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ORIGINAL ARTICLE

Greenhouse gas emissions associated with traditional and alternative concretes

ABSTRACT: Life Cycle Assessment (LCA) quantifies the environmental impacts associated with products throughout their life cycle. LCA also assists in the interpretation of impact assessment results, enabling improvements in a product or process. This paper applied the LCA methodology to quantify and compare the greenhouse gas emissions associated with different types of concrete: with a traditional binder (Portland cement) and with alkali-activated materials (Metakaolin, Lateritic Soil, and Lateritic Concretion) as precursors. The environmental impact was evaluated using greenhouse gas emissions (kg CO_2-eq/m^3), considering 1 m^3 of each binder and resistance of approximately 30 MPa, obtained by a recommended mix ratio. The main objective is to evaluate whether alkali-activated binders present lower emissions than Portland cement. The results demonstrated that Portland cement is responsible for over 92% of the emissions associated with traditional concrete production. The use of alternative materials in civil construction, such as laterite soil, reduces carbon dioxide emissions by 79% compared to traditional concrete.

Keywords: alkali-activated materials; concrete; life cycle assessment; Portland cement.

Emissões de gases de efeito estufa associadas a concretos tradicionais e alternativos

RESUMO: *A Avaliação de Ciclo de Vida (ACV) é um método que permite quantificar os impactos ambientais de um produto ou processo ao longo do seu ciclo de vida. Ela também auxilia na interpretação dos resultados, com a finalidade de permitir melhorias no produto ou processo. Este artigo aplicou a metodologia em questão para comparar o processo de obtenção do concreto com o ligante tradicional, o cimento Portland, e com materiais alcalinamente ativados tendo como precursores o metacaulim, o solo laterítico e a concreção laterítica. O impacto ambiental foi avaliado por meio das emissões de carbono (kg CO_2/m^3) considerando 1 m^3 de cada aglomerante, em função do* *traço recomendado para se obter concreto com resistência de aproximadamente 30 MPa. O objetivo principal deste trabalho foi avaliar se os aglomerantes alcalinamente ativados apresentam emissões mais baixas do que o cimento Portland. Os resultados demonstraram que o cimento Portland é responsável por mais de 92% das emissões associadas à produção do concreto tradicional. O uso de materiais alternativos na construção civil, como o solo laterítico, reduz as emissões de dióxido de carbono em 79% em comparação ao concreto tradicional.*

Palavras-chave: *avaliação do ciclo de vida; cimento Portland; concreto; material alcalinamente ativado.*

1 Introduction

Energy influences life and all related aspects, is strongly related to the development of countries and civilization, and is very important to ecosystems. Energy demands have been gradually increasing, and concerns about the scarcity of fossil fuels, sustainability, and climate change have motivated the search for renewable energy sources.

Sustainability is correlated to efficiency, time, and durability and is recognized as crucial for reducing pollution levels. Sustainability refers to meeting the needs of humans without compromising the ability to satisfy future generations (NIDHEESH; KUMAR, 2019).

Cement is considered the most consumed material worldwide (GURSEL *et al*., 2014; STAFFORD *et al*., 2016) and is widely applied in concrete and mortar composition (SINGH; MIDDENDORF, 2020). The global production of Portland cement was estimated at approximately 4.1 Gt in 2017 (KAN *et al*., 2019), and its growing demand has increased its production in recent years. China is currently the leading cement producer globally, producing more than 50% of the global volume, corresponding to over 2 million tonnes (NIDHEESH; KUMAR, 2019).

Cement demand estimated for 2050 indicate a need of 0.78-1.36 billion tonnes. The current and future cement demands cause preoccupation due to the energy-intensive character of its products and high requirements of raw materials, in addition to high levels of particulate materials and greenhouse gases. Thus, focusing on different production processes is necessary to reduce emission levels and increase sustainability (NIDHEESH; KUMAR, 2019).

Portland cement concrete contributes to high emissions of greenhouse gases and the depletion of natural resources. Considering all the critical global sustainability challenges, an alternative is the use of alkali-activated cement (MESGARI; AKBARNEZHAD; XIAO, 2020), which is formed by alkaline activation of a precursor, usually supplied as a reactive aluminosilicate powder (SALAS *et al*., 2018).

The technology of alkali-activated materials points to a positive potential for environmental improvement associated with the civil construction industry when compared to conventional materials (STAFFORD *et al*., 2016). Glass residues can also be added to cement, decreasing energy demand by 2% and emissions by 2% (SINGH; MIDDENDORF, 2020). This effect is obtained without changing the cement's compressive strength and still achieves a reduction of 20 kg of CO_2-eq when compared to pure Portland cement without additions.

It is estimated that approximately 5%-8% of all carbon emissions related to human activity result from cement and concrete production (KWASNY *et al*., 2018; NAZARI *et al*., 2019). In this context, it is essential to carry out a life-cycle analysis of cement and know the environmental impacts caused by its production. The Life Cycle Assessment (LCA) is an analytical tool that assesses the lifetime of materials and their associated ecological performance (BRUIJN *et al*., 2002), and can contribute to the realization of environmental benefits by indicating the margins for improvement. The sustainability of a product, process, or system can be quantified by identifying hotspots to where improvement efforts should be directed.

This study evaluates the greenhouse gas emissions associated with two binders: traditional (based on Portland cement) and alkali-activated materials, based on Metakaolinite (MK), Lateritic Soil (LS), and Lateritic Concretion with sodium silicate alkaline activator (LC). The mix ratio is based on a resistance of 30 MPa, which enabled the quantification of emissions on a standard basis. A comparison is also made to verify the potential of mitigating climate change. The study is organized as follows: section 2 is the theoretical background, which presents relevant information for the understanding of the context; section 3 is materials and methods, which presents the experimental setup and LCA data; section 4 is results and discussions, which presents the emissions associated with each type of concrete and discusses these results; and finally, section 5 presents the conclusions and suggestions for future research.

2 Theoretical background

Portland cement concrete is one of the most used materials in civil construction worldwide (GOMES *et al*., 2019). It is composed of aggregates such as gravel, sand, and pulverized material, in addition to a binder (STAFFORD *et al*., 2016). Portland cement provides high mechanical strength and good durability to the final product (BORGES *et al*., 2014).

According to the European Standard EN 197-1 (CEN, 2011), Portland cement is formed by clinker and plaster. Clinker is a hydraulic material formed by approximately two-thirds of calcium silicate (in mass) and one-third of Al, Fe, and other compounds. Clinker is obtained after thermal treatment at 1500 °C – this stage involves high emissions of CO_2, which has raised concerns about the sustainability of the clinker productive process (VAN OSS, 2018).

Alkali-activated materials (AAM) are alkaline-activated aluminosilicates of SiO_2 and Al_2O_3 and are synthesized through an alkaline solution. This process is referred to as alkaline synthesis. Several sources can be used as AAM precursors, and among them, metakaolin is the most common (PROVIS; VAN DEVENTER, 2009). The alkaline synthesis results in forming a disordered phase of an alkaline aluminosilicate gel, in which solid precursor particles and the gel pore network are incorporated. These pores contain alkaline activation solutions, normally constituted of sodium silicate, sodium hydroxides, and potassium hydroxides (OLIVEIRA *et al*., 2019).

Alkali-activated concrete is formed by alkaline liquids, silicon, aluminum, and a geological material or derivative, such as fly ash, blast furnace slag, and rice husk ash. These materials can produce cement binders (MESGARI; AKBARNEZHAD; XIAO, 2020). Alkali-activated concrete relieves the pressure associated with the consumption of natural resources, as it decreases energy use and carbon emissions compared to Portland concrete (BORGES *et al*., 2014). AAM can be a solution to the apparent Portland concrete problem, and there has been some research carried out on the durability and mechanical properties of alkali-activated binders (SALAS *et al*., 2018).

Metakaolin and other industrial by-products used to produce AAM may not be easily accessible due to geographic diversity, leading to economic or environmental unfeasibility. Therefore, it is necessary to analyze the possibility of using materials with lower purity levels, but highly available and naturally occurring, such as clays.

3 Material and methods

The Life Cycle Assessment (LCA) methodology quantifies the potential environmental impacts arising from using different materials and energy forms. LCA has been increasingly used in the development of sustainability-aimed projects and the evaluations of products, processes, or services already in operation (ÇANKAYA; PEKEY, 2019).

LCA addresses the environmental aspects and potential environmental impacts throughout the life cycle of a product, starting from the extraction of raw materials, until its final disposal, including also manufacturing, processing, transportation, use, and maintenance (BRUIJN *et al*., 2002). LCA is standardized by the International Organization for Standardization, ISO 14040 (ISO, 2006a), and 14044 (ISO, 2006b) standards.

There are four basic phases for an LCA (ISO, 2006a, 2006b): 1) definition of scope and objective (when the functional unit is defined, to which all material and energy flows relate to); 2) inventory analysis (which compiles all material and energy flows, as well as emissions and residues, associated with the functional unit); 3) selection of environmental impact assessment method; and 4) obtainment of results and conclusions.

The software employed herein for the development of the LCA was the Dutch software SimaPro (PRÉ SUSTAINABILITY, 2019), which follows the international ISO standards. The Ecoinvent version 3.5 database (ECOINVENT, 2019) was used to model the processes. Within phase 3, the Intergovernmental Panel on Climate Change method (IPCC, 2013) was used to express the environmental impact, measured in terms of greenhouse gas emissions emitted throughout a time horizon of 100 years.

The same transportation distances were considered for all study cases and were not present in the comparative analysis. This consideration is referred to as a cradle-to-gate assessment (HABERT; LACAILLERIE; ROUSSEL, 2011). The functional unit used for the LCAs was the manufacture of 1 m³ of concrete.

High Early Strength Portland Cement was used to manufacture traditional concrete. For the AAM concretes, MK was used as a standard precursor, and two types of residues (LS and LC) were used as alternative binders. Table 1 presents the chemical composition of the materials, obtained by X-Ray Fluorescence. These lab tests were carried out at the Rapid Solidification Laboratory (Federal University of Paraíba, Northeast Brazil).

Table 1 ► Chemical composition of the materials (%). *Source: research data*

Sample	SiO_2	Al_2O_3	Fe_2O_3	Na_2O	K_2O	CaO	MgO	Others
PC	21.16	4.71	1.89	0.39	0.26	68.08	0.48	3.03
MK	64.80	29.74	1.72	0.01	3.10	0.12	0.12	0.39
LS	47.19	15.98	29.66	0.01	0.55	0.68	0.09	5.84
LC	35.58	6.09	56.67	0.19	0.03	0.06	0.00	1.38

Tables 2 and 3 present the traces and inventories for the production of 1 m^3 concrete. The Abrams curve was used as a reference to obtain the correct proportion of Portland cement and water, by correlating the w/c factor and strength. The reference value of the w/c ratio adopted herein was 0.45.

Table 2 ► Trace and material composition of traditional concrete (density 2,280 kg/m^3). *Source: research data*

Mix ratio – Portland cement concrete (kg)				
Cement	**Sand**	**Gravel**	**Plasticizer**	**w/c***
1	2.59	2.71	1.48%	0.45
Material consumption (kg)				
Cement	**Sand**	**Gravel**	**Plasticizer**	**Water**
337.00	873.00	913.00	5.00	152.00

* *w/c* = water/cement factor

Table 3 ► Trace and material composition of the AAM-based concretes (density 2,200 kg/m^3). *Source: research data*

Mix ratio – AAM-based concrete (kg)				
AAM		**Sand**	**Gravel**	**w/b***
MK	1	1.40	2.01	1.08
LS	1	1.40	2.01	1.00
LC	1	1.40	2.00	1.00

Material consumption (kg)				
MK	**Na_2SiO_3**	**Sand**	**Gravel**	**Water**
334.10	82.83	585.00	836.00	362.07
LS	**Na_2SiO_3**	**Sand**	**Gravel**	**Water**
338.00	83.39	591.00	849.00	338.61
LC	**Na_2SiO_3**	**Sand**	**Gravel**	**Water**
354.00	65.98	586.00	840.00	354.03

**w/b* = water/binder factor (binder may be MK, LS, LC, or PC)

All materials employed were based on a minimum compressive strength of 30 MPa at 28 days, which is an average value indicated for structural purposes according to NBR 8953 (ABNT, 2015). In addition, the choice of concrete strength was based on the construction system used in small-scale buildings in the city of João Pessoa, and the concrete was assumed to be prepared on the construction site.

4 Results and discussion

Table 4 presents the results regarding the greenhouse gas emissions of traditional concrete.

Table 4 ► Greenhouse gas emissions per 1 m³ of traditional concrete. *Source: research data*

Portland cement concrete		
Material	**kg CO_2-eq**	**Percentages**
Portland cement	306.00	92.72%
Sand	3.69	1.12%
Gravel	9.53	2.89%
Water	0.11	0.03%
Plasticizer	10.70	3.24%
TOTAL	330.03	100.00%

Table 4 evidences the high contribution of Portland cement production, responsible for just over 92% of the emissions associated with concrete production. The major contributor to these emissions is the thermal energy consumed in the clinkerization process, where the chemical calcination reaction of limestone (the most consumed raw material in cement production) occurs, which releases large amounts of CO_2-eq. Limestone is calcinated inside rotary kilns at very high temperatures. Therefore, a possible way to reduce greenhouse emissions is to employ alternative raw materials and replace the fuels employed in the kilns (HOSSAIN *et al*., 2017).

Table 5 presents the results regarding the greenhouse gas emissions of AAM-based concretes. Lower greenhouse gas emissions were obtained for all AAM-based concrete alternatives, with considerably lower emissions for LS and LC-based concretes (see Table 5). However, there are still margins for improvement within the emissions of AAM-based concrete alternatives (i.e., the potential to further reduce greenhouse gas emissions).

Table 5 ► Greenhouse gas emissions per 1 m³ of AAM concretes. *Source: research data*

AAM MK concrete		
Material	**kg CO_2-eq**	**Percentages**
MK	78.20	49.16%
Sand	2.48	1.56%
Gravel	8.73	5.49%
Water	0.25	0.16%
Na_2SiO_3	69.40	43.63%
TOTAL	159.06	100.00%

Cont. on next page

Table 5 continued

AAM LS concrete		
LS	2.56	3.05%
Sand	2.50	2.98%
Gravel	8.87	10.56%
Water	0.24	0.29%
Na_2SiO_3	69.80	83.12%
TOTAL	83.97	100.00%
AAM LC concrete		
LC	2.69	3.87%
Sand	2.48	3.57%
Gravel	8.77	12.62%
Water	0.25	0.36%
Na_2SiO_3	55.30	79.58%
TOTAL	69.49	100.00%

From the analysis of Table 5, it has been demonstrated that alternative binders enable a steep reduction in the global warming potential when compared to traditional concrete: 330 kg CO_2-eq/m³ (conventional concrete) vs. 159.06 kg CO_2-eq/m³ (AAM-based concrete) which represents savings of approximately 52%. The potential for the mitigation of climate change is further enhanced when using AAM LS concrete (which presents a reduction of 75%) and even more when using AAM LC concrete (approximately 79%).

The reductions observed herein are corroborated by other studies, such as Borges *et al*. (2014), where decreases of 72.4% were verified in CO_2 emissions when geopolymer concrete was compared to Portland cement concrete: 271.9 kg CO_2/m³ with Portland cement concrete vs. 75.1 kg CO_2/m³ with geopolymer concrete.

Robayo-Salazar *et al*. (2018) used different precursors to produce AAM with the following proportions: 70% of natural volcanic pozzolan from Colombia and 30% of granulated blast-furnace slag plus NaOH and Na_2SiO as activator solution. The results also confirmed environmental advantages: its carbon footprint was 44.7% smaller than conventional concrete (AAM = 210.90 kg CO_2-eq/m³ versus conventional = 381.17 kg CO_2-eq/m³). According to McLellan *et al*. (2011), there was a 44%-64% reduction in greenhouse gas emissions when using geopolymer concrete – however, the authors highlight that these emissions are highly site-dependent. Salas *et al*. (2018) found a global warming potential (GWP) 64% lower for geopolymer when compared to conventional concrete. Still, these also confirm the dependency on local conditions: sodium hydroxide was produced with local salts, and the electricity mix employed different, low-carbon generating sources. As reported by Meshram and Kumar (2022), in the case of geopolymer cement, most emissions are due to the use of an alkali solution. However, it is still more sustainable than traditional cement and thus has good potential as an alternate binder. The study by Song *et al*. (2016) identified high emissions associated with producing an alkaline solution with sodium silicate and sodium hydroxide. This demonstrated the potential emission savings that can be realized.

Davidovits (2015) mentions that most published LCAs focus on additional emissions that correspond to long transportation distances for ingredients and chemicals (metakaolin, slag, alkali silicates), which can reach 6000 km for metakaolin or sodium silicate. This could contribute to doubling or even tripling the emission values. Carvalho and Delgado (2017) mentioned that wide variations in emission results can be obtained due to a lack of standardization when using the same methodology to model each inventory. Because the comparison presented herein is on a common basis, with the same database, the comparative assessment is consistent.

Finally, with the progress of industrialization, there is ever-increasing need for cement concrete materials, especially in developing countries. As a result, the amount of Portland cement production increases. It is hoped that the study presented will inspire additional and much-needed research on the environmental issues regarding alkali-activated cement mixtures. The results demonstrated that alkali-activated materials are an environmentally friendly and technically promising alternative to cement.

5 Conclusions

This study used the Life Cycle Assessment methodology to quantify the greenhouse gas emissions of the production of alkaline activated concretes that have Metakaolin, Lateritic Soil, and Lateritic Concretion as precursors, and conventional concrete with Portland cement as a binder.

The results demonstrated that the production of AAM-based concretes presents lower emissions than Portland cement concrete, as the latter emitted 330 kg CO2-eq/m3 versus 159, 84, and 70 kg CO_2-eq/m^3 for alkaline-activated concretes with Metakaolin, Lateritic Soil, and Lateritic Concretion, respectively.

The use of alternative materials decreased greenhouse gas emissions. Alternatives to further decrease emissions include using blast-furnace slag to replace metakaolin in the production of alkaline-activated concretes. Blast-furnace slag can ensure mechanical strength in the early ages of alkaline-activated concretes and reduce the consumption of the activator solution (sodium silicate) because it is less fine than metakaolin and, therefore, requires less solution for the same workability.

There is a growing demand for new building materials with low greenhouse gas emissions associated with their manufacture. Therefore, the studied binders can be widely used as a substitute for Portland cement, but this will only happen when an efficient supply chain for raw materials is available and a distribution network for these products.

Further research can focus on scaling up the Life Cycle Inventory from the laboratory scale to the industrial scale and investigate the effects of AAM on ceramics.

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Conflicts of interest

The authors declare no conflicts of interest.

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