed using the SimaPro software [50]. A part of the inventory data was obtained from literature and testing. Another part was obtained from databases such as Ecoinvent [51,52] and USLCI [53]. The inventory data sources are detailed in Section 2.4.

The impact assessment method known as CML 2001, developed by the Institute of Environmental Sciences (CML) of Leiden University [54], was used for the impact evaluation. The following impact categories were considered for the analysis: Abiotic Depletion for Fossil Fuels (ADPF), Climate Change (Global Warming Potential - GWP), Acidification Potential (AP), Eutrophication Potential (EP), Photochemical Oxidants Formation (POF) and Ozone Depletion (ODP).

2.1. Goal and scope of the study

The LCI of GC is scaled up from laboratory scale to industrial scale. Subsequently, the environmental performance of GC blocks of standard size (10 × 20 × 40 cm – 50% hollow) is assessed under different circumstances, and a comparison is made with CC blocks using a cradle to gate approach. Fig. 1 shows the system boundaries for GC blocks production for the base case scenario.

System boundaries include raw materials extraction and production, alkali activators production, and GC production. The functional unit is “1 m^3 of hollow blocks made of a GC with a specific compressive strength”. Specific compressive strengths used in this study are presented in Table 1. The most relevant processes to the overall environmental impacts are identified using LCA. Besides, the influence of the source of the alkali activators and the energy mix considered for its local production is addressed with scenario analysis.

2.2. Geopolymer concrete mix design

Ulloa et al. [41] developed and tested several mix designs. Three representative GC mixes (low, medium, and a high proportion of alkali activators) are analyzed. A CC design mix is included for a comparative analysis, in order to determine whether an environmental improvement is attained by the alternative GC technology. Although the exact proportions for each mix of GC were used for calculations, only ranges of components quantities are presented for GC in Table 1. The strength requirements for concrete masonry units in Ecuador are met by all the GC mixes [55].

2.3. Case scenarios

In Ecuador, a shift in the power production matrix towards a greater share of hydroelectricity has been promoted by the Master Electrification Plan during the last decade. In 2012, 62% of the energy mix was comprised of hydroelectricity, and, by 2018, hydroelectricity participation is expected to reach 85% [56]. The present LCA is elaborated upon three case scenarios, which are detailed in Table 2.

Scenarios S1 and S2 represent the ideal situation, in which sodium hydroxide is manufactured locally with local raw materials. In scenario S3, sodium hydroxide is imported from Europe. The detailed LCI differences of these two situations are addressed in Section 2.4.3. Regarding the LCI for the CC mix, 2018 energy mix is considered for its production, thus it is compared to S1 G3 mix.

2.4. Life cycle inventory

2.4.1. Inventory scale-up process

The factors that influence the scale-up process of the system are analyzed, and some processes are modified as explained below. Shibasaki et al. [57] analyze a method for undertaking a scale-up of a process from a pilot scale to industrial scale within an LCA study, in which processes proved to be relevant should be considered for scaling-up purposes. Piccinno et al. [58] developed a framework for scaling-up from laboratory to industrial scale, complementing the aforementioned method by including earlier points of products development. Although Shibasaki et al. [57] focus on a more developed phase than laboratory scale, they propose some considerations pertinent to the present study, such as: paying attention to processes that undergo a change of technology (e.g.