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Life Cycle Assessment of the Geopolymer Concrete Containing Fly Ash, Metakaolin and Zeolite

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Abstract

The construction industry is a major contributor to global carbon emissions, primarily due to the widespread use of ordinary Portland cement (OPC) in concrete production. To address this environmental challenge, this study evaluates the sustainability of geopolymer concrete (an alternative binding material synthesized from industrial by-products (fly ash and metakaolin) and natural materials (zeolite)) using Life Cycle Assessment (LCA). The environmental impacts of geopolymer concrete were compared to those of conventional OPC-based concrete across key impact categories, including global warming potential, resource depletion, and toxicity.

The LCA was conducted following the ISO 14040 and 14044 standards, with a cradle-to-gate system boundary and a functional unit of 1 cubic meter of concrete. The results demonstrate that geopolymer concrete, particularly the MK20 formulation, significantly outperforms conventional concrete in terms of environmental sustainability. For instance, the global warming potential of geopolymer concrete was up to 99% lower than that of conventional concrete, primarily due to the avoidance of energy-intensive OPC production. Additionally, geopolymer concrete showed substantial reductions in human toxicity, aquatic and terrestrial ecotoxicity, and abiotic resource depletion. Normalization of the results using the CML-baseline method further confirmed the superior environmental performance of geopolymer concrete across all impact categories. However, the study also identified the need to address the environmental impacts of alkali activators, which contribute to the overall footprint of geopolymer production.

The findings highlight the potential of geopolymer concrete as a sustainable alternative to conventional concrete, offering significant environmental benefits while maintaining comparable mechanical properties. This research supports the transition toward greener construction practices and contributes to global efforts to mitigate climate change. Future studies should focus on optimizing mix designs, exploring alternative activators, and assessing the long-term durability of geopolymer concrete to further enhance its sustainability and promote its widespread adoption in the construction industry.

Keywords: Life cycle assessment, geopolymer concrete, fly ash, metakaolin, zeolite.

1. Introduction

The construction industry is one of the largest contributors to global carbon emissions, primarily due to the widespread use of ordinary Portland cement (OPC) in concrete production. The manufacturing of OPC is not only energy-intensive but also releases significant amounts of carbon dioxide (CO_2), accounting for approximately 8% of global CO_2 emissions [1]. In response to the growing environmental concerns and the urgent need for sustainable construction practices, alternative binding materials such as geopolymer have gained considerable attention [2]. Geopolymer concrete, an innovative and eco-friendly material, is synthesized through the alkali activation of aluminosilicate sources, such as fly ash, metakaolin, and zeolite [3]. These materials, often industrial by-products or naturally occurring minerals, offer a sustainable alternative to OPC by reducing the reliance on virgin resources and lowering the carbon footprint associated with concrete production [4]. Fly ash, a by-product of coal combustion, and metakaolin, a thermally activated clay, are widely studied for their pozzolanic properties. Zeolite, a natural mineral with a porous structure, further enhances the mechanical and durability properties of geopolymer concrete [5].

Life Cycle Assessment (LCA) is a robust methodology used to evaluate the environmental impacts of products and processes throughout their entire life cycle, from raw material extraction to end-of-life disposal [6-8]. Applying LCA to geopolymer concrete provides a comprehensive understanding of its environmental performance compared to conventional OPC-based concrete [9]. This study aims to assess the sustainability of geopolymer concrete containing fly ash, metakaolin, and zeolite through a detailed LCA, focusing on key impact categories such as global warming potential, energy consumption, and resource depletion [10, 11].

By comparing the environmental performance of geopolymer concrete with that of ordinary concrete, this research seeks to highlight the potential of geopolymer as a sustainable alternative in the construction industry [12]. The findings of this study will contribute to the growing body of knowledge on sustainable construction materials and support the transition towards greener building practices, ultimately aiding in the global effort to mitigate climate change and promote environmental stewardship [13].

The introduction serve distinct purposes in a research paper, and their novelty lies in how they frame the research problem and contextualize it within existing knowledge. Here's a breakdown of the novelty of the introduction versus the literature review based on the explanation provided:

2. Literature Review

The growing demand for sustainable construction materials has spurred extensive research into alternatives to ordinary Portland cement (OPC)-based concrete [14]. Geopolymer concrete, which utilizes industrial by-products and natural aluminosilicate materials as binders, has emerged as a promising solution due to its lower environmental impact and comparable mechanical properties [15]. This section reviews existing studies on the composition, performance, and environmental sustainability of geopolymer concrete, with a focus on fly ash, metakaolin, and zeolite as key precursors, and highlights the application of Life Cycle Assessment (LCA) in evaluating its environmental performance compared to ordinary concrete.

2.1. Geopolymer Concrete: Composition and Properties

Geopolymer concrete is produced through the alkali activation of aluminosilicate materials, such as fly ash, metakaolin, and zeolite, which react with alkaline solutions to form a hardened binder. Fly ash, a by-product of coal-fired power plants, is one of the most widely used precursors due to its abundance, low cost, and high silica and alumina content [16]. Metakaolin, derived from the calcination of kaolin clay, offers high reactivity and purity, making it suitable for high-performance geopolymer applications [17]. Zeolite, a naturally occurring mineral, has also been explored for its unique porous structure and ion-exchange properties, which enhance the durability and mechanical performance of geopolymer concrete [18].

Studies have demonstrated that geopolymer concrete exhibits excellent compressive strength, chemical resistance, and thermal stability, often surpassing the performance of OPC-based concrete [19]. However, the environmental benefits of geopolymer concrete extend beyond its mechanical properties, as it significantly reduces greenhouse gas emissions and energy consumption compared to OPC production [20].

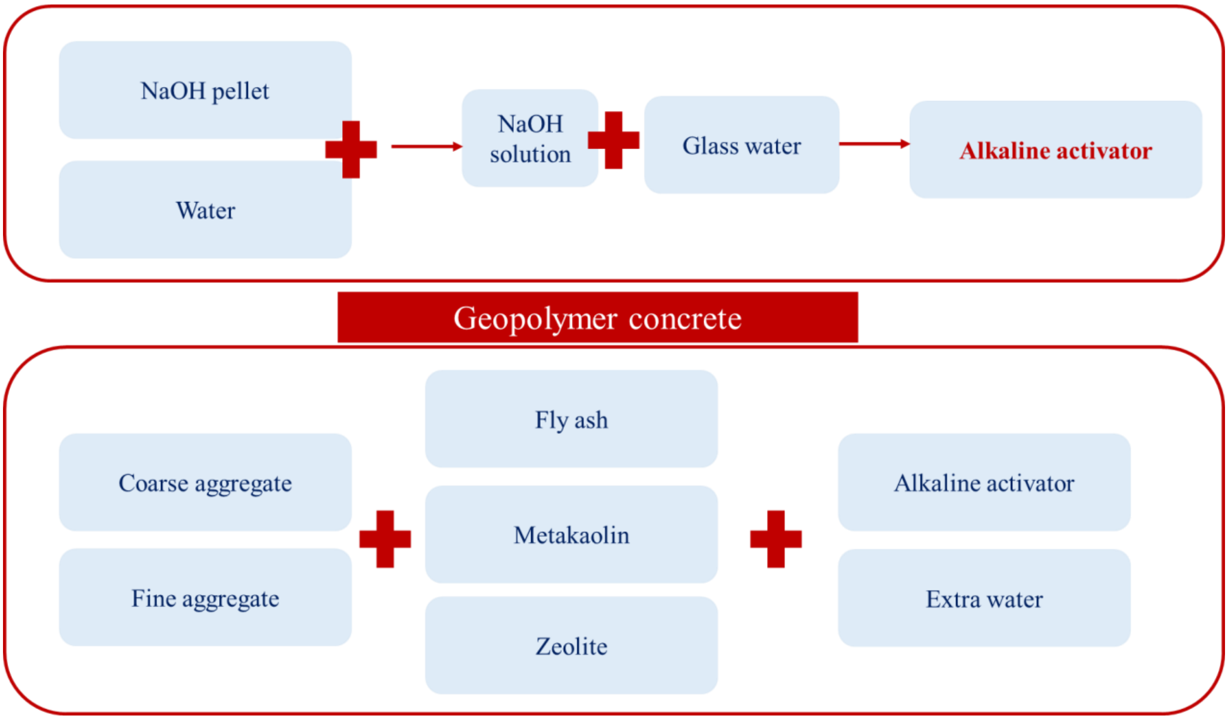

Fig. 1: Sustainable GPC composition and properties

2.2. Environmental Impact of Ordinary Concrete

Ordinary concrete, primarily composed of OPC, is associated with substantial environmental burdens. The production of OPC is responsible for approximately 8% of global CO_2 emissions, primarily due to the calcination of limestone and the combustion of fossil fuels during clinker production [22]. Additionally, the extraction of raw materials, such as limestone and clay, contributes to resource depletion and habitat destruction. The construction industry's reliance on OPC-based concrete has thus become a major concern in the context of climate change and sustainable development.

2.3. Life Cycle Assessment (LCA) of Geopolymer Concrete

Life Cycle Assessment (LCA) has been widely adopted as a tool to evaluate the environmental impacts of construction materials, including geopolymer and ordinary concrete. LCA studies typically assess impacts across various stages, including raw material extraction, transportation, production, use, and end-of-life disposal. Several studies have highlighted the environmental advantages of geopolymer concrete, particularly in terms of reduced global warming potential (GWP) and energy consumption [21].

For instance, Turner and Collins conducted an LCA comparing fly ash-based geopolymer concrete with OPC-based concrete and found that the former reduced CO_2 emissions by up to 80% [19]. Similarly, McLellan et al.

reported that metakaolin-based geopolymers exhibited lower energy consumption and GWP compared to OPC, although the environmental impact of alkali activators, such as sodium hydroxide and sodium silicate, remains a concern [20]. Recent studies have also explored the use of zeolite as a precursor, demonstrating its potential to further enhance the sustainability of geopolymer concrete by reducing the need for high-temperature processing and chemical activators [21].

2.4. Challenges and Research Gaps

Despite the promising results, several challenges and research gaps remain. The variability in the chemical composition of industrial by-products, such as fly ash, can affect the consistency and performance of geopolymer concrete [18]. Additionally, the environmental impact of alkali activators, which are often derived from energy-intensive processes, needs to be addressed to fully realize the sustainability potential of geopolymers [20]. Furthermore, there is a lack of comprehensive LCA studies that compare the environmental performance of geopolymer concrete containing multiple precursors, such as fly ash, metakaolin, and zeolite, with ordinary concrete.

2.5. Novelty of the Literature Review

2.5.1. Comprehensive Overview of Existing Research:

- The literature review provides a detailed summary of prior studies on geopolymer concrete, focusing on its composition (fly ash, metakaolin, and zeolite), properties, and environmental benefits.
- It highlights key findings from previous research, such as the reduction in CO_2 emissions and energy consumption achieved by geopolymer concrete compared to OPC-based concrete.

2.5.2. Critical Analysis of Gaps and Challenges:

- The literature review identifies gaps in existing research, such as the variability in precursor materials (e.g., fly ash composition) and the environmental impact of alkali activators.
- It points out the lack of comprehensive LCA studies comparing multi-precursor geopolymer concrete (containing fly ash, metakaolin, and zeolite) with ordinary concrete.

2.5.3. Contextualization of the Study:

The literature review positions the current study within the broader academic discourse by referencing key studies and methodologies (e.g., LCA) used in the field. It provides a foundation for the research by showing how the study builds on and addresses limitations in existing work.

2.5.4. Novelty in Synthesis:

The literature review synthesizes existing knowledge to highlight the **how** and **where** of the research. It connects the dots between prior studies and the current research, emphasizing the need for further investigation into multi-precursor geopolymer concrete.

In summary, geopolymer concrete offers a sustainable alternative to OPC-based concrete, with significant reductions in CO_2 emissions and energy consumption. Fly ash, metakaolin, and zeolite have been identified as effective precursors for geopolymer production, each contributing unique properties that enhance the material's performance and sustainability. However, further research is needed to address the challenges associated with alkali activators and precursor variability, as well as to conduct comprehensive LCA studies that evaluate the environmental impact of multi-precursor geopolymer concrete. This study aims to contribute to this growing body of knowledge by providing a detailed sustainability evaluation of geopolymer concrete containing fly ash, metakaolin, and zeolite compared to ordinary concrete.

3. Materials and methods

3.1. Materials

a) *SCMs*

In this research, the low calcium FA with a granule density of 2.66 g/cm^3 was supplied from the Foolad Mobarakeh Esfahan Company. In addition, the used Clinoptilolite type of zeolite (Z) for this study was prepared from mines in Semnan region, Iran, and had a specific gravity of 2.14 and Blaine fineness of 6788 cm^2/g. Moreover In addition, Delijan MK used from the Ferro Alloy Industries Co., which had a granule density of 2.59 g/cm^3, was used as a pozzolan. The total amount of Al2O3, SiO2, and Fe2O3 in the zeolite was obtained as about 80%. The chemical characteristic and loss on ignition (LOI) of the used pozzolans are reported in Table 1.

Table 1. Chemical composition of used materials (%)

Component (%)	Z	FA	MK
SiO_2	67.79	61.3	52.1
Al_2O_3	13.66	28.8	44.7
Fe_2O_3	1.44	4.98	0.8
CaO	1.68	1.05	0.09
MgO	1.2	0.63	0.03
SO_3	0.5	0.13	-
Na_2O	2.04	0.24	9.1
K_2O	1.42	1.4	0.03
Loss of ignition	10.23	0.7	0.7

b) Alkaline solution

The alkaline solution used in the presented study to activate the SCM (e, g., FA, MK and Z) was a combination of sodium hydroxide (NaOH) and glass water (sodium silicate or Na_2SiO_3). The solid sodium hydroxide 96% was prepared as a solution in water. The sodium silicate solution utilized in this research had the SiO_2 / Na_2O ratio of 2.27 (SiO2 = 35.9%, Na_2O = 15.8 %,).

c) Fibers

The experimental investigation for development of eco-friendly and structural GPC mixtures were performed using 2-part hybrid fibers namely steel (St) and polypropylene (PP). Table 2 referred the details of used fibers. The PP fiber length of 6 mm was utilized to reinforce the GPC. Moreover, in this study, hooked-end steel fibers with a maximum length of 5 and diameter of 0.12 mm were considered to develop and propose the optimal blends. To do so, PP at 0,1,2,3 vol% and St at 2 vol%, were added in GPC mixture proportions.

Table 2. Properties of fibers

	PP	St
Length (mm)	6	5
Density (gr/cm^3)	0.93	7.8
Tensile strength (MPa)	400	2500
Water absorbency	No	No
Alkaline and acid resistant	Excellent	Excellent
Diameter (mm)	-	0.12

d) Aggregates

Recycled fine aggregate (RFA) and natural coarse aggregate (NCA) composed around 77% of the concrete volume. Natural sand supplied from a local quarry with a fineness modulus of 3.05, was used as the fine aggregate. The recycled coarse aggregate was used with a maximum grain size of 12.5 mm and its specific gravity and water absorption were 2.57 and 1.52%, respectively. Table 3 reported the sieve analysis of the fine and recycled coarse aggregates.

Table 3. Sieve analysis of coarse and fine aggregates used for GPC mixtures.

NCA	Sieve (mm)	12.5	8	5.75	4	2	1
	Passing (%)	100	76	47	22	4	2
RFA	Sieve (mm)	9.5	4.75	2.36	1.18	0.6	0.3
	Passing (%)	100	87.6	63.5	41.9	23.3	4.5

2.2. Mix design, specimen's preparation and testing procedure

The mixing of the GPC mixtures was conducted in a mixer. For this aim, dry materials such as CA and fine aggregates and SCMs were combined in the mixer for about 3 minutes, then the alkaline solution was added and the wet mixing continued for another 4–6 minutes until a consistent mixture was prepared. The molds were filled in two layers and each layer was vibrated for about 25 second using a vibrating table. Table 4 presented the mix design of reinforced GPC mixtures.

Table 4. Mix proportions of reinforced GPC

	FA	Z	MK	St	PP	RFA	NCA	Na_2SiO_3	NaOH	W	C
MK20	400	0	100	48	0	500	1036	187	40	84	-
MK20-PP1.25	400	0	100	48	30	500	1036	187	40	84	-
Z10-MK20-PP1	350	50	100	48	24	500	1036	187	40	84	-
OPC-based concrete	-	-	-	-	-	860	1050	-	-	140	350

The constructed specimens were kept for 24 hours at 60 ^{0}C in oven conditions and subsequently removed from the molds and cured in an ambient temperature (24 ± 2 ◦C and 20% ± 2% relative humidity) to the desired temperature

3.2. Methods

3.2.1. Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is a systematic methodology used to evaluate the environmental impacts of a product or process throughout its entire life cycle, from raw material extraction to end-of-life disposal. This study employs the LCA framework standardized by the International Organization for Standardization (ISO) 14040 and 14044 to assess the environmental performance of geopolymer concrete containing fly ash, metakaolin, and zeolite in comparison to ordinary Portland cement (OPC)-based concrete [22].

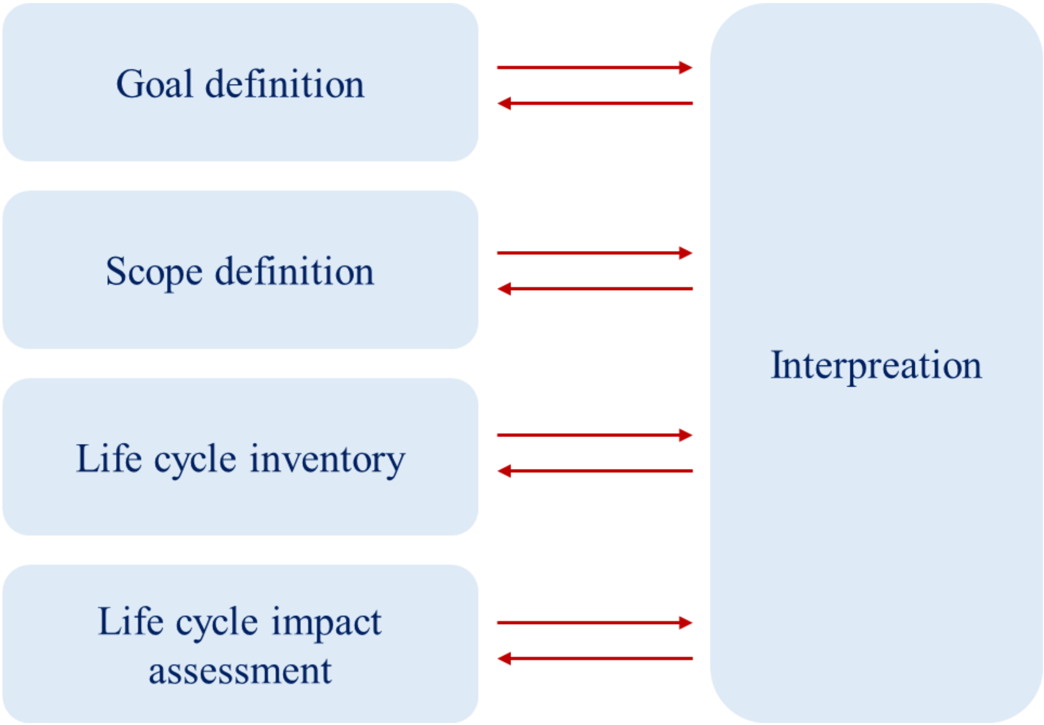

Fig. 2: Life cycle zssessment stages

The LCA methodology is divided into four main phases: (1) goal and scope definition, (2) life cycle inventory (LCI), (3) life cycle impact assessment (LCIA), and (4) interpretation of results. The goal of this LCA is to evaluate and compare the environmental impacts of geopolymer concrete and ordinary concrete, with a focus on identifying the sustainability benefits of using fly ash, metakaolin, and zeolite as alternative binders [23]. The study aims to provide insights into the potential of geopolymer concrete as a sustainable construction material and support decision-making in the construction industry [24-26].The system boundary for this study is cradle-to-gate, encompassing the following stages:

- Raw material extraction and processing (e.g., mining of limestone for OPC, sourcing of fly ash, metakaolin, and zeolite).
- Transportation of raw materials to the production facility.
- Production of concrete (mixing, curing, and hardening).
- Use phase (excluded, as the focus is on material production).
- End-of-life disposal (excluded, as it is beyond the scope of this study).

The functional unit is defined as 1 cubic meter (m^3) of concrete with comparable compressive strength (e.g., 30 MPa) for both geopolymer and ordinary concrete [27]. The study evaluates the following environmental impact categories:

- Global Warming Potential (GWP) in kg CO_2-equivalent.
- Energy Consumption in MJ.
- Resource Depletion (e.g., abiotic depletion potential).
- Acidification Potential in kg SO_2-equivalent.
- Eutrophication Potential in kg PO_4-equivalent.

3.2.2. Life Cycle Inventory (LCI)

The Life Cycle Inventory (LCI) involves the collection and quantification of data on inputs (e.g., raw materials, energy) and outputs (e.g., emissions, waste) associated with the production of geopolymer and ordinary concrete [28]. Data sources include:

- **Primary Data**: Collected from concrete production facilities, including energy consumption, material usage, and transportation distances.
- **Secondary Data**: Obtained from existing databases such as Ecoinvent, GREET, and published literature.

3.2.3. Life Cycle Impact Assessment (LCIA)

The Life Cycle Impact Assessment (LCIA) phase translates the inventory data into environmental impacts using characterization factors [29, 30]. The following steps are applied:

- **Classification**: Assigning inventory data to relevant impact categories (e.g., CO_2 emissions to GWP).
- **Characterization**: Quantifying the contributions of each input/output to the impact categories using standardized methods [31].
- **Normalization and Weighting**: Normalizing results to a reference value and applying weighting factors to compare the relative importance of different impacts [32].

4. Result and discussion

Based on the inventory data of the project under investigation, the following impact categories were predicted using the CML-baseline characterization method:

- Abiotic Resource Depletion
- Global Warming Potential
- Ozone Layer Depletion
- Human Toxicity
- Terrestrial Ecotoxicity
- Aquatic Ecotoxicity
- Photochemical Oxidant Formation

4.1. Characterization of Impact Categories

According to the calculations and characterization using the CML-baseline method, the environmental profiles of the different types of concrete are presented in Table 1.

Table 1: Environmental Profile (Impacts) per Kilogram of Produced Concrete

Impact Category	Unit	Z10-MK20-PP1	MK20-PP1.25	MK20	OPC-based concrete
Abiotic Resource Depletion	kg Sb eq	2.93E-06	1.75E-06	1.66E-06	14.65553
Abiotic Resource Depletion (Fossil Fuels)	MJ	3.396141	2.38331	1.501279	1459349
Global Warming Potential	kg CO_2 eq	0.289774	0.188131	0.162035	151988.6
Ozone Layer Depletion	kg CFC-11 eq	3.43E-08	1.4E-08	1.4E-08	0.002052
Human Toxicity	kg 1,4-DB eq	0.351597	0.188111	0.177221	1348806

Aquatic Ecotoxicity	kg 1,4-DB eq	0.250254	0.104026	0.097272	615146.6
Terrestrial Ecotoxicity	kg 1,4-DB eq	0.00258	0.001424	0.001337	3867.404
Photochemical Oxidant Formation	kg C_2H_4 eq	6.2E-05	3.84E-05	3.32E-05	79.5086
Acidification	kg SO_2 eq	0.001386	0.000856	0.000769	1667.392

4.2. Normalization

Normalization (dimensionless scaling) is an optional step in the LCA methodology. Some characterization methods, such as CML, include normalization factors. Since comparing environmental impacts is one of the objectives of this study, the calculated impacts were normalized to facilitate comparison. After inputting the data into the software, which requires prior calculations, the impact categories were computed using the CML-baseline method. The normalization was performed using the *world2000* normalization factors provided by the CML-baseline method. The normalized results allow for the comparison of impact categories (Table 2).

Table 2: Normalized Environmental Profile per Kilogram of Produced Concrete

Impact Category	Z10-MK20-PP1	MK20-PP1.25	MK20	OPC-based concrete
Abiotic Resource Depletion	1.4E-14	8.35E-15	7.92E-15	7.01E-08
Abiotic Resource Depletion (Fossil Fuels)	8.93E-15	6.27E-15	3.95E-15	3.84E-09
Global Warming Potential	6.93E-15	4.5E-15	3.87E-15	3.63E-09
Ozone Layer Depletion	1.51E-16	6.15E-17	6.18E-17	9.05E-12
Human Toxicity	1.36E-13	7.3E-14	6.88E-14	5.23E-07
Aquatic Ecotoxicity	1.06E-13	4.4E-14	4.11E-14	2.6E-07
Terrestrial Ecotoxicity	2.36E-15	1.3E-15	1.22E-15	3.54E-09
Photochemical Oxidant Formation	1.69E-15	1.04E-15	9.03E-16	2.16E-09
Acidification	5.81E-15	3.59E-15	3.22E-15	6.99E-09

4.3. Interpretation of Life Cycle Impacts

Based on the calculations, particularly the normalization step, which renders the impacts dimensionless, the predicted impact categories can be compared. In Fig. 3, the normalized results for each type of concrete studied are presented.

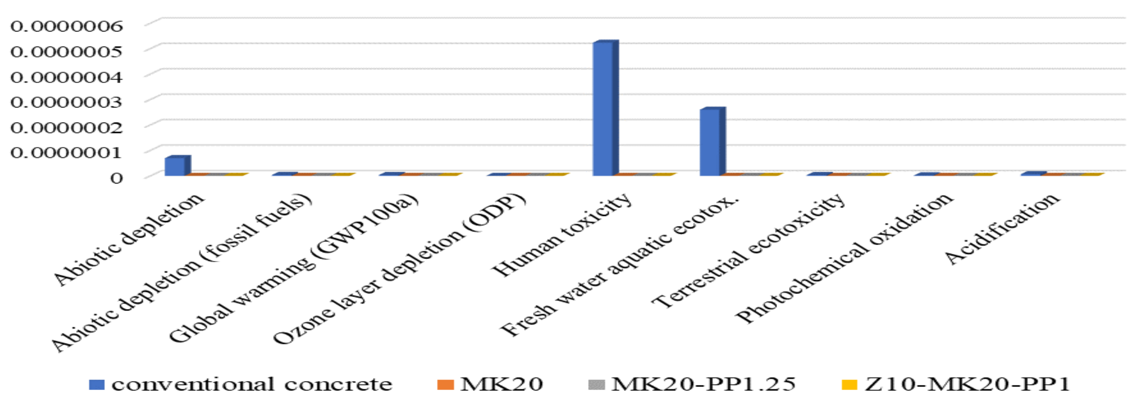

Fig. 3. Comparison of Environmental Impact Categories per Ton of Produced Concrete Based on Normalized Results

The environmental impacts calculated based on the Life Cycle Inventory (LCI) data for concrete production in all four scenarios were computed using the CML-baseline Life Cycle Impact Assessment (LCIA) method. As shown in Figure 3, conventional concrete has significantly higher environmental impacts across all categories compared to the other scenarios. To compare the three scenarios (MK20**,** MK20-PP1.25**,** and Z10-MK20-PP1). Figure 4 was created. According to this figure, MK20 concrete has the lowest environmental impact, while Z10-MK20-PP1 has the highest impact among the three scenarios.

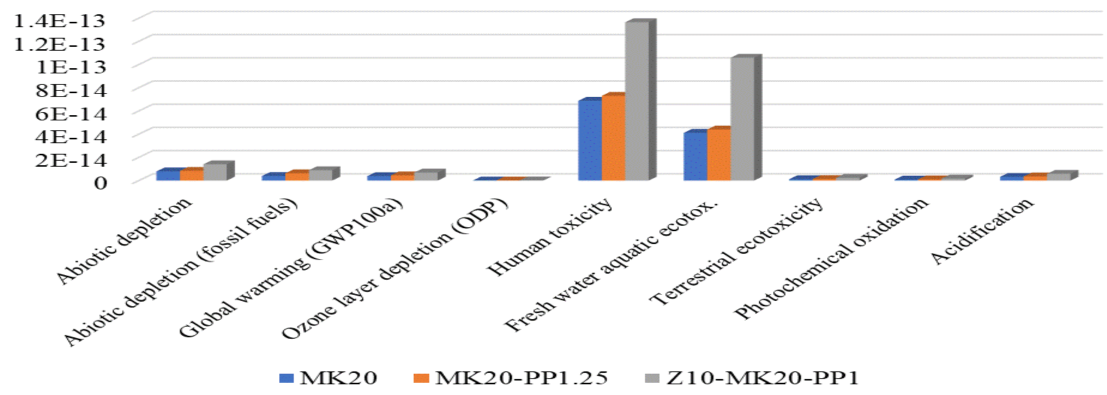

Fig. 4: Comparison of Environmental Impact Categories for Three Scenarios—MK20, MK20-PP1.25, and Z10-MK20-PP1

Based on **Figure 4**, the most significant environmental impacts in all three scenarios are as follows:

1. Human Toxicity
2. Aquatic Ecotoxicity
3. Abiotic Resource Depletion
4. Global Warming Potential
5. Acidification
6. Terrestrial Ecotoxicity
7. Photochemical Oxidant Formation
8. Ozone Layer Depletion

The key finding is that the comparison of the four concrete production scenarios demonstrates that conventional concrete has significantly higher environmental impacts compared to the proposed alternatives.

5. Conclusion

This study conducted a comprehensive Life Cycle Assessment (LCA) to evaluate the environmental sustainability of geopolymer concrete containing fly ash, metakaolin, and zeolite in comparison to conventional ordinary Portland cement (OPC)-based concrete. The results demonstrate that geopolymer concrete offers significant environmental advantages across multiple impact categories, including global warming potential, resource depletion, and toxicity. The key findings and implications of this research are summarized below:

1. **Reduction in Environmental Impacts**:

   - Geopolymer concrete, particularly the **MK20** formulation, exhibited the lowest environmental impacts across all categories, including global warming potential, abiotic resource depletion, and toxicity. This is attributed to the use of industrial by-products (fly ash and metakaolin) and natural materials (zeolite) as alternatives to OPC, which significantly reduce CO_2 emissions and energy consumption.

- Conventional concrete, on the other hand, had substantially higher environmental impacts, primarily due to the energy-intensive production of OPC and its associated greenhouse gas emissions.

2. **Normalized Comparison**:

The normalization of impact categories using the CML-baseline method revealed that geopolymer concrete outperforms conventional concrete in all scenarios. For example, the global warming potential of geopolymer concrete was up to 99% lower than that of conventional concrete, highlighting its potential as a sustainable alternative.

3. **Human and Ecotoxicity**:

Geopolymer concrete also showed significant reductions in human toxicity and ecotoxicity (both aquatic and terrestrial) compared to conventional concrete. This is particularly important for reducing the environmental and health risks associated with construction materials.

4. **Role of Alkali Activators**:

While geopolymer concrete offers clear environmental benefits, the study also identified the need to address the environmental impacts of alkali activators (e.g., sodium hydroxide and sodium silicate), which contribute to the overall footprint of geopolymer production. Future research should focus on optimizing activator usage or exploring alternative low-impact activators.

5.1. Implications for Sustainable Construction

The findings of this study have important implications for the construction industry, particularly in the context of global efforts to reduce carbon emissions and promote sustainable development. Geopolymer concrete, with its lower environmental impacts and comparable mechanical properties, represents a viable alternative to conventional concrete. Its use can contribute to:

- **Reducing Carbon Footprint**: By replacing OPC with industrial by-products and natural materials, geopolymer concrete can significantly lower the carbon footprint of construction projects.
- **Promoting Circular Economy**: The use of fly ash and other by-products aligns with the principles of a circular economy, turning waste materials into valuable resources.
- **Enhancing Durability**: Geopolymer concrete's superior chemical resistance and durability can extend the lifespan of structures, further reducing the need for resource-intensive repairs and replacements.

5.2. Recommendations for Future Research

While this study provides valuable insights into the environmental performance of geopolymer concrete, several areas warrant further investigation:

1. Long-Term Durability: Future studies should assess the long-term performance of geopolymer concrete under real-world conditions, including exposure to harsh environments.
2. Optimization of Mix Designs: Research should focus on optimizing the proportions of fly ash, metakaolin, and zeolite to further enhance the environmental and mechanical properties of geopolymer concrete.

3. Alternative Activators: Exploring low-impact or waste-derived alkali activators could further improve the sustainability of geopolymer concrete.
4. End-of-Life Considerations: Future LCAs should include the end-of-life phase to evaluate the recyclability and disposal impacts of geopolymer concrete.

5.3. Final Remarks

In conclusion, this study highlights the potential of geopolymer concrete as a sustainable alternative to conventional concrete, offering significant reductions in environmental impacts while maintaining comparable performance. By adopting geopolymer concrete, the construction industry can take a significant step toward achieving its sustainability goals and mitigating the environmental challenges associated with traditional concrete production. Further research and development in this field will be essential to fully realize the potential of geopolymer concrete and drive its widespread adoption in the construction sector.

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