

# Life Cycle Assessment of Precast Geopolymer Products

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Reducing the embodied carbon footprint caused by construction projects is being pushed by many countries. One potential solution is the large-scale use of low-carbon building materials like geopolymers (GPs). GPs result from the chemical activation of aluminosilicate materials using an alkaline liquid, resulting in an inorganic polymeric network; it can also allow repurposing of the waste or by-products of industries. The sustainability of this new type of material is assessed here using Life Cycle Assessment (LCA). This study quantifies the cradle-to-gate environmental impacts of a localized geopolymer process in the Philippines and contrasts the impacts of Ordinary Portland Cement (OPC). The Life Cycle Inventory (LCI) analysis was performed using OpenLCA software and Life Cycle Impact Assessment (LCIA) using IPCC 2013 methodology. LCA results show that GP concrete with an RHA-based activator has a similar Global Warming Potential (GWP) as GP made using a commercial activator. The main contributors to the impacts are the production of the alkali activators, which indicates that the electricity generation mix has a significant influence on the environmental sustainability of GP.

## 1. Introduction

Reducing the construction industry's carbon footprint is a goal of many countries to manage the effects of greenhouse gases (Van Deventer et al., 2012). The large carbon footprint is caused by the high-temperature decomposition of the calcareous materials to make Ordinary Portland Cement (OPC) (Miller, 2018). Lehne and Preston (2018) report that OPC accounts for about 8% of global greenhouse gas (GHG) emissions.

The large-scale use of low-carbon building materials like geopolymers (GPs) became a potential solution to reduce this embodied carbon footprint. Conceptualized by Davidovits and Sawyer (1985), geopolymers are structured matrices of aluminum and silicon-rich materials, such as coal ash and fly ash, which have been chemically activated using an alkaline or acidic medium. The final formed product has a network similar to polymers but is compositionally inorganic and is likened to construction products that use OPC as the base (Fernández-Jiménez and Palomo, 2009).

Based on the study of Kumar and Kumar (2013), the economies of production of geopolymer-based products are like conventional concrete. However, the commercial adoption of geopolymer technology is still low. Acceptance is still short-term and is only driven by a market that is becoming more environmentally aware (Van Deventer et al., 2012). Thus, the potential commercialization entry for GPs is with niche products. Non-structural, non-load-bearing precast products such as pavers, deco panels, and tiles can be initial entry points for geopolymer technology. Precast production, as compared to onsite production, has lower embodied energies because of the reduced inventories, raw material waste, land use, and additional production cycles (Myhr et al., 2019).

In addition, the sustainability of GPs can be proven by environmental accounting using LCA. However, there is still a variation of the literature results versus OPC (Ouellet-Plamondon and Habert, 2015). The differences come from disregarding the GHG contributions of the alkali activation components, sodium hydroxide, sodium silicate, and the localization of production (Miller, 2018).

A recent study by Kamseu et al. (2017) shows a potential GHG drop when using a sodium silicate activator made from locally available Rice Husk. A study by Longos et al. (2020) has proven that a GP mixture from locally sourced coal fly ash and nickel mine waste was seen to have the guideline compressive strength

pavements, pavers, and bricks. However, no study has investigated quantifying the cradle-to-gate environmental impacts of a precast geopolymer process in the Philippines.

This study addresses these research gaps in the GP literature by performing process synthesis and LCA of a representative GP plant and contrasting the impacts of a precast OPC concrete process. Three types of concrete mixes are considered for this study: Ordinary Portland Cement concrete mix (OPC blend); fly ash geopolymer with commercial sodium silicate and NaOH activators (GP-Orig); fly ash geopolymer with rice husk ash-based sodium silicate and NaOH activators (GP-RHA). The results of this study shall determine how feasible and sustainable geopolymers are for local commercial adoption.

## 2. Materials and methods

### 2.1 Case study and site location

The local availability of fly ash is the main factor in implementing geopolymer-based production, as the transportation of the fly ash also contributes a lot to the total emissions (Miller, 2018). The geopolymer facility shall be in Alas-Asin, Mariveles, Bataan, Philippines (14°26'17.61"N, 120°31'34.08"E) and is chosen near the fly ash source. The facility shall also be proximate to the source of aggregates and the National Capital Region as the target primary market.

### 2.2 Process network and synthesis

P-graph Studio (P-graph, 2021) was used to generate the structure of the process network of the local case geopolymer facility and solve the synthesis problem. This program presents a bipartite graph of the materials (raw, intermediate, and products) and the operating units. The layout is based on stoichiometric inflows and outflows of the process and relevant cost information of these materials and operations (Friedler et al., 1992). The problem is solved using the accelerated branch and bound (ABB) algorithm (Friedler et al., 1996) implemented in P-graph Studio. This procedure gives the process configuration with maximized profit. The optimized OPC and geopolymer facilities are presented in Figure 1.

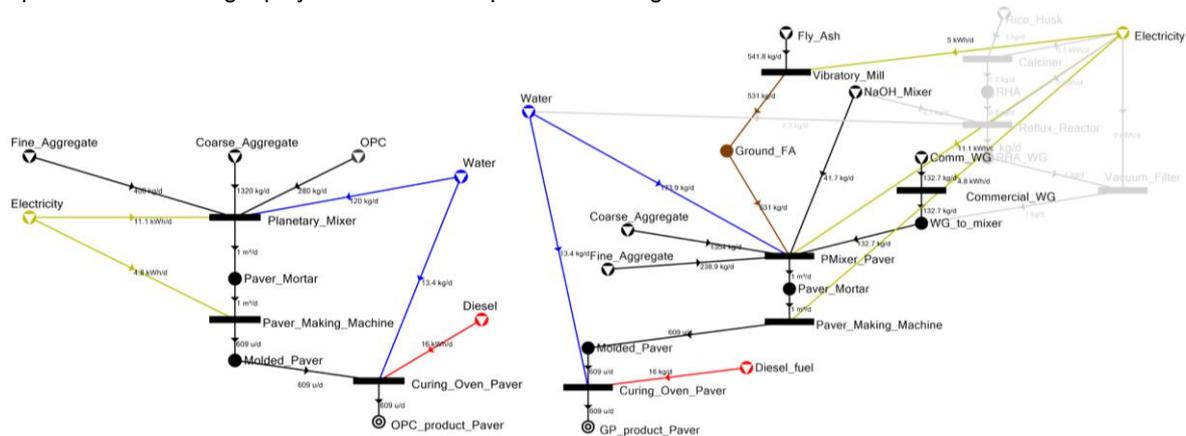


Figure 1: Optimized structure for the process network synthesis of the localized OPC and GPC facility

### 2.3 Goal and Scope of LCA

This study evaluates the environmental impacts of a synthesized and localized geopolymer process in the Philippines and contrasts the impacts of a GP-based scenario to a standard localized OPC process. A cradle-to-gate LCA of a facility is performed following the guidelines of ISO 14040 (ISO, 2006). The environmental aspects are measured based on a 'functional unit' of product or per daily production such that the products being compared are of an equitable function. The functional unit applied in this study is 1.0 m<sup>3</sup> of concrete to produce approximately 609 units of concrete pavers. Three types of concrete mixes are considered for the analysis: Ordinary Portland Cement concrete mix (OPC blend), fly ash geopolymer with commercial sodium silicate and NaOH activators (GP-Orig), and fly ash geopolymer with Rice husk ash-based sodium silicate and NaOH activators (GP-RHA). The system boundaries are shown in Figure 2 for all concrete mixes. The volumetric equivalence of the mixes is kept, achieving the three different types of concrete.

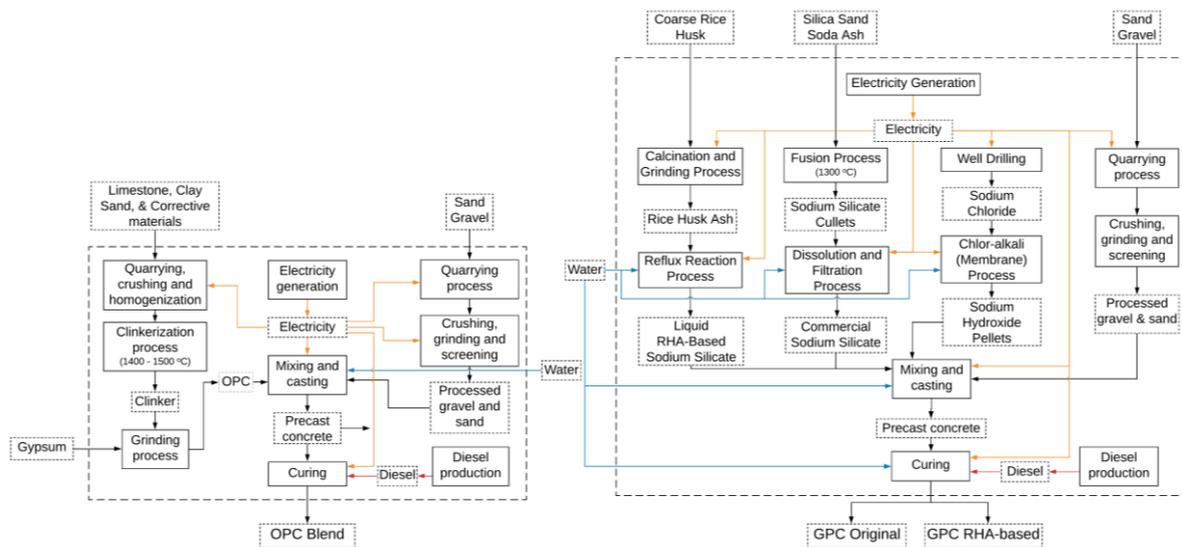


Figure 2: System boundary and process flow model for OPC Blend, GP-Orig, and GP-RHA blends

OpenLCA version 1.10.3 (GreenDelta, 2021), an open-source software for LCA, was used to perform the assessment calculations. Emission assessments include machine and equipment usage, raw materials, utilities, and transportation.

## 2.4 Life cycle inventory analysis

The LCI is based on the procedure specified in the ISO 14040, and the inventory values are acquired through the free sets of the Ecoinvent 3.0 database (Wernet et al., 2016). The total GHG emissions were carried out using OpenLCA, which catalogs all the component weights, volumes, and transportation distances in the synthesized system. The mix design for the GP blends is from first-hand data using locally sourced materials, considering the relevant synthesis preferences in the optimization study by Sumabat et al. (2015) and the resulting data from P-Graph Studio from Section 2.2. The OPC blend is based on the study by Turner and Collins (2013). The inventory data of raw materials and utilities used and the transportation distances from the local suppliers are presented in Table 1.

Table 1: Mix design formulations ( $\text{kg} / \text{m}^3$ ) and cradle-to-gate inventory data

Raw Material / Utilities	OPC Blend	GP-Orig	GP-RHA	Land transport distance, km	Sea transport distance
Cement	328.0	-	-	192	-
Fly ash	-	541.8	541.8	10.0	-
NaOH	-	41.68	135.9	100	1,445
$\text{Na}_2\text{SiO}_3$	-	132.7	-	170	1,498
Fine aggregates (Sand)	781.0	238.9	238.9	50.0	-
Coarse aggregates (Gravel)	1,242	1,354	1,354	50.0	-
Rice Husk	-	-	297.4	121	-
Electricity (kWh)	15.18	20.84	51.38	-	-
Diesel (fuel)	18.67	16.02	16.02	-	-
Water	203.4	187.3	491.3	-	-

## 3. Results and discussion

### 3.1 Impact assessment results

The impact assessment was performed using the baseline model of the Intergovernmental Panel on Climate Change (IPCC) 2013, indicating the global warming potential (GWP) for a 100-year horizon. The environmental impact indicators considered for this study are three-fold climate change categories from a) Biogenic carbon sources, b) Fossil sources, and c) Land use and land transformation. The geographic scope

of this indicator is on a global scale, and the reference process location is in the Philippines. The results of the impact assessments for one functional unit of the concrete mixes are shown in Table 2.

Table 2: GWP100 impact assessment results for the concrete blends

Impact Category	Unit	OPC Blend	GP-Orig	GP-RHA
Climate change, Fossil	kg CO <sub>2</sub> eq.	354.8	241.3	249.8
Climate change, Biogenic	kg CO <sub>2</sub> eq.	6.021	17.23	6.193
Climate change, Land Use, and Transformation	kg CO <sub>2</sub> eq.	0.121	0.169	0.316

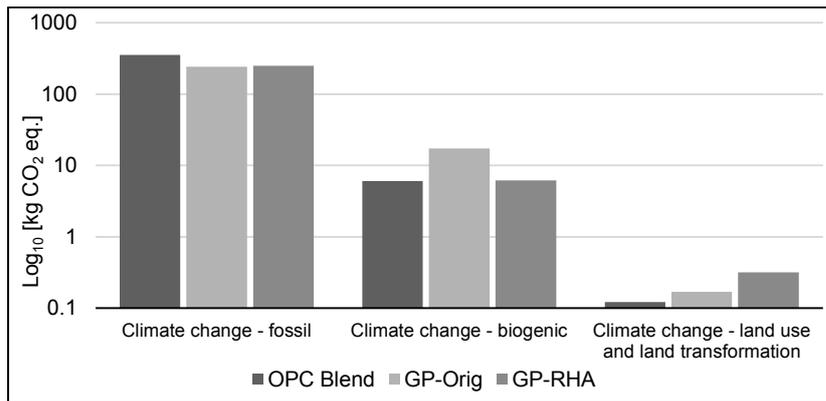


Figure 4: Impact assessment comparison between localized OPC and GP concrete production

Table 2 and Figure 4 show that there are varying environmental impacts of the three mixes. For fossil sources, OPC has the maximum burden caused by fossil fuel burning for the high-temperature clinkerization process (Miller et al., 2016). As a result, carbon savings of 32 % were seen for GP-Orig and 30 % for GP-RHA concrete. For biogenic sources, GPC-Orig carries a considerable environmental burden, mainly caused by the high-temperature fusion process to melt soda ash and silica sand in sodium silicate production (Passuello et al., 2017). Finally, GPC-RHA carries the biggest GWP for land use and Transformation as the land-use changes and management of the Chlor-alkali process have considerable emissions. Considering that fossil and biogenic sources have the most significant weights in terms of equivalent emissions, it can be inferred that the OPC blend has the most undesirable environmental impacts.

3.2 Contribution analysis

The contribution of the different components per cubic meter for each impact category is shown in Figure 5. For GWP100, Portland cement contributes about 78 to 83 % of carbon emissions in all sources, confirming the source of the relatively high carbon footprint of OPC. Diesel, land transport, and coarse aggregates have secondary impacts.

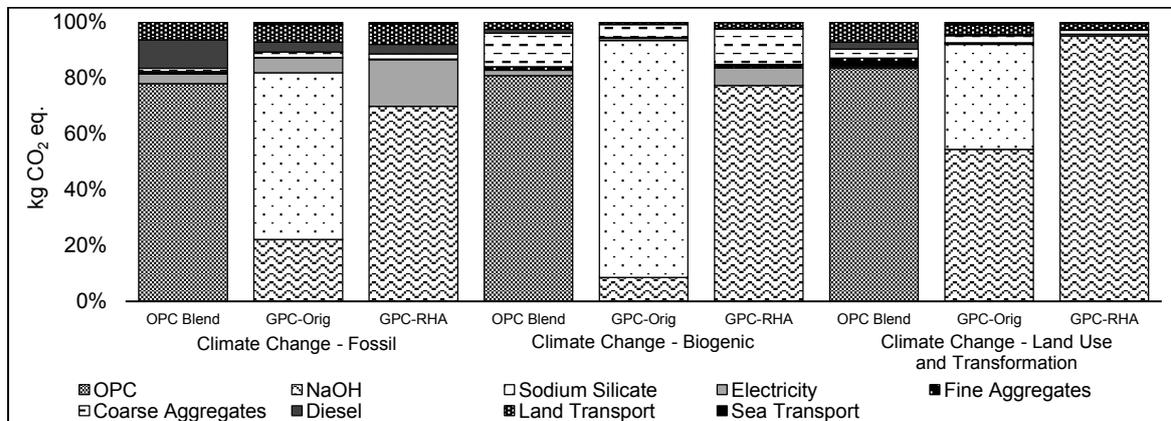


Figure 5: Impact contribution of ingredients and utilities of localized OPC and GPC production

For GP-Orig, the commercial sodium silicate is the dominant contributor for biogenic and fossil sources with about 60 % contribution for fossil sources and 85 % contribution for biogenic sources. For the GP-RHA, the most significant contribution is from NaOH with 70 to 95 %. Consistent with previous studies, the alkali activators are the components that reduce the sustainability of geopolymers (Bajpai et al., 2020). Additional carbon savings can be achieved using more waste materials such as ground granulated blast-furnace slag, silica fume, and other aluminosilicate materials (Huseien et al., 2018). Electricity use, land transport, and coarse aggregates are secondary impacts. The Chlor-alkali process can have additional carbon savings if the process is facilitated through renewable energy sources. On the other hand, transportation GHG can be minimized by optimizing material routes and the modes of transportation (Miller, 2018). Other components have minimal impacts (0.3 to 5 %). Sea transport has the lowest environmental impacts on all categories for the GP mixes.

### 3.3 Sensitivity analysis

A sensitivity analysis based on the effects of transportation and local sources of raw materials is seen in Figure 6. The raw materials in GP-Orig (option 1) are adjusted to the maximum available distance for the local source of fly ash (option 2), sodium hydroxide (option 3), commercial sodium silicate (option 4), and by making use of all the maximum distances from the previous options (option 5). There is only a relatively low change in emissions, and thus, transportation distance does not significantly alter the impacts of the GP mixes. The change of impacts is about -0.39 % to 8.89 %.

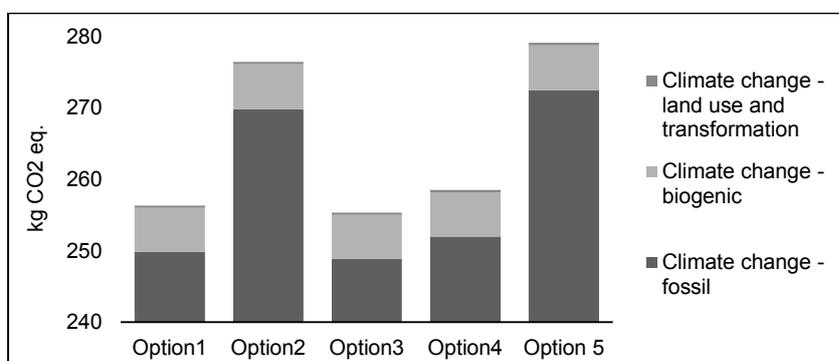


Figure 6: Sensitivity of emissions due to transportation of raw materials

## 4. Conclusion

In this study, P-Graph was used to synthesize the product and profit flows of a localized precast GP facility based on literature and experimental data. LCA was then applied to compare the cradle-to-gate environmental impacts of this facility to an OPC-based facility. Based on the assessment results, the GP concrete with an RHA-based sodium silicate fared better than GP concrete made with a commercial sodium silicate in terms of biogenic climate change impact but fared poorer on land use and transformation. Overall, GP-RHA has a similar Global Warming Potential (GWP) as GP-Orig. In addition, precast products made from geopolymers had a global warming reduction of about 28% compared with OPC concrete products. The alkali activators were seen to contribute to the impact categories for GPC. Using rice husk as a replacement activator can have additional benefits in biogenic CO<sub>2</sub> reduction. Although changes in transportation distances had minimal impacts, potential savings for fossil fuel CO<sub>2</sub> can be improved by minimizing transportation and using more sustainable energy sources and precursors. Focus can also be given to improve the chlor-alkali process by adopting renewable energy sources and by using emergent technologies in lowering the electricity requirements during electrolysis. This study shows that precast geopolymer production has global warming reduction potentials, and commercialization entails some sustainability gains. Further development of this work could be a study on the social impacts and techno-economic evaluation on the commercial scale adoption of this alternative material.

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