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Environmental Impact of Blended Cement Produced with Ground-Granulated Blast Furnace Slag Substitution in the South African Cement Industry

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Abstract

The production of Portland cement clinker is associated with substantial energy consumption and significant environmental consequences, driven by raw material extraction and Carbon dioxide (CO_2) emissions. However, its production contributes to approximately 5-8% of anthropogenic CO_2 emissions, with each ton of Portland cement yielding about 1.0-1.2 tons of CO_2. This paper used life cycle assessment (LCA) to compare the environmental impact of three types of blended cement (CEM II A-S, CEM II/B-S and CEM III/A) that use ground granulated blast furnace slag (GGBFS) as a substitute for clinker in the South African cement industry using SimaPro 9.2.0.1 software developed by PRé Consultants, Amersfoort, Netherlands at ReCiPe2016 midpoint (H) V1.04. The study found that CEM III/A cement products with a high proportion of GGBFS had the lowest CO_2-equivalent emissions per ton of cement compared to other blended cement with GGBFS substitution. The CO_2-equivalent emissions of CEM III/A cement were about 74% lower than those of CEM I cement, which has the highest emissions. The global warming potential of CEM II A-S and CEM II/B-S cement was 30% and 24% higher than that of CEM III/A cement. CEM III/A cement is the most environmentally friendly option for cement production.

Keywords
Portland cement; ground-granulated blast furnace slag; life cycle assessment; blended cement; characterization.

1. Introduction

The production of Portland cement clinker requires significant energy input (equivalent to 850 kCal per kg clinker) and has a significant environmental impact. This process entails extensive quarrying of raw materials such as limestone and clay, with a production ratio of 1.7 tons to 1 ton of clinker. Portland cement (PC) is the building material produced and used on the largest scale in construction due to its numerous benefits, such as remarkable workability and mechanical strength (Mohamad et al. 2022). Cement production has recently experienced substantial growth, with outputs reaching 4200 metric tons in 2021 and it is estimated that global production will further rise to 4682 metric tons by the year 2050 (Oliveira et al. 2019). As one consequence, cement production is responsible for approximately 5-8% of total anthropogenic Carbon dioxide (CO_2) emissions (Miller et al. 2018;

Sánchez et al. 2021) and each ton of PC resulted in about 1.0–1.2 tons of CO_2 released into the atmosphere (Summerbell, Barlow, and Cullen 2016). These emissions primarily originate from the calcination process of limestone and the burning of fuel in the rotary kiln (Nie et al. 2022; Danner, Norden, and Justnes 2018; Maraghechi et al. 2018; Pillai et al. 2019; Edenhofer et al. 2011). The cement industry actively seeks solutions to address these challenges, aiming to achieve sustainability while adhering to the obligations outlined in the Kyoto Protocol and Paris Agreement (Van Oss and Padovani 2003; Fonta 2017). As a result, researchers are investigating innovative approaches to produce cement types that are less energy-intensive during production, have fewer pollutants and have a lower environmental impact.

The objective of the 2015 Paris Agreement is to ensure that the increase in global warming remains below 1.5 °C (Fonta 2017). This means that by 2050, the world should achieve a state where there is Net Zero greenhouse gas (GHG) emissions. The International Energy Agency (IEA) has emphasized that it is possible to reduce up to 37% in cumulative CO_2 emissions related to cement production by 2050 by reducing the clinker-to-cement ratio from the current level of 0.65 to 0.60 (IEA 2018b). As a result, many countries have prioritized climate change as a crucial political issue (Bouckaert et al. 2021). This has motivated industries to be more conscious of their GHG emissions and actively work towards reducing them (GCCA 2021). However, the most recent Intergovernmental Panel for Climate Change (IPCC) report indicated that without strong policies, GHG emissions could push global warming up to 3.2 °C by 2100 (IPCC 2022). With the increasing demand for construction materials, particularly in developing nations where they experience higher rates of population growth and urbanization, cement production is projected to rise by 12 to 23% by 2050 (IEA 2018a); therefore, there will be an inevitable rise in greenhouse gas (GHG) emissions. The cement industry can make its production more environmentally friendly by using industrial waste and by-products as substitutes for fuel, raw materials, or clinker, the main ingredient in cement, which can significantly save energy, emissions, and costs. The cement industry can reduce its emissions of GHG and other pollutants while conserving natural resources by using alternative materials. It is a win-win solution that can help to protect the environment and reduce costs.

International organizations like the IPCC and the IEA have emphasized the importance of cement industries adopting effective strategies to reduce CO_2 emissions. These strategies include energy efficiency improvement via dry technologies, substituting clinker with supplementary cementitious materials (SCMs), increasing the utilization of alternative fuels and implementing carbon capture, utilization and storage (CCUS) methods (Habert et al. 2020). This aligns with the 12th Sustainable Development Goal (SDG) "responsible consumption and production," as set forth by the United Nations. The SDG emphasizes the need to utilize resources effectively, improve energy efficiency and develop sustainable infrastructures (Fonta 2017). One of the most favored solutions among the available options is using SCMs to replace clinker. Unlike ordinary Portland cement, Blended Portland cement has economic and environmental benefits, as blends reduce fuel costs and CO_2 emissions into the atmosphere during Portland cement production and somewhat solve waste utilization problems (Gomes et al. 2019). This supported by research that shows significant savings in energy costs when using ground-granulated blast furnace slag (GGBFS) as a component in cement (Lee, Kim, and Kim 2021). According to Schneider (2019), substituting clinker with SCMs is the most significant opportunity for reducing CO_2. These materials should possess suitable performance and durability characteristics as clinkers, but they should emit significantly less CO_2 during production and are easily accessible. The potential replacement of 40% of clinker used in cement production has the theoretical capability to reduce annual global CO_2 emissions by as much as 400 million tons.

2. Literature Review

In South Africa, the cement industry is dedicated to reducing emissions and one of the primary strategies employed to attain this objective is the utilization of clinker alternatives. This goal is ambitious, but it is achievable with the continued support of government and industry. The benefits of clinker substitution are clear: it can reduce CO_2 emissions, improve the quality of concrete, and save money. By working together, we can make the cement industry more sustainable. Granulated blast furnace slag (GBFS) is not a product but a large co-product with iron from the iron and steel industry in a blast furnace. As a standard procedure, the furnace is operated at a temperature of 1500 OC. The blast furnace is fed carefully with the controlled limestone, coke and iron ore mixture. Iron and slag are produced molten when these materials are melted together in the blast furnace. GGBFS is derived from the fine grinding of GBFS, formed by rapidly cooling the molten slag extracted from blast furnaces in the iron and steel industry. The country cement industry has significantly reduced emissions per ton of cement since 2008 due to the increased use of clinker substitutes, such as fly ash and GGBFS.

AfriSam is a leading slag cement producer in South Africa, with an annual production capacity of 800,000 tons (slag cement) and 200,000 tons of blended cementitious materials at its Vanderbijlpark operation (AfriSAm 2013). AfriSam Cement has been a sustainability champion in South Africa for the past 30 years (AfriSam 2022). The company has reduced the clinker content in its composite cement by using blast furnace slag, a by-product of the steel industry. AfriSam cement plant has a strategic partnership with ArcelorMittal South Africa, a steel producer that provides blast furnace slag used to produce slag cement. ArcelorMittal steel plant is very close to the AfriSam plant (Jeffery 2023). This has helped AfriSam to produce more sustainable products and reduce its carbon emissions. In 2000, the company launched Project Green Cement, a sustainability initiative to increase the use of extenders in cement production to reduce the clinker ratio (Jeffery 2023). Extenders are materials used to replace some clinker in cement without compromising the strength or performance. Using extenders, such as GGBFS and pulverized fly ash, the company reduced its clinker factor by 20% since 1990 while maintaining the same quality (Jeffery 2023). As shown in Table 1, the percentage of clinker substitution in South Africa rose from 12% in 1990 to 41% in 2009 and by 2030, the industry aims to produce 60% of its cement using clinker substitutes (ACMP 2011). This would represent a significant reduction in emissions and help to mitigate climate change. The clinker substitution rate in South Africa is higher than the global average of 30%.

The cement industry commonly employs material substitution with SCMs as the primary approach to address the greenhouse effect (Aziz et al. 2021). The utilization of SCMs is rapidly increasing as cement industries face pressure to reduce their CO_2 emissions for environmental preservation (Poudyal and Adhikari 2021). This approach is highly preferred because it is cost-effective and helps to reduce CO_2 emissions. This strategy is effective because it addresses the two primary sources of GHG emissions in cement production: limestone calcination and fuel burning. The substitution of PC with SCMs can reach up to 50%, depending on the specific cement-like properties of the SCM (Gupta 2020). The commonly used SCMs for this purpose are granulated blast furnace slag (GBFS) and fly ash (FA) (Scrivener, John, and Gartner 2018). In this context, various SCMs such as FA, GBFS, limestone filler, silica fume and metakaolin, among others, are chosen as partial replacements for Portland cement for their environmentally friendly properties to reduce CO_2 emissions while maintaining concrete's mechanical strength and durability.

Using SCM to reduce cement consumption has been a topic of interest among scholars and policymakers (Wang et al. 2022). According to the IPCC (2022), due to the projected increase in the need for cement, there is a concern that the supply of SCMs may not be sufficient. Alternative SCMs like steel slag, biomass ash, and waste glass have started to emerge to address this issue. Using GGBFS will significantly reduce CO_2 emissions per ton of SCMs and help to reduce waste from industrial production processes (Thomas et al. 2012). The reason for this is that slag cement does not require high temperatures and energy inputs to produce traditional cement. Therefore, using GBFS is vital to mitigate the environmental impact of cement production. However, the scarcity of most SCMs has become challenging due to economic and technological factors (Alzaza, Ohenoja, and Illikainen 2021; Osmanovic, Haračić, and Zelić 2018).

2.1 Objectives

Consequently, the availability of these materials poses difficulties in their utilization. GGBFS is a sustainable and environmentally friendly alternative to cement, with the potential to reduce CO_2 emissions and other environmental impacts. The cement industry should not implement the clinker substitution approach without considering its environmental impact. As a result, it is suitable to utilize a standardized tool called life cycle assessment (LCA). LCA is a comprehensive methodology used to assess the environmental impacts of a product or process throughout its life cycle. It offers the opportunity to evaluate the complete life cycle of cement, from raw material extraction until final disposal, rather than just focusing on the cement production stage. This approach can help identify ways to reduce the environmental impact of cement production. Several studies have used LCA to evaluate the environmental impact of cement production (Çankaya and Pekey 2019; Ali et al. 2014; Ali et al. 2016; Salas et al. 2016; García-Gusano et al. 2015; Tun, Bonnet, and Gheewala 2020; Ige, Olanrewaju, et al. 2022; Ige and Olanrewaju 2023). For example, one study used LCA to investigate the environmental impact of cement production in South Africa and predicted the long-term environmental impact and future dynamics (Ige, Duffy, et al. 2022). Using LCA, the cement industry can move towards more sustainable production methods and reduce its environmental impact.

Therefore, this paper compares the environmental impact of three blended cement types with GGBFS contents as a substitute material in Portland cement production in South Africa. The selected cement types include Portland slag cement CEM II A-S and CEM II/B-S contained 6-20% and 21-35% of GGBFS, while blast furnace slag cement (CEM III/A) contained 36-65% of GGBFS, respectively. SCMs such as GGBFS are employed during cement production to replace clinker, which can reduce costs, energy consumption and CO_2 emissions.

3. Materials and Methods

The International Organization for Standardization (ISO) has developed a series of LCA standards, including ISO 14040 and ISO 14044, which provide guidelines and principles for conducting LCA studies ISO (2006a); (ISO 2006b) and the latest extended version of organizational assessments 14071 ISO/TS (2014a) and 14072 ISO/TS

(2014b). When applying LCA to cement production according to ISO standards, the following four steps are considered: goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), and interpretation.

3.1 The scope and system boundaries

The purpose of this study is to compare the environmental impacts of 1 kg of Portland cement and 1 kg of blended cement with GGBFS from cradle to gate. The functional unit is 1 kg of cement. This means that all of the environmental impacts in the study are expressed in terms of the amount of cement produced. The system boundary involved six stages: Raw materials, cement production, power generation, GGBFS, electricity and transportation. The boundary excluded the use and disposal stages, as shown in Figure 1.

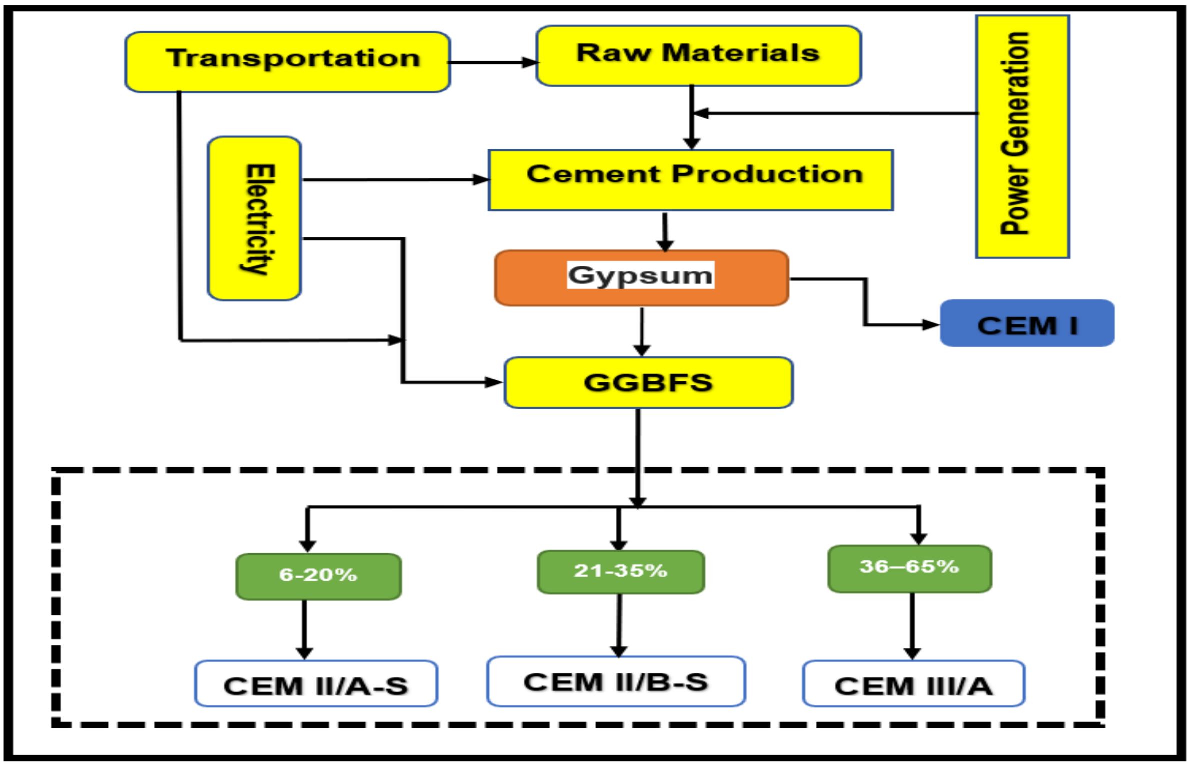

Figure 1. The system boundary of cradle-to-gate LCA of blended cement production

The study compared three types of cement: traditional Portland cement, blended cement, and blast furnace slag cement. According to the South African standard for ordinary cement (SANS 50197-1), CEM I consist of 95-100% clinker and suitable gypsum. The Portland slag cement CEM II A-S and CEM II/B-S contained 6-20% and 21-35% of GGBFS, while blast furnace slag cement (CEM III/A) contained 36-65% of GGBFS, respectively. Electricity is the energy source for producing all the cement products across various plants in South Africa. Grinding clinker or GBFS into GGBFS is a major electricity consumer in all plants, especially in producing blast furnace slag cement, which does not produce clinker.

3.2 Life Cycle Inventory (LCI)

Collect data on the inputs and outputs of cement production, from the extraction of raw materials to the end of life. The inputs include raw materials (e.g., limestone, clay), energy and water. The outputs include emissions (e.g., carbon dioxide, sulfur dioxide), waste and the final product disposal. Following the ISO 14040 and 14044 standards, the Ecoinvent LCI database is a suitable and compliant data source for studies and assessments. The methodology used in this assessment relies on ReCiPe 2016, a comprehensive and dependable approach for evaluating environmental impacts. The inventory data source in this study for environmental impact assessment is the Ecoinvent 3.8 database for South African cement production. The study considered blended cement produced between 2017 and 2021 in five South African plants that produced Portland cement, complying with the SANS 50197-1 standard.

3.3 Life Cycle Impact Assessment (LCIA)

Evaluate the potential environmental impacts associated with the inputs and outputs identified in the LCI. The main objective of the impact assessment task is to convert inventory data, such as data relating to emissions of CO_2, So_x and other GHGs, into particular and more applicable environmental impact categories, such as climate change. The LCIA evaluates different impact categories, such as the impact of global warming (measured in terms of CO_2 equivalents), eutrophication potential, acidification potential and resource depletion. The methods and indicators for LCIA are chosen according to scientific agreement and their significance to the research. In this paper, the environmental impact of blended cement was analyzed using SimaPro 9.2.0.1 software created by PRé Consultants in Amersfoort, Netherlands. The choice of this software is justified due to its reputation, comprehensive functionalities, user-friendly interface, robust database, integration capabilities and compatibility with existing studies. The assessment was done using the ReCiPe2016 midpoint (H) V1.04 approach to assess and calculate the environmental impact of blended cement. The climate impact categories of three blended cement types and traditional cement were assessed and compared, including global warming (GWP), terrestrial acidification (TAP), ozone depletion (ODP), fine particulate matter formation (PMFP), carcinogenic toxicity (HTPc), fossil fuel scarcity (FFP), land use (LOP) and water consumption (WCP).

3.4 Interpretation

The interpretation of the LCA results includes the following methods:

- Sensitivity analysis is used to assess the impact of changes in input data or assumptions on the overall results of the LCA.
- Normalization compares the environmental impacts of different products or systems on a common scale.
- Weighting of impact categories is used to assign different levels of importance to different environmental impacts.

These methods are used to provide a comprehensive perspective on the environmental performance of the cement production system and to identify opportunities for improvement.

4. Results and discussion

The results of the LCA were analyzed and interpreted to identify the following:

- The environmental hotspots, or the areas of the cement production system, have the most significant environmental impact.
- Identify the significant contributors to impacts or the processes or activities causing the most environmental harm.
- Assessing the overall environmental performance of cement production.

Table 1 shows the results of a comparative analysis of the environmental impact of 1 kilogram of each of the four types of cement: CEM I, CEM II A-S, CEM II/B-S and CEM III/A. The analysis was conducted using the midpoint method.

Table 1. Characterization results of different types of blended cement produced in South Africa (Midpoint)

Impact category	Unit	**CEM I**	**CEM II A-S**	**CEM II/B-S**	**CEM III/A**
Global warming	kg CO_2 eq	0,9936844	0,82391245	0,74899686	0,573309
Stratospheric ozone depletion	kg CFC11 eq	1,96E-07	1,71E-07	1,69E-07	1,43E-07
Ionizing radiation	kBq Co-60 eq	0,010244	0,00936904	0,00943823	0,0084
Ozone formation, Human health	kg NOx eq	0,0021014	0,001779467	0,00166771	0,001332
Fine particulate matter formation	kg PM2.5 eq	0,0007934	0,00071738	0,0007094	0,000621
Ozone formation, Terrestrial ecosystems	kg NOx eq	0,0021171	0,00179651	0,0016851	0,001349
Terrestrial acidification	kg SO2 eq	0,0024447	0,002136918	0,00209525	0,001765
Freshwater eutrophication	kg P eq	0,0003163	0,000272567	0,00025852	0,000212
Marine eutrophication	kg N eq	1,95E-05	1,79E-05	1,75E-05	1,55E-05
Terrestrial ecotoxicity	kg 1,4-DCB	1,0373255	1,1772185	1,228786	1,305966
Freshwater ecotoxicity	kg 1,4-DCB	0,0156181	0,020381051	0,02243574	0,025777
Marine ecotoxicity	kg 1,4-DCB	0,0211871	0,027289533	0,02993015	0,034164
Human carcinogenic toxicity	kg 1,4-DCB	0,0244197	0,025576463	0,02648533	0,026531
Human non-carcinogenic toxicity	kg 1,4-DCB	0,4964611	0,56135142	0,59409206	0,62892
Land use	m2a crop eq	0,1421415	0,12339966	0,11671934	0,09707
Mineral resource scarcity	kg Cu eq	0,0021737	0,007869057	0,01007057	0,01452

Fossil resource scarcity	kg oil eq	0,1389681	0,11842089	0,11135895	0,089642
Water consumption	m3	0,001383	0,001540917	0,00162211	0,001701

4.1 The characterization results at midpoint analysis

The results of the selected impact indicator were analyzed by comparatively evaluating the impacts of producing 1 kg of CEM I (100%), CEM II A-S (20% of GGBFS), CEM II/B-S (30% of GGBFS) and CEM III/A (50% of GGBFS). The impact categories are calculated using the ReCiPe2016 midpoint (H) V1.04 method and their characterization values for each impact category are presented in Figure 2.

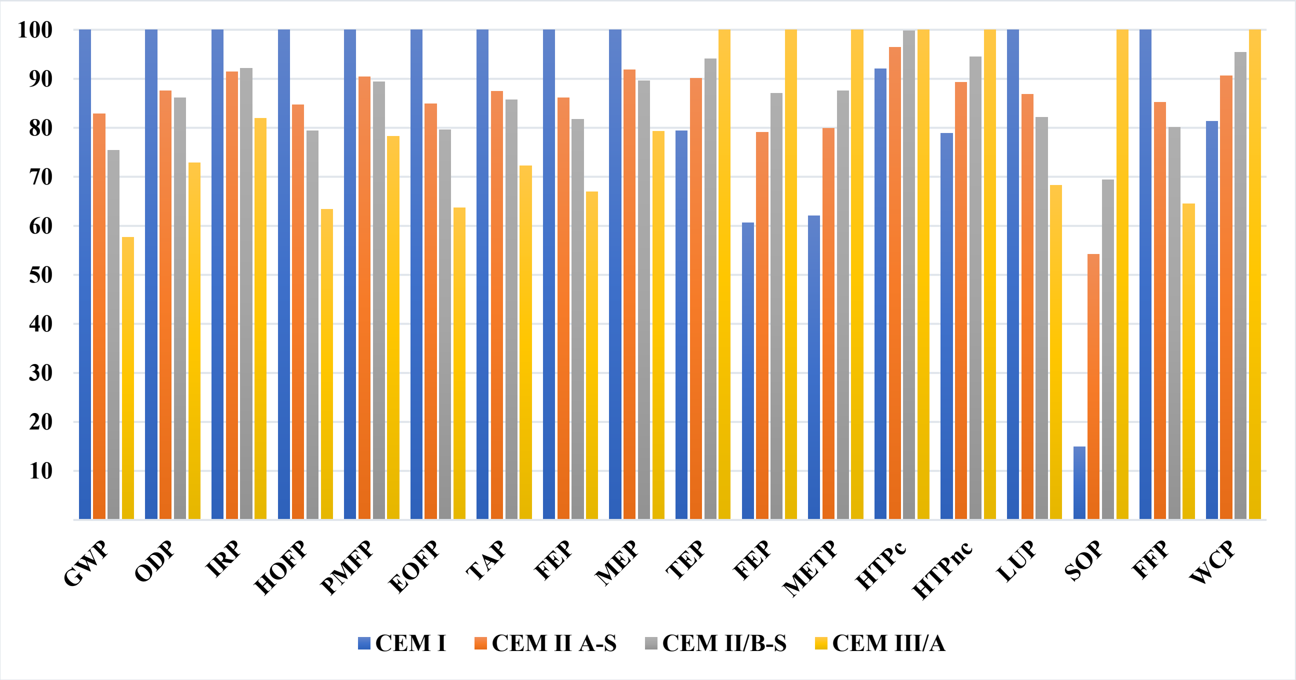

Figure 2. Characterization results at midpoint level for 1 kg of blended cement with GGBFS

The substantial influence of GGBFS on the environmental impacts of blended cement becomes obvious. This contribution decreases gradually from CEM I to CEM III/A as the GGBFS content is reduced and significantly more so in the case of CEM III/A cement due to the substitution ratio. The environmental impact analysis shows that the GWP impact of the CEM I cement with 0.99 kg eq CO_2 is higher than other products due to calcination and coal burning operation in the kiln. It is 74% higher than CEM III/A cement 0.57 kg CO_2 eq, which is the lowest environmental impact. The GWP of CEM II/A-S cement is 0.82 kg CO_2 eq, which is 17% less than CEM I. Also, the GWP of CEM II/B-S cement is 0.75 kg CO_2 eq, which is 24% lower than CEM I.

Acidification refers to the increase in the pH of precipitation. This can be caused by the release of air pollutants such as sulfur dioxide (SO_2), nitrogen oxides (NO_x) and ammonia (NH_3) into the atmosphere. These pollutants are released into the atmosphere from human activities, such as burning fossil fuels and agricultural production. The TAP of GGBFS-based cement is 2.14×10^{-3} kg SO_2 eq for CEM II/A-S, 2.10×10^{-3} kg SO_2 eq for CEM II/B-S and 1.77×10^{-3} kg SO_2 eq for CEM III/A and of CEM I is 2.44×10^{-3} kg SO_2 eq. due to the higher content of GGBFS.

ODP is the reduction of the ozone layer in the stratosphere caused by ozone-depleting substances such as chlorofluorocarbons (CFCs). ODP offers a comparative assessment, using Tri-chloro-fluoro-methane (R11) as a reference, for the emission of gas per unit mass in relation to CFC-11 over a specific time. The ODP of CEM III/A cement is 1.43×10^{-7} kg CFC11 eq/kg lower than CEM II/A-S (1.71×10^{-7} kg CFC11 eq/kg) and CEM II/B-S (1.69×10^{-7} kg CFC11 eq/kg), respectively. However, it is lower than CEM I (1.96×10^{-7} kg CFC11 eq/kg). Fossil fuel scarcity is an environmental impact indicator that measures the extraction of non-living natural resources, such as minerals and fossil fuels. FFP is a substance's potential to contribute to fossil fuel depletion. The extraction of these resources is expressed in kg oil eq., which measures their scarcity**.** FFP of CEM I is primarily caused by the consumption of naturally occurring resources such as coal, clay, and limestone. The FFP of CEM III/A cement is 35.5% lower than CEM I, as shown in Figure 2. Similarly, the FFP impact category of

CEM III/A cement is 8.96×10^{-2} kg oil eq., mainly due to the GGBFS. Therefore, Blended cement will help to save mineral resources.

Health toxicity potential (HTP) is an indicator that measures the potential health effects of exposure to air pollutants, both carcinogens and noncarcinogens. HTPcarcinogenic is the ability of a substance to cause cancer and HTPnon-carcinogenic is the ability of a substance to cause other health effects, such as respiratory problems or heart disease. It is calculated by first converting the concentration of each pollutant and expressing the carcinogenic potency of air pollutants in 1,4-Di-chlorobenzene (DCB) equivalence. The release of toxic organic compounds, heavy metals, and NOx is the main cause of the problem. The release of these pollutants into the environment can have a serious impact on human health and the environment. HTPn of CEM II/A-S 0.56 kg 1,4-DCB, CEM II/B-S (0.59 kg 1,4-DCB) and CEM III/A (0.63kg 1,4-DCB) are higher than CEM I (0.5 kg 1,4-DCB) in South Africa. However, the results show that HTP is high due to GGBFS. Nevertheless, it is important to note that slag is not listed as a carcinogen by IARC, NTP, or OSHA.

4.2 Contribution analysis

The cement production stage represents all pollutants directly emitted by the kiln during clinker and cement production. Figure 3 shows a clear trend indicating that the GWP decreases as the content of the GGBFS increases. This phenomenon occurs because substituting a certain amount of cement clinker leads to reduced decarbonization of limestone and decreased kiln activity, resulting in less GHG emissions released into the atmosphere. This finding is consistent with the results of a study by Boesch and Hellweg (Boesch and Hellweg 2010). This study also identified the main processes that caused each environmental impact category and the findings revealed that raw material, electricity usage and cement production were the main contributors. The impact of other processes, such as GGBFS production, power generation, and transportation, only slightly affected each environmental impact category.

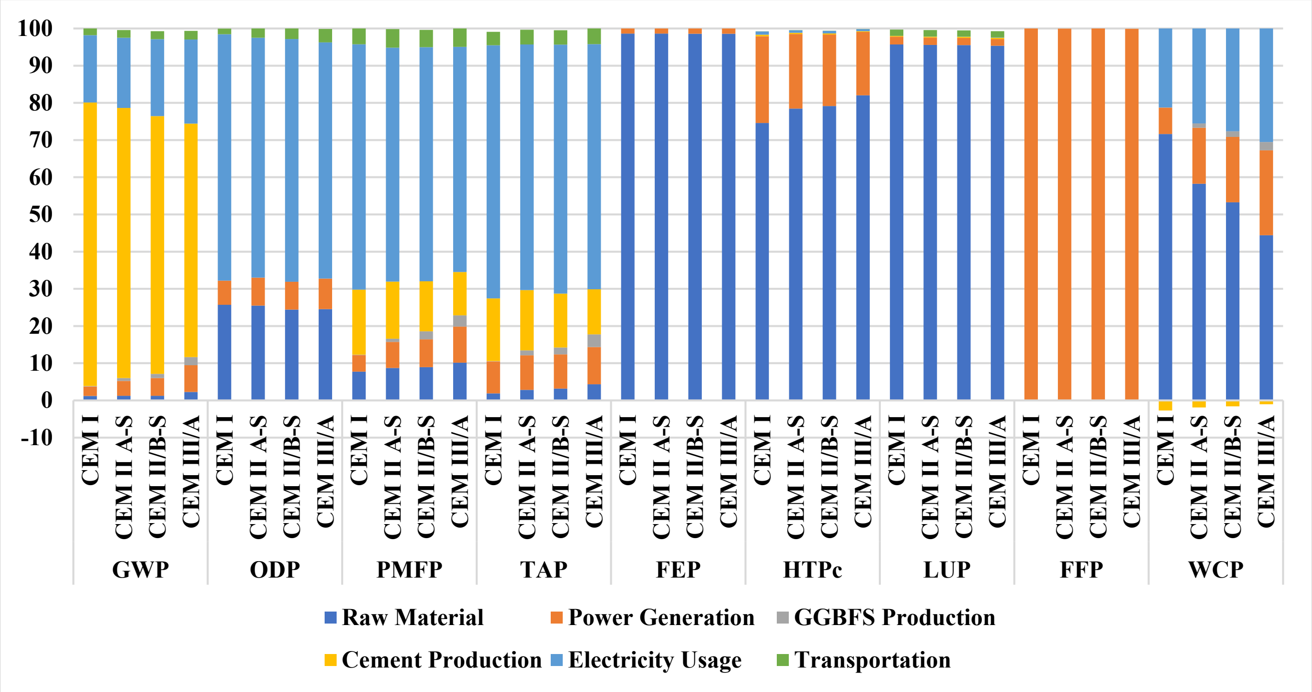

Figure 3. Contribution analysis results at the midpoint method

The result showed that the GWP is the most important environmental impact category for cement production and electricity usage, accounting for 76% (CEM I), 73% (CEM II A-S), 69% (CEM II/B-S) and 63% (CEM III/A) of the total environmental impact for cement production are direct CO_2 and CH_4 emissions come from the direct combustion of coal and the decomposition of limestone, followed by electricity usage which contributed 18% (CEM I), 19% (CEM II A-S), 21% (CEM II/B-S) and 23% (CEM III/A) to the total environmental impact. The electricity usage process is the major contributor to PMFP, followed by the cement production, power generation, and raw materials processes. PMFP contributed 66% (CEM I), 63% (CEM II A-S), 63% (CEM II/B-S) and 61% (CEM III/A) to the total environmental impact for the electricity usage process, 18% (CEM I), 15% (CEM II A-S), 13% (CEM II/B-S) and 12% (CEM III/A) to the total environmental impact of cement production process and

8% (CEM I), 9% (CEM II A-S), 9% (CEM II/B-S) and 10% (CEM III/A) to the total environmental impact of raw material process, respectively. While TAP contributed 65% (CEM I), 66% (CEM II A-S), 67% (CEM II/B-S) and 68% (CEM III/A) to the total environmental impact on the electricity usage process mainly due to the consumption of GGBFS, followed by 22% (CEM I), 16% (CEM II A-S), 14% (CEM II/B-S) and 12% (CEM III/A) to the total environmental impact of cement production and 8% (CEM I), 9% (CEM II A-S), 9% (CEM II/B-S) and 10% (CEM III/A), respectively. According to Li et al. (2016), TAP is the most important climate impact caused by slag-based cement production.

Furthermore, the raw materials process mainly contributed to FEP and LUP, accounting for 99 % of CEM I, CEM II A-S, CEM II/B-S and CEM III/A for FEP and 96% for (CEM I), (CEM II A-S), (CEM II/B-S) and 95% (CEM III/A). The result showed that raw materials from industrial (occupation) was the most significant impact on LUP. ODP was the main contributor to the electricity usage process, accounting for 66 % (CEM I), 65% (CEM II A-S), 65% (CEM II/B-S) and 64% (CEM III/A), followed by raw materials process, accounting for 26% (CEM I), 25% (CEM II A-S), 24% (CEM II/B-S) and 25% (CEM III/A). However, GGBFS substitution for clinker in cement can reduce the impact on land use. The raw materials process is the most significant contributor to HTPc, accounting for 75% (CEM I), 78% (CEM II A-S), 79% (CEM II/B-S) and 82% (CEM III/A) of the negative impact. The FEP was the main contributor to the power generation, accounting for 99 % of CEM I, CEM II A-S, CEM II/B-S and CEM III/A, while WCP contributed 72% (CEM I), 58% (CEM II A-S), 53% (CEM II/B-S) and 44% (CEM III/A) to the total environmental impact of the raw materials process, 24% (CEM I), 27% (CEM II A-S), 29% (CEM II/B-S) and 31% (CEM III/A) to the total environmental impact of the electricity usage process and 7% (CEM I), 15% (CEM II A-S), 18% (CEM II/B-S) and 23% (CEM III/A) to the total environmental impact of the power generation process, respectively. The contributions of transportation and GGBFS Production processes were minor, accounting for less than 5% of the total environmental impact **for** CEM I, CEM II A-S, CEM II/B-S and CEM III/A cement.

5. Conclusion

This study investigated the environmental impact of using GGBFS as a substitute material in Portland cement production. LCA methodology was used to evaluate the environmental impacts of traditional Portland (CEM I), Portland slag cement (CEM II A-S and CEM II/B-S) and blast furnace slag (CEM III/A) cement in typical cement plants in South Africa. However, it is important to note that the production of CEM I releases a significant amount of CO_2 due to the burning of limestone during calcination and the burning of fuel. Environmentally friendly measures such as improved energy efficiency, alternative fuels and other related approaches for production industries can help reduce the environmental impact of cement production. Still, they do not address the issue of calcined CO_2 emissions. Comparing the CEM I, which is 0.99 kg eq CO_2, in this study, GWP showed that the blended cement was 0,82 kg eq CO_2 for CEM II A-S, 0,75 kg eq CO_2 for CEM II/B-S and 0,57 kg eq CO_2 for CEM III/A. The results show that CEM III/A (36- 65% of GGBFS) with 0,57 kg eq CO_2 has the lowest GWP compared with other blended cement used in this study. This has successfully reduced emissions per kg of cement by nearly 50%. The GWP of CEM II A-S cement is 44% higher than CEM III/A cement and CEM II/B-S cement has 31.6% higher GWP than CEM III/A cement.

Also, the results showed that GGBFS cement had a lower environmental impact than traditional Portland cement in terms of global warming, acidification, and eutrophication potential. The GGBFS-based cement requires less energy, i.e., its production does not require burning fossil fuels and releases less CO_2 into the atmosphere, a major source of GHG emissions because GGBFS is a by-product of the steel industry. Additionally, GGBFS can help improve cement's properties, such as its strength and durability, reducing the amount of cement needed in construction. In conclusion, cement production is a very energy-intensive process and the most effective way to improve the environmental impact of cement production was to reduce the amount of limestone by using SCMs such as GGBFS and energy consumption used in the process by switching to renewable energy sources or using more efficient production methods.

The economic analysis of using GGBFS as an alternative for clinker in cement production involves evaluating this alternative material's potential cost savings and benefits. By incorporating GGBFS, the cement industry can reduce production costs by utilizing a by-product of the iron manufacturing industry instead of relying solely on clinker. This can lead to lower raw material costs and potentially decrease the overall cost of cement production. Additionally, using GGBFS as a substitute for clinker can contribute to environmental sustainability by reducing CO_2 emissions and minimizing the reliance on natural resources. GGBFS, as a clinker alternative, has gained attention as a sustainable alternative to traditional cementitious materials in concrete production. However, challenges related to the availability and quality of GGBFS still need to be addressed. Some areas for future research on overcoming these challenges include:

1. Investigating methods to improve the availability and accessibility of Ground-Granulated Blast Furnace Slag, such as optimizing steel production processes or developing more efficient methods for slag collection and processing.
2. Exploring innovative techniques for enhancing the properties of Ground-Granulated Blast Furnace Slag, such as modifying its composition or incorporating it with other supplementary cementitious materials to improve its performance further.
3. Investigating the potential economic and environmental benefits of using Ground-Granulated Blast Furnace Slag in other construction applications, such as road construction or precast concrete elements.
4. Examining the feasibility of using alternative sources of Ground-Granulated Blast Furnace Slag, such as by-product slag from industries other than steel production, to expand its availability and reduce reliance on the steel industry.

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