

## Carbon emissions associated with two types of foundations: CP-II Portland cement-based composite vs. geopolymer concrete

Kelly Cristiane Gomes<sup>1</sup>, Monica Carvalho<sup>1</sup>, Daniel de Paula Diniz<sup>2</sup>,  
Rafael de Carvalho Costa Abrantes<sup>2</sup>, Michel Alves Branco<sup>2</sup>,  
Paulo Roberto Oliveira de Carvalho Junior<sup>3</sup>

<sup>1</sup> Department of Renewable Energy Engineering, Federal University of Paraiba, CEP: 58051-970, João Pessoa, PB, Brazil.

<sup>2</sup> Graduate Program in Renewable Energy, Federal University of Paraiba, CEP: 58051-970, João Pessoa, PB, Brazil.

<sup>3</sup> Graduate in Mechanical Engineering, Federal University of Paraiba, CEP: 58051-970, João Pessoa, PB, Brazil.

e-mail: gomes@cear.ufpb.br

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### ABSTRACT

The cement industry is the second-largest single industrial emitter in the world and therefore has an important role to play in reducing the intensity of its carbon emissions: participation of the sector is important to contribute to the goal of the Paris Climate Change Agreement to limit global warming. One of the strategies for reducing the carbon footprint of the cement industry is substitution of Portland cement, which is a component of the concrete mix widely used as a construction material worldwide. Geopolymer cement has emerged as an alternative for Portland cement, with several advantages. This study applied the Life Cycle Assessment methodology to quantify the carbon emissions associated with 1m<sup>3</sup> of two types of concrete (concrete PC-II cement-based Portland cement vs. geopolymer concrete). Geopolymer concrete presented almost 43% less carbon emissions, while also presenting high physic-chemical performance. It was verified that geopolymer concrete has the potential to help mitigate climate change, and can be employed as part of the plan to minimize the emissions associated with the construction sector.

**Keywords:** Portland Cement, Geopolymer Cement, Life Cycle Assessment, Carbon Emissions, Construction Sustainability.

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### 1. INTRODUCTION

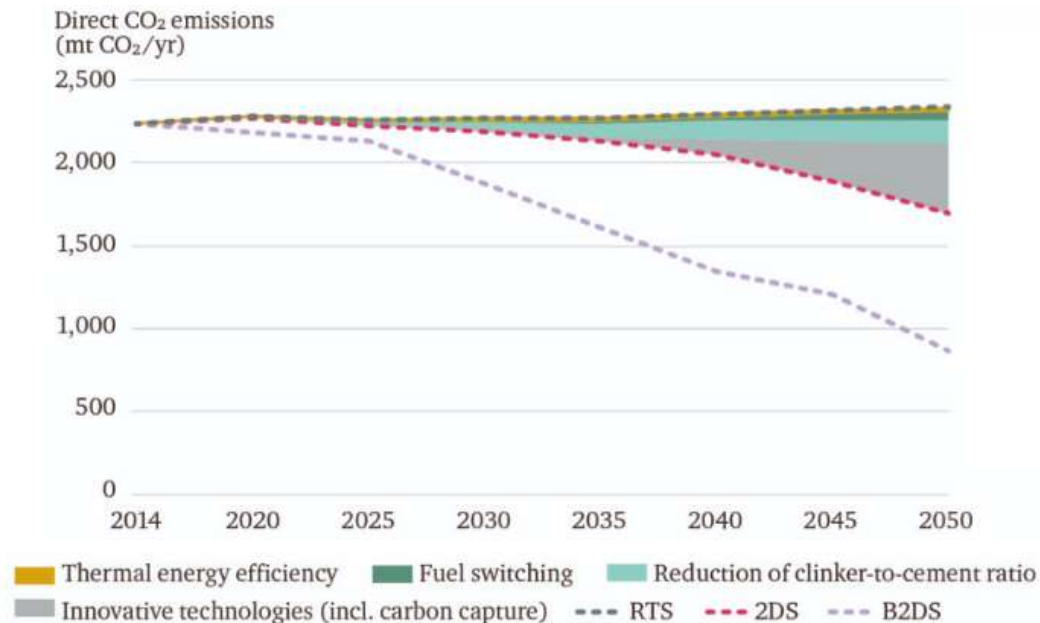
The environmental degradation caused by anthropic activities has become a worldwide problem, and there are three main sources of anthropogenic carbon emissions to the atmosphere [1]: (i) oxidation of fossil fuels, (ii) deforestation and other land-use changes, and (iii) carbonate decomposition. Society has recently developed a sense of environmental awareness and concern about the environmental impacts associated with products or services [2], and has started to demand more environmentally friendly processes. This quest for *greener* products has reached the construction sector.

Cement is the major contributor to emissions due to the decomposition of carbonates [1]. The atmospheric pollutants emitted are especially important because CO<sub>2</sub> emissions are intrinsic to the production process of cement, encompassing chemical transformation of raw materials and combustion of fuels [3]. Limestone (CaCO<sub>3</sub>) is calcinated at high temperatures in a cement kiln to produce lime (CaO), leading to the release of waste CO<sub>2</sub>, as shown in Equation 1:



As the majority of emissions are associated with the clinkering process, they cannot be reduced by changing fuel or increasing energy efficiency. Strategies to cut emissions focus therefore on carbon capture and storage, substitution of clinker, reducing the use of cement in the building industry, and alternative ce-

ments. As Portland cement is the most used construction material in the world, especially in the composition of concrete and mortars (with the function of improving mechanical strength and durability) [4], it is therefore an easy target for environmental impact improvements. Geopolymer-based cements, for example, have been researched since the 1970s [5] and present several advantages. The International Energy Agency and the Cement Sustainability Initiative (CSI) published a low-carbon roadmap, showing how emissions can be reduced (Figure 1) [6].



**Figure 1:** Strategies potentially employed to reduce cement emissions.

In Figure 1, the *business as usual* scenario is referred to as “reference technology scenario” (RTS), and “2°C scenario” (2DS) and “beyond 2°C scenario” (B2DS) refer to 2°C and beyond 2°C scenarios, respectively (regarding the Paris agreement). It becomes clear that the minimization of carbon emissions, and overall environmental impacts in general, should be prioritized, leading to the realization of benefits in a reasonable period of time [6].

As much as possible, the design of buildings should combine the consideration of environmental, social, economic and cultural dimensions [7]. Within economic limits, a coherent selection of materials and components integrated into the design details can result in lower environmental impacts and higher social benefits [8]. The environmental impacts of civil construction depend on a long production chain: raw material extraction, production and transportation of raw materials and components, conception and design, construction, use and maintenance practices, and after its lifetime, demolition/disassembly, in addition to the destination of the waste produced throughout its life cycle [9-11].

One of the major obstacles to the adoption of sustainable practices in construction is the difficulty to understand and quantify environmental and financial costs associated with *greener* buildings. The Life Cycle Assessment (LCA) methodology can be employed to quantify and analyze the environmental impacts associated with a life cycle, or specific stage [7] of a product, process, or activity. LCA can therefore support the communication of the benefits associated with sustainable construction practices, and should be applied from the beginning of the design process, as its early adoption integrates the design of buildings and helps reduce project and construction costs [12,13].

LCA has been applied to quantify the environmental impacts associated with the red ceramics industry [14] and firewood consumption [15], to evaluate four disposal scenarios for urban pruning waste [16], within thermodynamic analyses [17, 18], to analyze of two options for hand drying at an university campus [19], to compare two frying processes for homemade potato chips [20], to quantify the carbon and water footprints of irrigated corn and non-irrigated wheat [21], and to evaluate a refrigeration system [22]. Finally, considerations regarding the use of LCA within the optimization of systems was the focus of [23].

Within the construction sector, LCA can be employed to evaluate design projects, and help establish sustainability levels. LCA assists in the study and development of construction technologies and techniques that result in enhanced sustainability, as the minimization of environmental impacts is crucial to the development of a new concept of sustainable cities [24].

Currently LCA is used and recognized in the field of building sustainability assessment as the most reliable method to assess the environmental impacts originated by different stages of construction (production of products and materials employed, use of machinery, *etc.*) [7]. Although most databases employed within LCA studies are international, adaptation of databases has been increasingly carried out in Brazilian studies with successful results [25-28].

Because concrete is one of the most-used construction materials worldwide, its environmental impacts are significant in terms of the use of natural resources and atmospheric emissions. Recognizing its importance within the life cycle of a construction, the objective of the study presented herein is to compare two alternatives for the foundation of a specific single-family house: i) CP-II Portland cement-based concrete (cement, sand, gravel and water), and ii) geopolymer concrete (metakaolin, sand, gravel and alkaline solution). An LCA was developed to quantify the environmental impacts associated with each option, and identify the most polluting components regarding the foundation of the specific house. This study is part of a wider project, focused on the architectural design of a single-family house considering sustainable concepts.

## 2. MATERIALS AND METHODS

### 2.1 Life Cycle Assessment

The LCA methodology is a consolidated, validated methodology that is standardized by the International Organization for Standardization (ISO), in its 14040 [29] and 14044 [30] standards, which have been discussed by [31]. These have been translated by the Brazilian Association of Technical Standards (in Portuguese, ABNT) [32,33].

LCA comprises four inter-related steps, which include objective and scope definitions, construction of an inventory, evaluation of impacts, and interpretation of results. More details can be consulted in [34, 35]. The objective of the analysis is directly related to the application of the study and target audience. The scope must be defined to guarantee that study extension, depth and level of compatible details are sufficient to reach the objective. Assembling an inventory includes data collection on the relevant material and energy flows associated with the functional unit. An environmental impact assessment method is then chosen to analyze the inventory, followed by interpretation of results and recommendations.

Regarding the scope of the study, a cradle-to-gate LCA was carried out herein, which encompassed from the extraction of raw materials until construction of the house. The functional unit considered, to which all inputs and outputs relate to, was 1 m<sup>3</sup> concrete utilized for the foundation of the house.

Simapro 8.5.2.0 [36] software was utilized to develop the LCA, along with the Ecoinvent database [37] and IPCC 2013 GWP 100y [38] environmental impact assessment method. This method was chosen because of current concerns on climate change, and converts the emissions of greenhouse gases into a common metric (CO<sub>2</sub> emissions) through the utilization of the conversion factors published by the Intergovernmental Panel on Climate Change (IPCC) for a timeframe of 100 years.

### 2.2 Study case

The location considered for the construction of the single-family house is the city of João Pessoa (Northeast Brazil). The lot has an area of 360.00 m<sup>2</sup> with regular rectangular dimensions of 12 m width and 30 m length. The Urbanization Code of the Municipality of João Pessoa was followed herein, which specifies a minimum setback of 5 m at the front, 3 m at the back and 1.5 m on each side [39], orthogonal to the perimeter borders of the lot.

The house has a two-car garage, an integrated living-dining-family room, three ensuites (one designed and equipped for disabled individuals, according to the Brazilian standard NBR 9050 [40]), a gourmet outdoor area with washroom, and a full bathroom between the two ensuites, facing the east façade (Figure 2). The total built area is 198 m<sup>2</sup>.



**Figure 2:** Floor plan layout for the study case.

The functional unit of  $1 \text{ m}^3$  of concrete was adopted as the concretes analyzed present the same resistance to axial compression and the same age of control. According to the soil type at the site, an isolated type structure was defined for the foundation of the building with a resistance of 40 MPa.

The first type of foundation uses CII-E Portland cement-based concrete, with a maximum of 34% blast furnace slag. This cement was selected because it is widely used in the metropolitan region of João Pessoa. The concrete is constituted by natural aggregates (natural sand and limestone gravel) with 40 MPa strength at 28 days. Table 1 shows the material composition of the conventional concrete studied herein ( $1 \text{ m}^3 = 2400 \text{ kg}$ ).

**Table 1:** Material composition of conventional concrete.

Component	Amount ( $\text{kg}/\text{m}^3$ )	Trace
PC II Portland Cement	425 kg	1
Water	194 kg	0.46
Natural Sand	730 kg	1.72
Limestone Gravel	1048 kg	2.47
Plasticizer	5 kg	0.01

The alternative foundation is composed of geopolymer cement, which, according to Buchwald *et al.* [41] presents  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$  alkali-activated aluminosilicate in the appropriate ratio and reactive forms (ashes, active clay, pozzolans and slag), mixed with an activating aqueous alkaline solution that could contain potassium hydroxide, sodium hydroxide and sodium or potassium silicate. In this study, metakaolin and sodium silicate were employed as the alkaline solution. This concrete was selected based on the results obtained with geopolymer matrices in previous projects [42].

In the formulation of the geopolymer concrete, the ratio of the dry materials was identical to the traces of the traditional concrete (Portland cement:sand:gravel ratio identical to metakaolin:sand:gravel ratio). An alkaline solution:metakaolin ratio of 0.84 was applied to guarantee mechanical strength and good workability of the final product. The amount of material required for the production of  $1 \text{ m}^3$  of this type of concrete was calculated from its density at fresh state ( $2300 \text{ kg}/\text{m}^3$ ). Table 2 presents the material composition of geopolymer concrete.

**Table 2:** Material composition of geopolymer concrete

Component	Amount ( $\text{kg}/\text{m}^3$ )	Trace
Metakaolin	353.50 kg	1
Alkaline solution (Sodium Silicate + Sodium Hydroxide + Water)	156.94 kg	0.84
Water	304.56 kg	0.46
Natural Sand	610.00 kg	1.72
Limestone Gravel	875.00 kg	2.47

### 3. RESULTS AND DISCUSSION

When the inventories presented in Tables 1 and 2 were introduced into Simapro using the Ecoinvent database, after selection of the IPCC 2013 GWP 100y method the results shown in Tables 3 and 4 were obtained.

**Table 3:** Carbon emissions associated with 1m<sup>3</sup> conventional concrete

Component	kg CO <sub>2</sub> -eq	%
PC II Portland Cement	392.00	93.600
Water	0.143	0.034
Natural Sand	3.24	0.770
Limestone Gravel	11.60	2.770
Plasticizer	11.80	2.826
<b>Total (kg CO<sub>2</sub>-eq/m<sup>3</sup>)</b>	<b>418.783</b>	<b>100</b>

Table 3 demonstrates that the production of Portland cement is responsible for the majority of the total emissions, and this occurs because of the clinkering process [1]. According to Humphreys and Mahasenan [43], the cement industry was already responsible for approximately 3% of the greenhouse gas emissions worldwide in 2002; in 2016, global process emissions were  $1.45 \pm 0.20$  GtCO<sub>2</sub>, equivalent to about 4 % of emissions from fossil fuels [1]. [44] mention that “ if the cement industry were a country, it would be the third largest emitter in the world.” The results obtained herein are corroborated by an analysis of the emissions of the cement industry, which demonstrated that approximately 50% are caused by the production process, 5% from transportation, 5% from the use of electricity, and 40% are related to the clinkering process [43].

**Table 4:** Carbon emissions associated with 1m<sup>3</sup> geopolymer concrete.

Component	kg CO <sub>2</sub> -eq	%
Metakaolin	87.60	36.530
Alkaline solution (Sodium Silicate + Sodium Hydroxide + Water)	139.50	58.170
Water	0.346	0.144
Natural Sand	2.71	1.130
Limestone Gravel	9.66	4.026
<b>Total (kg CO<sub>2</sub>-eq/m<sup>3</sup>)</b>	<b>239.816</b>	<b>100</b>

The geopolymer cement-based foundation presented lower carbon emissions than Portland-based, conventional concrete. Nevertheless, some processes still consume large amounts of energy. For example, to obtain sodium silicate, the fusion and dissolution steps are the primary contributors to the energy demand [45].

The CO<sub>2</sub> emissions associated with the production of geopolymer concrete are mostly associated with the production of metakaolin and sodium silicate. In both production processes, carbon emissions originate from the combustion of fossil fuels [4].

The results indicate that significant reductions in the emissions in concrete geopolymer could be achieved by implementing changes in the production process of metakaolinite as well as in the manufacture of the alkaline activator. An alternative would be the use of calcined metakaolinite (burning temperature under 700°C, in laboratory settings) as suggested by Gomes et al.[42] or an alternative sodium silicate as developed by Fernandes Filho [46]. Utilization of these types of materials would further enhance the reduction of the carbon footprint associated with the production of geopolymer concretes.

Considering that the required foundation volume for the house is 6.48 m<sup>3</sup>, the total carbon emissions associated with the foundation are 2.714 t CO<sub>2</sub>-eq for conventional concrete and 1.554 t CO<sub>2</sub>-eq for geopolymer concrete. These results show that the utilization of geopolymer concrete could be a potentially employed strategy to help mitigate climate change, decreasing carbon emissions by approximately 43%. Of course, this is only one step within the lengthy process of building a house. If similar low-carbon improvements were implemented throughout all the steps of the construction of the house, the overall result could achieve an impressive value, especially when extrapolated to a neighborhood, or a city. Considering the area

of the house, the carbon emissions associated with the foundation are kgCO<sub>2</sub>-eq and kgCO<sub>2</sub>-eq, for Portland-based and geopolymer concrete, respectively.

LCA-based approaches are starting to become more frequent in scientific literature within the construction sector. Environmental assessment of façade-building systems and thermal insulation materials for different climatic conditions was performed by [47], while [48] verified the environmental implications of the use of agglomerated cork as thermal insulation in buildings. Environmental assessment at an urban level combining LCA-GIS methodologies for the Barcelona metropolitan area was accomplished by [49]. An interesting application of life cycle thinking towards sustainable cities was presented by [50]. When considering concrete and cement, more specifically, traditional and ‘green’ concretes were studied from an environmental viewpoint by [51], who presented a literature review and theoretical calculations. The study by Marceau and VanGeem [52] compared the environmental impacts (via LCA) of a masonry/concrete house with a wood house in five North American cities and concluded that house occupation was the most polluting (from energy-using appliances). The study by Porhinčák and Eštoková [53] produced the environmental profile of a single-family residence using LCA, obtaining overall construction emission values of approximately 35 t CO<sub>2</sub>-eq for an 80 -m<sup>2</sup> house.

However, a systematic and detailed review of the scientific literature returned limited information on the specific environmental impacts of foundation within the construction of a single-family residence. The study by Sedláková *et al.* [54] showed that foundations with the highest percentage of concrete (Portland-based) have a greater impact on the environment. Ondova and Estokova [55] showed that for a masonry house, the foundation could represent approximately 23% of the overall carbon emissions associated with the construction (for a wood house the foundation could represent 98%) and values between 25 and 75 kg CO<sub>2</sub>-eq/m<sup>2</sup> were obtained. Ondova and Estokova [56] studied the environmental impacts of different foundations in different houses, concluding that the foundation accounted for 20% of the total greenhouse gas emissions associated with construction, ranging from 22.59 to 113.67 kg CO<sub>2</sub>-eq/m<sup>2</sup> for the foundation (mean = 74.61 kg CO<sub>2</sub>-eq/m<sup>2</sup>). The foundations used by Ondova and Estokova [55, 56] contained conventional concrete and asphalt or PVC waterproofing, which explains the higher values.

Regarding the specific environmental impacts of Portland cement, Borges *et al.* [4] observed some advantages of replacing clinker with alternative cement additives: (i) a decrease in the use of natural resources when industrial waste is used for the mineral additives; (ii) reduced CO<sub>2</sub> emissions; (iii) less calcinated raw material used in the production of the Portland cement, reducing the emissions from calcination and fossil fuel combustion; and (iv) lower energy demands, if there are reductions in the grinding, the process with the highest energy demand in the production of Portland cement. Finally, the production of cement using alternatives to clinker, such as blast furnace slag, fly ash, artificial pozzolan or lime filler, along with diversification of the specific applications and characteristics of cement, help reduce the carbon emissions by decreasing the production of clinker and consequently the combustion of fuel and emissions from decarbonation.

According to Torgal and Jalali [57], materials with higher durability that use less energy or recyclable materials are options that can provide higher sustainability to construction, such as the use of ligands. The production of sodium silicate has been the object of an LCA carried out by Fawer *et al.* [45], who also provided scientific data for use in subsequent LCAs. The study by Torgal and Jalali [57] discussed the use of geopolymer ligands as an alternative to Portland cement, concluding that the ligands were characterized by better durability and lower CO<sub>2</sub> emissions. The reduction in carbon emissions could be as high as 70% [57]. Additionally, Wein *et al.* [58] found that although Portland cement is less expensive than geopolymer ligands, when the cost/strength is considered, geopolymer ligands become competitive. Heede and Belie [51] developed an LCA for two types of concrete: traditional and “green” (with the incorporation of waste) and concluded that the magnitude of the environmental impact associated with blast furnace slag and fly ash was lower than in Portland cement.

According to Meyer [59], the principles of sustainable development and green buildings have been implemented in civil construction at an accelerated rate in recent years, especially for concrete. The study by Ortiz *et al.* [60] compiled and presented the LCA highlights from 2000 to 2007 in the construction field and concluded that the application of LCA is fundamental to guarantee sustainability and improvement in civil construction. Huntzinger and Eatmon [61] used LCA to evaluate the environmental impact of four cement production processes, concluding that natural pozzolans reduce the most environmental impacts. The study by Gursel *et al.* [12] presented a review of 12 published studies on the life-cycle compositions of different types of concrete, concluding that, as long as there is a demand for “greener” products and systems, there will be LCA studies on concrete and construction.

Herein the material with the lowest carbon emissions was identified: geopolymer concrete presented approximately 17% lower CO<sub>2</sub>-eq emissions than conventional concrete. However, this is only one step in the architectural project of a single-family residence, considering on sustainable concepts. Although the difference in carbon emissions in the foundation step could seem insignificant, decision-making at each step of the project should achieve incremental environmental benefits. Although the research is applied and has a Brazilian focus, in terms of the case study adopted, the work is of global scientific importance. The local dimension is just a way to demonstrate the relevance of the science.

#### 4. CONCLUSIONS

The results obtained herein show that the material with the lowest carbon footprint was the geopolymer concrete with approximately 43% lower CO<sub>2</sub>-eq emissions than conventional concrete, per m<sup>3</sup> manufactured.

The results showed that cement production generates more than 93% of the overall carbon footprint associated with the process of manufacturing traditional concretes, whereas in the production of the geopolymer concrete, metakaolinite and the sodium silicate-based alkaline activator are responsible for approximately 36% and 58%, respectively.

The environmental viability of the geopolymer concrete was evidenced on the basis of CO<sub>2</sub>-eq emissions. Although this is just the first step in the architectural design of a single-family residence, based on sustainable concepts, the results reinforce that the application of LCA is fundamental nowadays to ensure sustainability and improvement in the civil construction sector.

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**ORCID**

Kelly Cristiane Gomes	<a href="http://orcid.org/0000-0002-0255-8740">http://orcid.org/0000-0002-0255-8740</a>
Monica Carvalho	<a href="http://orcid.org/0000-0002-8524-3452">http://orcid.org/0000-0002-8524-3452</a>
Daniel de Paula Diniz	<a href="http://orcid.org/0000-0002-8056-9912">http://orcid.org/0000-0002-8056-9912</a>
Rafael de Carvalho Costa Abrantes	<a href="https://orcid.org/0000-0002-4203-6648">https://orcid.org/0000-0002-4203-6648</a>
Michel Alves Branco	<a href="https://orcid.org/0000-0003-1782-4762">https://orcid.org/0000-0003-1782-4762</a>
Paulo Roberto Oliveira de Carvalho Junior	<a href="https://orcid.org/0000-0003-3958-6523">https://orcid.org/0000-0003-3958-6523</a>