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ORIGINAL PAPER

Comparative life cycle assessment (LCA) of geopolymer cement manufacturing with Portland cement in Indian context

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Abstract
India is the second-leading cement producer in the world after China. Cement causes huge carbon footprint during the production and transportation of materials. Various efforts are being made to reduce the environmental impacts. Among the notable developments are the use of by-product or secondary material to develop new binders such as geopolymer cement. This paper contains a cradle-to-gate life cycle impact assessment of two types of geopolymer cement produced from blending fly ash and slag, and blending fly ash and cement in an Indian scenario. As there is no standard data available for geopolymer cement production, the primary data used were collected by producing geopolymer cement at pilot scale (5 t/d). In an Indian context, the geopolymer cement significantly reduces the global warming potential (267 kg CO_2-Equiv.), abiotic depletion potential fossil (3092 MJ), abiotic depletion potential element (1.18 e^{-3} kg Sb-Equiv.), human toxicity potential (249 kg DCB-Equiv.), and terrestrial ecotoxicity potential (0.438 kg DCB-Equiv.) with blending fly ash and slag. The geopolymer cement produced from fly ash and slag reduces the global warming potential by 70%, abiotic depletion potential fossil by 49%, abiotic depletion potential element by 34%, and terrestrial ecotoxicity potential by 77% when compared with ordinary Portland cement of the building and construction industries. In case of geopolymer cement, the maximum impact on the environment is due to the use of an alkali solution. Based on the analysis, geopolymer cement appears more sustainable than traditional cement and thus has good potential as an alternate binder.

Keywords Geopolymer cement · Life cycle assessment · Portland cement · Industrial waste

Abbreviations

ADP	Abiotic depletion potential
AP	Acidification potential
Al	Aluminum
BF	Blast furnace
CFC	Chloro-fluoro-carbons
CPCB	Central Pollution Control Board
DCB	Di-Chloro Benzene
EP	Ecotoxicity potential
GGBFS	Ground granulated blast-furnace slag
GHG	Greenhouse gas
GWP	Global warming potential
HFC	Hydro-chloro-fluoro-carbon
h	Hours
HTP	Human toxicity potential
IARC	International Agency for Research on Cancer
IS	Bureau of Indian Standard
ISO	International Organization for Standardization
LCA	Life cycle assessment
Mt	Million tons
NTP	National Toxicology Program
OSHA	Occupational Safety and Health Administration
OPC	Ordinary Portland cement
ODP	Ozone depletion potential
PPC	Portland Pozzolana cement
PSC	Portland slag cement
Si	Silicon
Sb	Antimony
t/d	Tons per day
y	Year

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Introduction

The building and construction is considered as one of the major climate impact sectors (Penadés-Plà et al. 2017) and the key contributor to this sector is Portland cement. It creates an enormous carbon footprint during the production and transportation of materials (Zhao et al. 2013). It is estimated that 1.0 t of Portland cement production releases approximately 0.85–1.0 t of CO_2 (Davidovits 2015). The global cement production released 1.45 ± 0.20 Gt of CO_2 in 2016 (Andrew 2018).

The environmental impacts of manufacturing 1.0 t Portland cement is different in different geographic areas such as the USA, Europe, Asia, Africa, and Australia. Authors have compiled the environmental impact data of Portland cement production in different countries and is given in Table 1.

From the table, it is seen that few countries like Japan, Europe, etc., have a smaller environmental impact. This can be attributed to better energy efficiency, waste co-processing, and efficient electricity production (Boesch and Hellweg 2010; Moya et al. 2011; Li et al. 2014; Josa et al. 2007). However, the Brazilian cement industry has shown significantly higher environmental impact (Stafford et al. 2016a) mainly due to transportation including clinkering and fossil fuels production.

Various efforts are being made to reduce the environmental impacts for the construction sector (Akadiri et al. 2012). To make cement production more sustainable, the practice of using solid recovered fuel along with an energy-efficient kiln process was proposed (Mikulčić et al. 2016). The most notable developments are the use of by-products or secondary materials such as fly ash and ground granulated blast-furnace slag (GGBFS) (Jiang et al. 2014), the use of mechanically activated slag that can replace nearly 85% of clinker (Kumar et al. 2008), and the partial replacement of clinker with fly ash or GGBFS that reduces 13–22% GHG emission (Flower and Sanjayan 2007). Another line of development is the use of alternative fuels in the rotary kiln, which offers favorable effects in terms of cleaner cement production (Strazza et al. 2011). The third research direction is to develop new binders with low CO_2 emission, such as alkali-activated slag concrete (Douglas et al. 1992) and geopolymer cement. Geopolymer cement, or inorganic polymer cement, is the new class of binder produced by the reaction between oxides of Si and Al under highly alkaline conditions (Živica et. al. 2014). The product formed as a result of geopolymerization has a rigid three-dimensional network and exhibits properties similar to Portland cement. It has been reported in the literature that CO_2 emission in geopolymer cement production is significantly less than in Portland cement (Davidovits 2013). Geopolymer cement is considered as a potential binder for the future, because of good mechanical properties, durability, and low environmental impact.

Few studies have been carried out to analyze the life cycle of geopolymer cement/concrete and both positive and negative impacts have been reported. Various researchers reported the advantage of geopolymer cement over Portland cement in terms of CO_2 emission (McLellan et al. 2011; Robayo-Salazar et al. 2018; Bajpai R et al. 2020). However, Habert et al. (2010, 2011) and Turner and Collins (2013) have reported an increased CO_2 release for geopolymer cement. Davidovits (2015) countered the high CO_2 impact of geopolymer cement mentioned above.

The increasing global interest in this binder is visible from the patent data given in Figs. 1 and 2.

As per Fig. 1, globally 1683 geopolymer patents have been filed till March 2021, out of which more than 45% are from Asian countries, which clearly shows the growing interest in geopolymer cement.

Table 1 Countrywise environmental impact of Portland cement/t

Sr. no	Country*	GWP (kg CO_2-Equiv.)	ODP (kg R11-Equiv.)	AP (kg SO_2-Equiv.)	ADP (elements) (kg Sb-Equiv.)	HTP (kg DCB-Equiv.)	Terrestrial EP (kg DCB-Equiv.)
1	China (Li et al. 2015)	798.7	–	1.467	–	1.994	–
2	Brazil (Stafford et al. 2016a)	2160	$2.54e^{-4}$	7.86	–	$2.69e^{2}$	$1.86e^{-1}$
3	Europe (Garcı´a-Gusano et al. 2015)	799	–	3.40 (molc H^+ eq.)	–	$1.25e^{-6}$ (CTUh)	–
4	South Korea (Kim and Tae 2016)	948	–	1.28	–	–	–
5	Japan (Li et al. 2015)	779.16	–	1.14	–	1.697	–
6	Southern Europe (Stafford et al. 2016b)	632	–	1.97	1.81	–	–

*The data available on a mass basis (per ton) are listed. However, the studies presented on a volumetric basis (per m^3) either for cement or concrete production are excluded

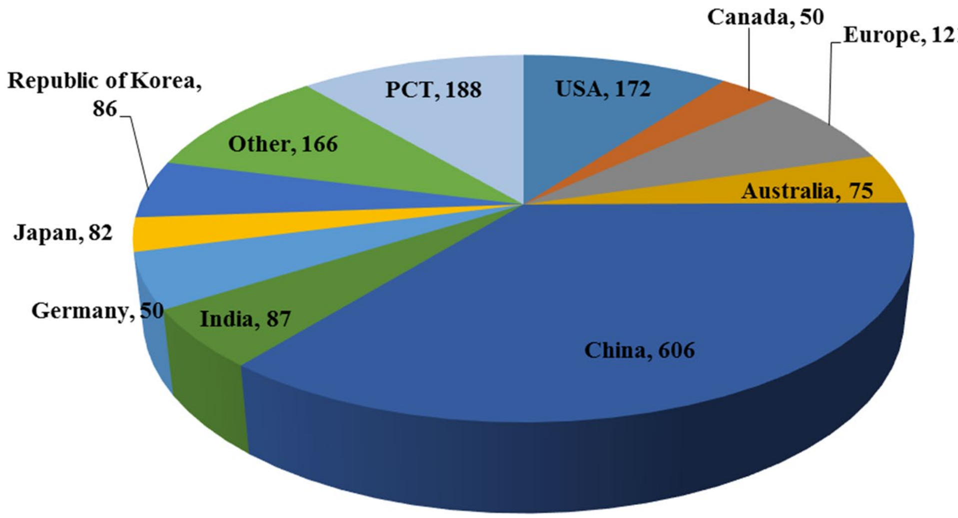


Fig. 1 Global patent filled status on geopolymer (March 2021) (Countrywise) compiled from the WIPO data (World Intellectual Property Organization (WIPO 2021)

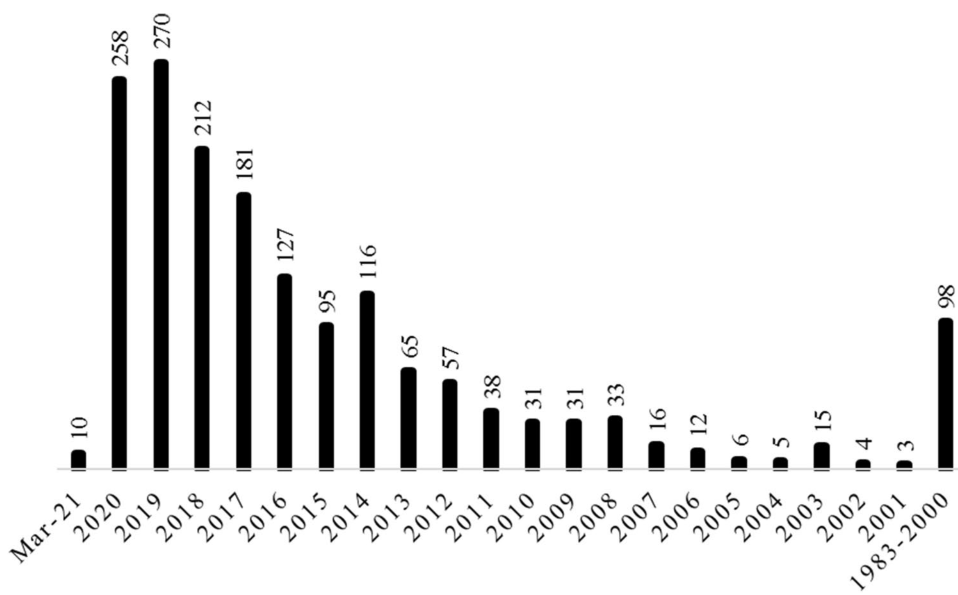


Fig. 2 Patent filled yearly on geopolymer (March 2021) (World Intellectual Property Organization (WIPO 2021)

India is the second-leading cement producer in the world after China, with the production capacity of 340 Mt expected in the year 2020 (Statista Market report 2021). The research on geopolymer cement and its development and technology has rapidly grown in India. Authors have attempted to enlist the possible reasons for this growth and future prospects as follows:

(1) Easy and cheap availability of raw materials such as fly ash (only the transportation cost is charged, i.e., \$2 to 5/t) and blast-furnace (BF) slag (\$25 to 30/t).
(2) The hot and humid environment throughout the year in most parts of the country leads to ambient temperature processing.
(3) Low water demand of geopolymer cement, as water is scarce in many areas.
(4) The short curing time of geopolymer cement, thus overcoming the time and space constraints.

Geopolymer cement is a recent development and the majority of the information is based on the laboratory-scale progress. It has been found that no literature is available on the detailed life cycle assessment (LCA) of geopolymer cement in India. Thus, getting the authentic data for LCA is a major challenge. To overcome this problem, geopolymer cement has been produced on the pilot-scale (5 t/d capacity) continuously. This information has been used as input data for LCA analysis. The objective of the current study is to evaluate cradle-to-gate environmental impacts of two types of geopolymer cement namely (a) fly ash and slag and (b) fly ash and cement. The obtained data are incorporated in GaBi software and its impacts are compared with the production of ordinary Portland cement (OPC), Portland Pozzolana cement (PPC), and Portland slag cement (PSC) in India for the year 2020–2021.

Materials and methods

Raw materials

Traditional Portland cement

OPC, PPC, and PSC are basically made using "clinker." Limestone is the prerequisite to make clinker. Limestone, i.e., calcium carbonate, is a natural resource either extracted or mined for various purposes. In India, 65% of its limestone comes from Madhya Pradesh, Rajasthan, Andhra Pradesh, Gujarat, and Chhattisgarh. Limestone, together with additives and correctives, is heated to 1350–1450 °C in a kiln to form hard material, clinker. Depending on the quality of limestone, the additives and correctives are added. Usually, 1.5 t of limestone produces 1.0 t of clinker at high temperature, which can be obtained by firing coal or petcoke. Gypsum, a mineral, is added to cement to provide binding and set retardation. Clinker, along with gypsum is milled to produce OPC. Supplementary cementitious material or blending material such as fly ash or BF slag is used to substitute clinker for cost, energy, and CO_2 minimization. Thus, most of the cement manufacturing units often occur near a thermal power plant or steel plant to reduce transportation across a long distance (Damani and Jaiswal 2017). The typical range of cement components is given in Table 2.

Geopolymer cement

The patented invention is particularly directed to the process of producing geopolymer cement in two parts, e.g., dry powder or aggregates as one part, and liquid activator as the second part (Kumar et. al. 2010, 2017).

Dry powder The Class F fly ash conforming to the IS-3812 standard is used as the main component in dry powder. OPC 53 grade (IS-12269) is also utilized as an additive to geopolymer cement. BF slag (IS-16714) is added as a substitute to cement for the comparative study, as it shows cementitious properties which can enhance performance and durability. The metakaolin-anhydrous calcined form of the kaoline is used as pozzolanic material. Approximately 1 kg of metakaolin produced from 1.16 kg of kaolin (Chandrasekhar 1996; NLK Project EA2860 2002).

Table 2 Composition (wt%) of Indian Cement

Component	OPC	PPC	PSC
Clinker	90–95%	60–65%	45–50%
Gypsum	5–10%	5–10%	5–10%
Fly ash	–	25–30%	–
Slag	–	–	40–50%

Liquid activator Sodium hydroxide is the main alkaline activator. It is produced by electrolysis of NaCl, known as the Chlor-alkali process. In India, nearly 70–79% of NaOH production is based on membrane cells and the remaining 21–30% on mercury cell capacity (CPCB 2008).

Sodium silicate is the second alkaline activator. Silica sand (SiO_2) and soda ash are melted at 1200 °C–1400 ºC to produce sodium silicate according to reaction 1:

$$Na_2CO_3 + x\,SiO_2 \rightarrow x\,SiO_2 : Na_2O + CO_2 \quad (1)$$

It is then solubilized in water at raised temperature and pressure to yield a 37% solid solution (Fawer et al. 1999).

Utilities The electric power system is a basic utility along with water considered in the present study. In India, electricity is generated mainly from hard coal. Water is required for dilution of sodium hydroxide flakes/pellets. The emphasis is given to the zero wastage of water. The overall water requirement is computed based on molarity. The groundwater is processed for desalination and deionization before its use.

Production of geopolymer cement

Authors have developed the process of making geopolymer cement from fly ash and BF slag/ cement. This process has been upscaled to 5 t/d capacity using the pilot plant. The process of making geopolymer cement is shown in Fig. 3.

Dry powder

The three solid raw materials, namely fly ash, BF slag/ cement, and metakaolin as an additive, are taken into the hopper of appropriate size. From the hopper, the raw materials come to a common conveying system through the automatic batch weighing system. Through conveyor, the raw material goes to the feeding system of the ball mill. The accuracy of the weighing and feeding system should be ± 0.5%. The ball mill offers size reduction as well as the mixing of raw materials. The ball mill used is the single compartment continuous type. The time of ball milling depends on feed size. The grinding and mixing process occur in a ball mill which is an open system. Once the production of dry geopolymer cement completed, the finished

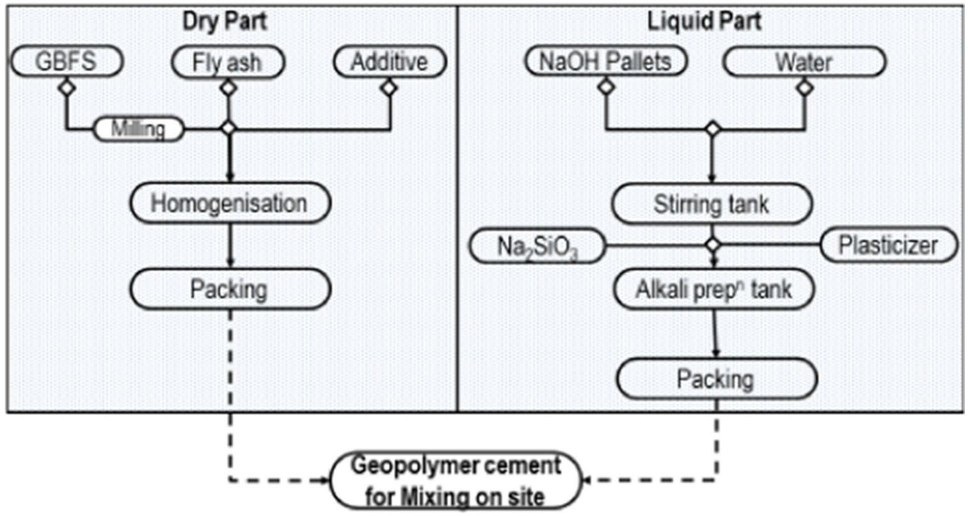


Fig. 3 Process flow diagram for geopolymer cement production

Table 3 Properties of geopolymer cement

Sr. no	Properties	Values
1	Setting time	Initial 40–60 min Final 120–160 min
2	Compressive strength	3-day 34 MPa 7-day 38 MPa 28-day 43 MPa
3	Shrinkage/Expansion	0.18–022 expansion

product transferred using bucket elevators and conveyors to large, product storage silo for packing.

Liquid activator

Sodium hydroxide solution of required molarity is prepared by mixing commercial grade of sodium hydroxide (NaOH) flakes/pellets in water. The pellets dissolve in water by stirring the solution continuously for 30 min at an ambient temperature. The solution is prepared at least 24 h before use so that it should get sufficient time to stabilize.

Similarly, sodium silicate ($Na_2O \sim 8\%$ and $SiO_2 \sim 26\%$) is also kept in the sodium silicate tank. Both the tanks are provided with agitator for proper mixing. From the respective tank, both the solutions pumped into the desired ratio through a flow controller. The level controllers are provided on pump outlet for safeguarding of the pump. After proper mixing, the liquid alkaline activator is transferred to the drum filling unit for packaging.

The developed geopolymer cement properties are given in Table 3.

Life Cycle Assessment

LCA is a tool for systematic analysis of environmental impacts of products, up- and downstream processes from cradle-to-grave, cradle-to-gate, gate-to-gate, or gate-to-grave. It helps manufacturer to reduce their processes emissions to the environment.

As per ISO 14040, LCA is followed in four phases (ISO 14040 2006):

(1) Goal and scope
(2) Life cycle inventory analysis
(3) Life cycle impact assessment
(4) Life cycle interpretation

Goal and scope

The goal of the present paper is to conduct a cradle-to-gate LCA of two types of geopolymer cement and compare it with traditional Portland cement including OPC, PPC, and PSC in an Indian context. Generally, most of the results are reported based on 1 m^3 of cement/concrete as a functional unit (McGrath et al. 2018). In the present study, 1.0 t production of cement is considered a functional unit that ensures a reasonable quantitative and qualitative comparison among all cement.

Life cycle inventory analysis

The inputs and outputs used to produce geopolymer cement are identified and quantified. For inventory analysis of geopolymer cement, mass balance is calculated on per ton basis. Both fly ash and BF slag are considered as an intermediate product. To analyze emissions from geopolymer cement, primary data are collected from the pilot plant (5t/d) and secondary data are developed from the GaBi software (Indian extension database). The data on electrical load during production are gathered from the primary source. There is no liquid or solid waste generated during geopolymer cement production.

The transportation required to get the raw materials, including fly ash, cement, BF slag, sodium hydroxide, and sodium silicate solution from the production site to the geopolymer cement plant, is also included in the inventory. In India, transportation usually occurs via diesel truck Bharat stage IV, and accordingly an average distance of 100 km is assumed.

Life cycle impact assessment

In impact assessment, the data collected till inventory phase are evaluated for the potential human health and environmental impacts. The climate impact categories such as global warming potential (GWP), ozone depletion potential (ODP), acidification potential (AP), Abiotic Depletion Potential (ADP) for fossil fuels and elements, human toxicity potential (HTP), and terrestrial ecotoxicity potential (Terrestrial EP) of two types of geopolymer cement vis a vis traditional cement has been accessed and compared.

The midpoint (problem-oriented) and endpoint (damage-oriented) impact assessment methods such as Centrum voor Milieukunde Leiden (CML), International Reference Life Cycle Data (ILCD), Cumulative Energy Demand (CED), ReCiPe, Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI), and Eco-indicator 99 were developed by universities and scientific groups to perform LCA. In this paper, the CML 2001 is used as its emission categories are global.

Life cycle interpretation

In the interpretation phase, outcomes are checked and analyzed with life cycle inventory and impact assessment phase. It helps to derive robust conclusions and structured recommendations.

During the use and handling phase at the construction site, there can be the emission of particulate matter from cement. Similarly, at the end of life or disposal phase, cement can be discarded in landfills or used as aggregate. However, the product's use phase, end-of-life phase, and recycling phase are not considered in the present study.

The environmental impact of individual raw material production (per ton) as per the GaBi software (Indian extension database) is given in Table 4.

Results and discussion

A potential impact assessment is implemented in order to convey the information contained in the inventory and its environmental significance. The process flow scheme for geopolymer cement based on fly ash and slag developed in GaBi software is shown in Fig. 4. GaBi Professional (with Indian Extension Database) software is used to analyze the impacts. The environmental impacts are discussed in detail.

Global warming potential (GWP)

The GWP evaluates the rise in Earth's average temperature due to different greenhouse gases, namely the CO_2, CH_4, N_2O, chloro-fluoro-carbons (CFC), hydro-chloro-fluoro-carbon (HFC), and SF_6. These gases have different abilities to absorb energy with different lifetimes in the atmosphere. Hence, they are relatively converted and compared to the emissions of CO_2 over a given period of time. Higher GWP value indicates increase in temperature of Earth's atmosphere by absorbing energy over the time period, which is usually considered as 100 y.

The GWP of geopolymer cement is mainly caused by alkali solution as shown in Fig. 5. The GWP of sodium silicate (105 kg CO_2-Equiv.) is the maximum and is followed by sodium hydroxide (50 kg CO_2-Equiv.). The manufacturing of sodium silicate associates the calcination of sodium carbonate and quartz at 1400 and 1500 °C which produces CO_2 as a secondary product (Turner and Collins 2013). Luukkonen et. al. (2018) also found that 80–90% environmental footprint of geopolymers is only due to the sodium silicate solution. The overall GWP is considerably low if both component's impacts are excluded.

Table 4 Cradle-to-gate environmental impact of raw material input

Sr. no	Raw material	GWP (kg CO_2-Equiv.)	ODP (kg R11-Equiv.)	AP (kg SO_2-Equiv.)	ADP (fossil) (MJ)	ADP (elements) (kg Sb-Equiv.)	HTP (kg DCB-Equiv.)
1	Fly ash	63.1	$1.69e^{-13}$	0.546	632	$1.72e^{-7}$	24.3
2	Cement	895	$2.08e^{-11}$	2.66	$6.09e^{3}$	$1.8e^{-3}$	279
3	BF slag	37.1	$6.61e^{-13}$	$1.2e^{3}$	611	$3.89e^{-6}$	527
4	Metakaolin	778	$1.94e^{-11}$	7.08	$7.82e^{3}$	$9.46e^{-6}$	292
5	Sodium hydroxide	1390	$1.29e^{-9}$	2.83	$1.6e^{4}$	0.0165	62.4
6	Sod. silicate solution (37% solid)	696.7	$4.02e^{-11}$	5.07	$8.37e^{3}$	$3.83e^{-3}$	123

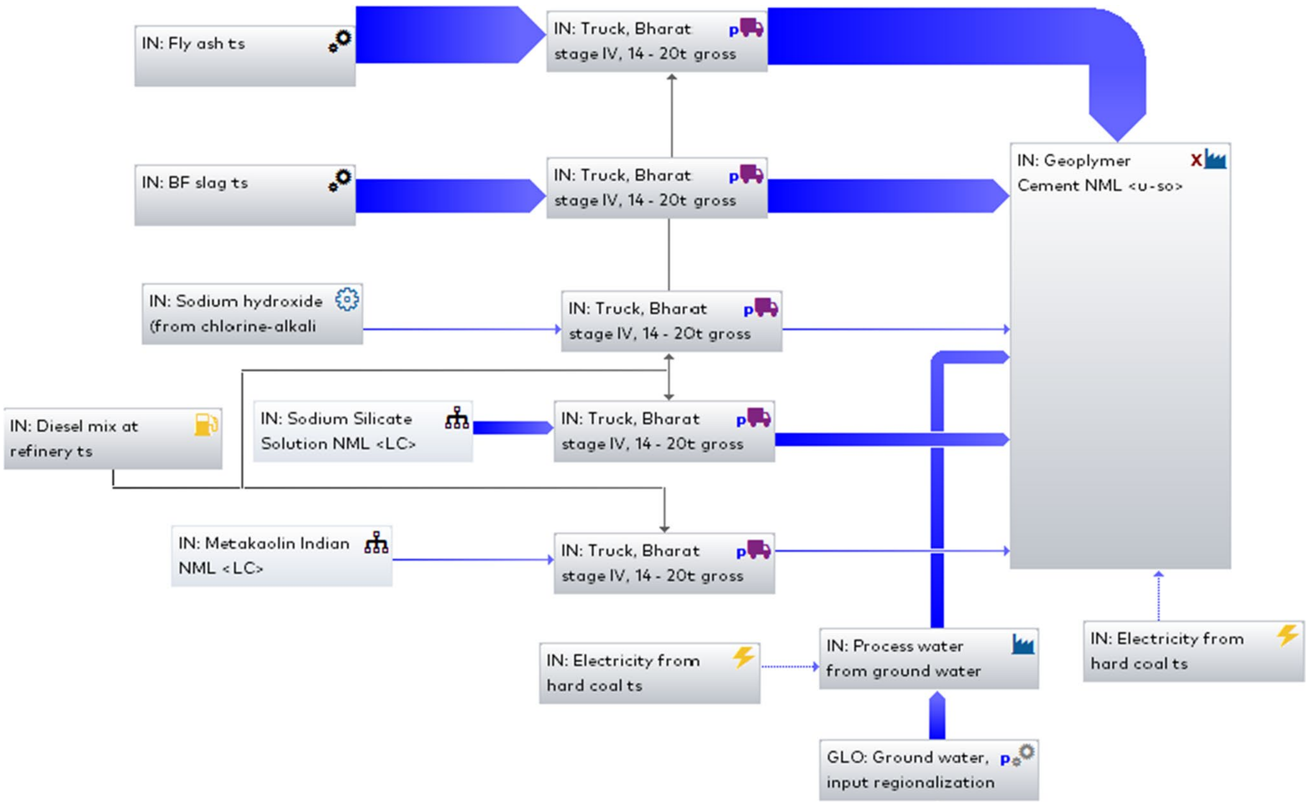
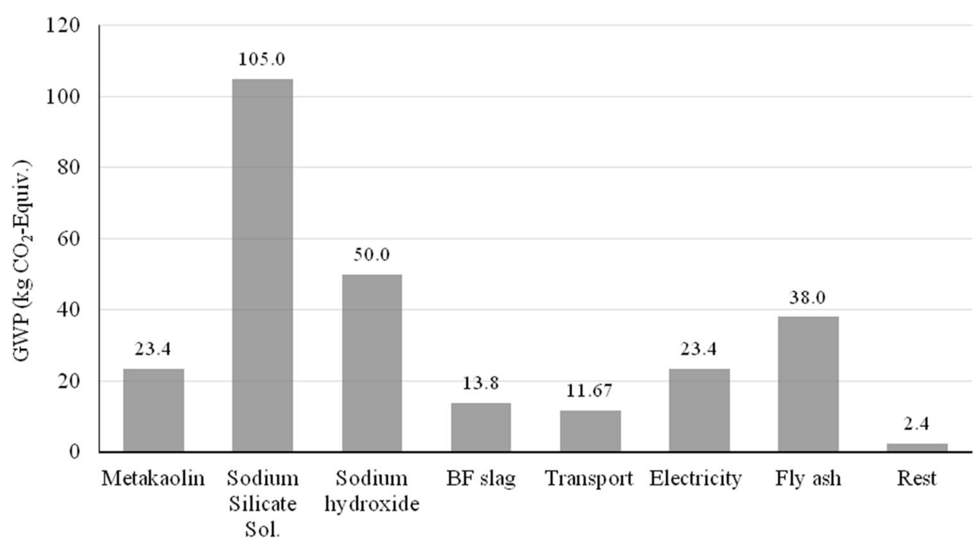


Fig. 4 Geopolymer cement production process flow in GaBi

Fig. 5 GWP of geopolymer cement based on fly ash and slag



On comparison with other traditional cement, geopolymer cement allows significant reduction in GWP. The fly ash and slag-based geopolymer cement releases 267 kg CO_2-Equiv. compared to OPC, PPC, and PSC as 895, 788, and 662 kg CO_2-Equiv., respectively. GWP of OPC is higher because of the many energy-intensive steps such as raw material grinding, calcination (decarbonization) of limestone occurred at 1400–1450 °C, and then grinding of clinker. Similarly, the GWP of geopolymer cement based on fly ash and cement is 351 kg CO_2-Equiv as shown in Fig. 6.

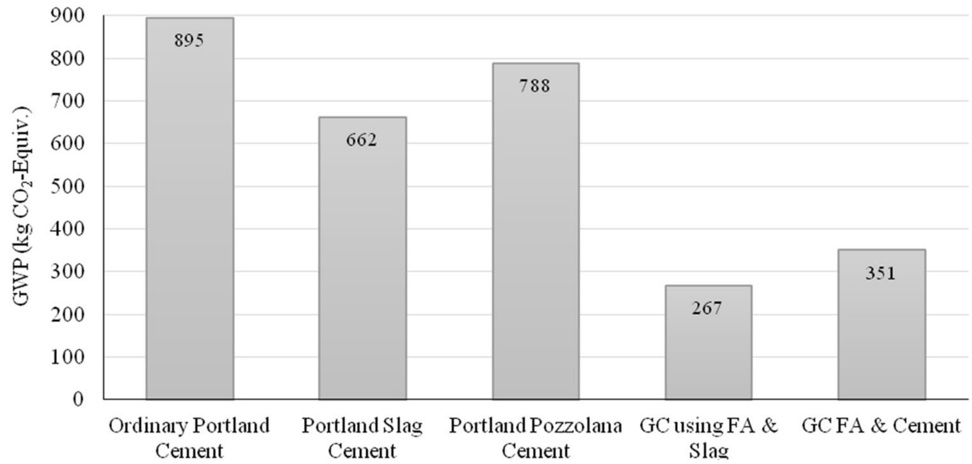


Fig. 6 GWP of geopolymer cement versus traditional cement in India

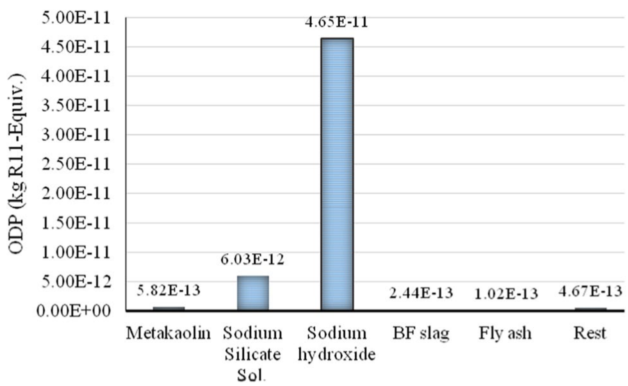


Fig. 7 ODP of geopolymer cement based on fly ash and slag

Ozone depletion potential (ODP)

Ozone depletion is the reduction in the protective ozone concentration caused due to the release of ozone-depleting substances such as CFCs within the stratosphere. The World Meteorological Organization proposed the metric to calculate the relative contribution of CFCs, HFCs, and halons on the ozone layer (PCI 2009). ODP provides a relative measure in terms of Tri-chloro-fluoro-methane (R11) of per unit mass emission of gas compared to that of CFC-11 integrated over time. The ODP of geopolymer cement based on fly ash and slag is mainly due to sodium hydroxide (Fig. 7). Abbas et. al. (2020) also mentioned that geopolymer cement has a negative impact on various climate indices such as carcinogens, ionizing radiation, and the ODP.

On comparison with traditional cement, the ODP of geopolymer cement (fly ash and slag) is between 2.6 and 4.6 times higher than OPC and PSC, respectively (Fig. 8). However, it is lower than the fly ash and cement-based geopolymer (5.56e^{-11} kg R11-Equiv.).

Acidification potential (AP)

Acidification is the increase in the pH-value of precipitation caused due to the washout of air pollutants, essentially SO_2, NH_3, and NOx in rivers/streams and soil. Acid formation potential is calculated against a reference substance,

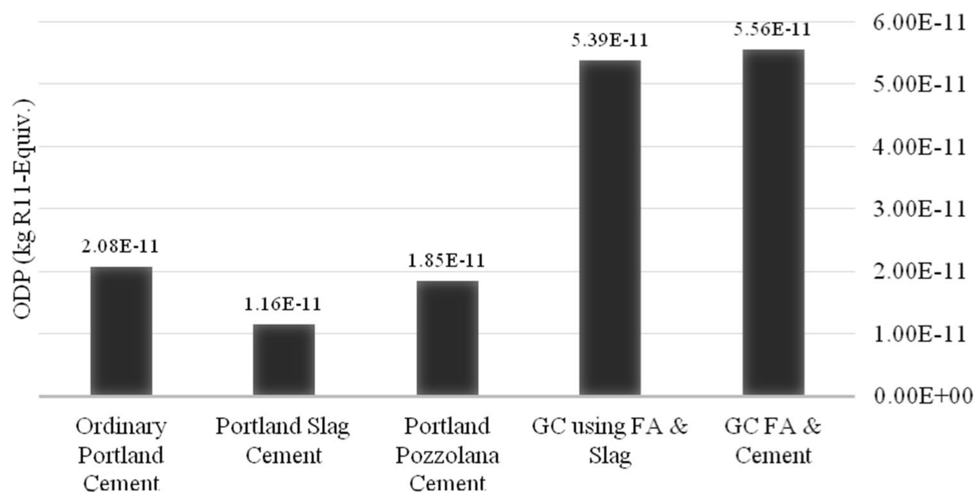


Fig. 8 ODP of geopolymer cement versus traditional cement in India

SO_2. The movement and leaching behavior of heavy metals increases over time in the soil, which in turn has an impact on aquatic and terrestrial floras and faunas (Kim and Chae 2016). The AP of fly ash and slag-based geopolymer cement is 445 kg SO_2-Equiv. and of PSC is 302 kg SO_2-Equiv. due to the higher content of BF slag (Fig. 10). AP was the most significant climate impacts occurred by slag-based cement production (Li et al. 2016). However, it is interesting to note that granulated blast furnace slag is typically 1–2 mm in size, whereas clinker is 10–40 mm in size. Also, the grindability of clinker is poor than GBFS so theoretically GBFS should have lower AP.

The lower AP for PSC is mainly the result of the BF slag content (22–25%) considered in the GaBi-PSC production database. However, for the present, fly ash and slag-based geopolymer cement, the BF slag content is considered as 37% (Fig. 9).

Abiotic depletion potential (ADP) for fossil and elements

Abiotic depletion is one of the most frequently discussed impact indicators related to the extraction of natural non-living resources, including minerals and fossil fuels. The extraction of minerals and fossil fuels are determined and represented in terms of the kg Sb-equivalent. It is the ratio of concentration of ultimate reserves and de-accumulation rates.

ADP of OPC is mainly due to the consumption of naturally occurring resources such as coal, clay, and limestone. The ADP fossil of geopolymer cement (fly ash and slag) is 49% lower than OPC (Figs. 11a and 12a). Similarly, the ADP element is 1.18 e^{-3} kg Sb-Equiv. mainly due to the sodium hydroxide and sodium silicate solution as shown in Figs. 11b and 12b. Thus, geopolymer cement will help to reserve mineral resources.

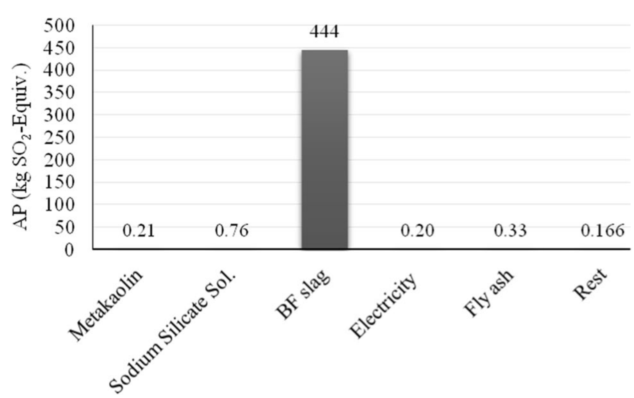


Fig. 9 AP of geopolymer cement based on fly ash and slag

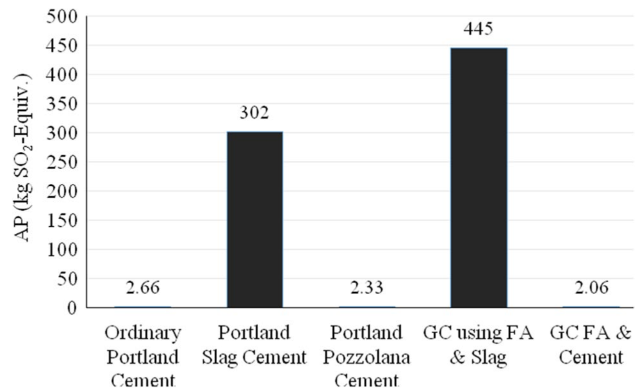


Fig. 10 AP of geopolymer cement versus traditional cement in India

Human toxicity potential (HTP) and terrestrial ecotoxicity potential (Terrestrial EP)

The HTP is an indicator for health impact from exposure to carcinogens and noncarcinogens. It is usually evaluated in terms of 1,4-Di-chlorobenzene (DCB, $C_6H_4Cl_2$) equivalence (carcinogens) and toluene equivalents (noncarcinogens). It is governed by release of toxic organic compounds, heavy metals, and NOx. HTP of fly ash and slag-based geopolymer cement is 249 kg DCB-Equiv., which is lower than OPC

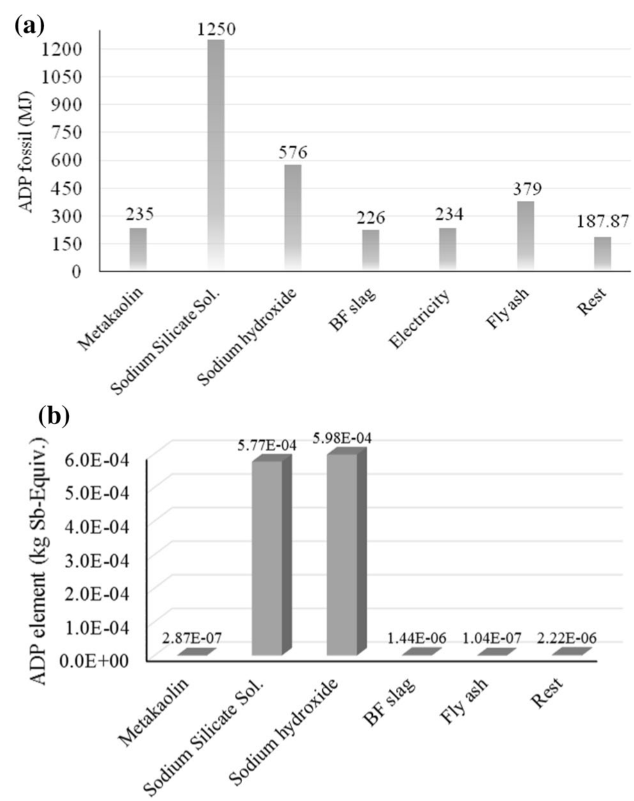


Fig. 11 ADP of geopolymer cement based on fly ash and slag **a** ADP fossil **b** ADP elements

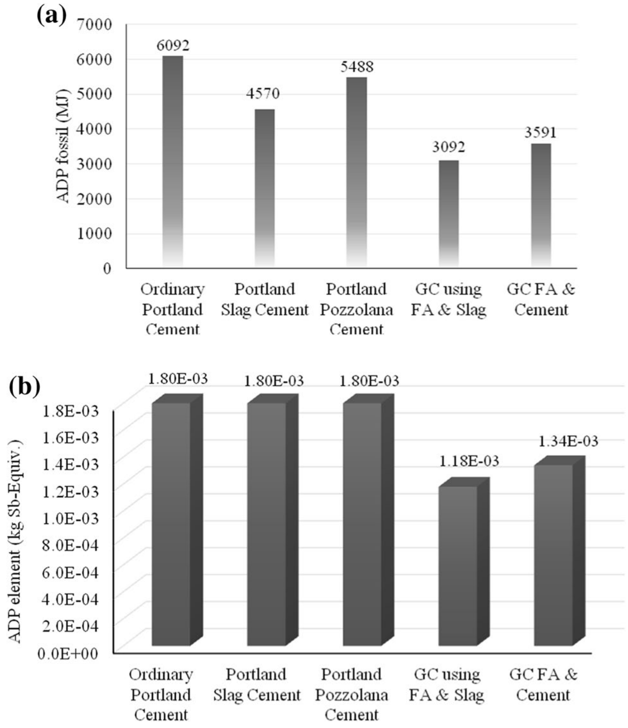


Fig. 12 ADP of geopolymer cement versus traditional cement in India **a** ADP fossil **b** ADP elements

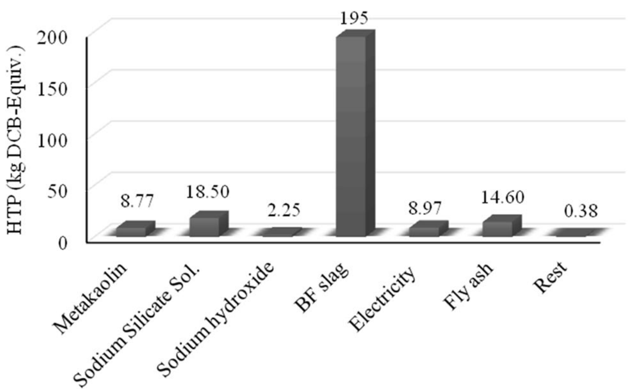


Fig. 13 HTP of geopolymer cement based on fly ash and slag

and PSC but higher than PPC in India (Figs. 13 and 14). Although the results show that the HTP is high due to BF Slag, it is necessary to mention that as per IARC, NTP, and OSHA, slag is not listed as a carcinogen (MSDS 2010).

Terrestrial EP is related to the measure of toxic substance released in the soil. The terrestrial EP of geopolymer cement (fly ash and slag) is 0.438 kg DCB-Equiv., which is much lower (70%) than OPC in India (Fig. 15). Terrestrial EP is mainly contributed by the cement and natural resources.

The comparative environmental impacts of clay (as per literature) and fly ash-based geopolymer cement (calculated from the GaBi software) are given in Table 5. It is clear that

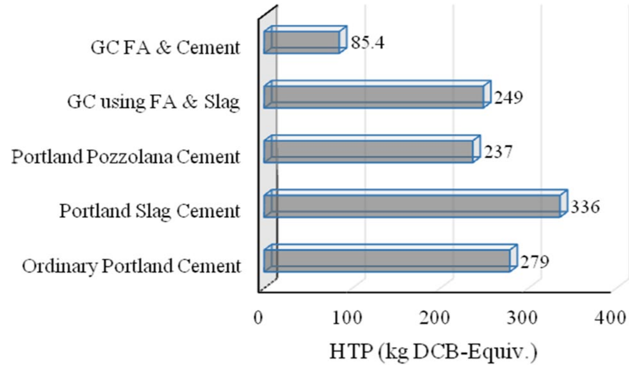


Fig. 14 HTP of geopolymer cement versus traditional cement in India

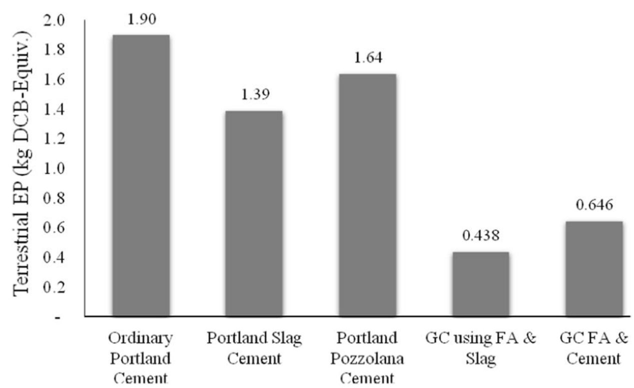


Fig. 15 Terrestrial EP of geopolymer cement versus traditional cement in India

clay based geopolymer has higher GWP, ODP, ADP (elements) and terrestrial EP than the fly ash based geopolymer. The AP and HTP impact of fly ash based geopolymer is higher due to BF slag.

Conclusion

This paper on LCA methodology provides a detailed environmental evaluation and implications of the production of (a) fly ash and slag and (b) fly ash and cement-based geopolymer in comparison to OPC, PPC, and PSC in India. The present study highlights the production of fly ash-based geopolymer cement, which has lower impacts on the environment than traditional Portland cement.

The detailed analysis of results concludes that (a) fly ash and slag and (b) fly ash and cement-based geopolymer reduce the GWP to 70% and 61%, ADP fossil to 49% and 41%, ADP element to 34% and 26% respectively compared to OPC mainly due to energy-intensive cement production process. The fly ash and slag-based geopolymer decreases HTP to 26% when compared with PSC and cuts terrestrial

Table 5 Quantitative environmental impacts between clay and fly ash-based geopolymer

Sr. no	Geopolymer (per kg)	GWP (kg CO_2-Equiv.)	ODP (kg R11-Equiv.)	AP (kg SO_2-Equiv.)	ADP (elements) (kg Sb-Equiv.)	HTP (kg DCB-Equiv.)	Terrestrial EP (kg DCB-Equiv.)
1	Clay-based geopolymers- Metabentonite (Heath et al. 2014)	0.434	$4.07e^{-8}$	$1.07e^{-3}$	$3.48e^{-3}$	0.0717	$9.07e^{-4}$
2	Clay-based geopolymers- Metakaolin (Heath et al. 2014)	0.421	$3.98e^{-8}$	$1.03e^{-3}$	$3.39e^{-3}$	0.0694	$8.66e^{-4}$
3	Geopolymer (Fly ash and slag)	0.267	$5.39e^{-14}$	0.445	$1.18e^{-6}$	0.249	$4.38e^{-4}$
4	Geopolymer (Fly ash and cement)	0.351	$5.56e^{-14}$	$2.06e^{-3}$	$1.34e^{-6}$	0.085	$6.4e^{-4}$

EP to 77% when compared with OPC. The ODP for (a) fly ash and slag and (b) fly ash and cement-based geopolymer was found higher than the traditional cement due to the usage of sodium hydroxide. The fly ash and slag-based geopolymer cement increases the ODP to 159% and AP to 47% compared with OPC and PSC, respectively. The lower AP for PSC is mainly the result of the BF slag content (22–25%) considered in the GaBi-PSC production database. However, for the present fly ash and slag-based geopolymer cement, the BF slag content is considered as 37%.

The fly ash-based geopolymer cement has also shown a drop in GWP, ODP, ADP (elements) and terrestrial EP from the clay-based geopolymer. In case of geopolymer cement, the maximum impact on the environment was due to the use of an alkali solution (NaOH and silicate). Careful optimization of alkali solution can further reduce the impact. Further use of more calcium-based activator in place of sodium-based activator will add to the advantage. Geopolymer cement appears to be more sustainable than traditional Portland cement in the Indian context. The results reveal that fly ash-based geopolymer cement can be valuable to several global industries, including construction, and those that are committed to a more sustainable planet.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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