JURNAL ONLINE SKRIPSI
MANAJEMEN REKAYASA KONSTRUKSI POLINEMA

Journal homepage: http://jurnal.polinema.ac.id/ **ISSN: 2722-9203 (media online/daring)**

LITERATURE STUDY OF THE ENVIRONMENTAL IMPACT ASSESSMENT AND LIFE CYCLE OF GEOPLYMER MORTAR MATERIAL AS A LOW-CARBON ALTERNATIVE

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ABSTRACT

The manufacturing of intensive cement requires a lot of energy, which leads to large greenhouse gas (GHG) emissions, and the conventional concrete (CC) is notorious for having a big environmental impact. This study offers a thorough analysis of the literature on the life cycle and environmental impact evaluation of geopolymer mortar materials, investigating them as a low-carbon substitute for conventional concrete. Concrete types covered by the analysis include self-healing geopolymer concrete (SHGPC), conventional concrete (CC), and geopolymer concrete (GC). The findings indicate that GC offers substantial environmental benefits over CC, particularly in terms of climate change mitigation and fossil depletion, due to the use of fly ash and silica fume. However, the chemical activators in GC, such as NaOH and Na_2SiO_3, have significant negative impacts on human health and freshwater ecosystems. Additionally, while SHGPC reduces global warming potential, it increases fossil fuel consumption and ozone depletion due to sodium silicate production and self-healing microcapsule synthesis. Transportation of raw materials like fly ash and silica fume also plays a crucial role in the overall environmental impact but can be minimized by sourcing locally. This review highlights the need for further research and development in optimizing geopolymer production processes, utilizing local materials, and enhancing self-healing technologies to promote sustainable construction practices.

Keywords : environmental impact assessment, geopolymer mortar, life cycle analysis, low-carbon alternative

1. INTRODUCTION

The rapid expansion of global populations and urban areas has increased the demand for sustainable infrastructure. Climate change has exacerbated a range of issues, including global warming, ecological disruptions, technological challenges, economic difficulties, and societal impacts (Abeydeera et al., 2019). As concerns about climate change rise, there is growing recognition of the need to reduce carbon emissions, particularly those arising from construction activities.

Concrete remains the most widely used building material, consisting of a mix of aggregates, water, and Portland cement. Its popularity is due to the local availability of ingredients, affordability, and relatively simple manufacturing technology. However, industrial progress and the construction sector have come under scrutiny due to their significant role in climate change. Portland cement, a key component in concrete, is a major source of CO2 emissions, accounting for about 7% of global carbon dioxide emissions (Kumar Mehta, 2001).

To mitigate the environmental impact of traditional cement, alternative materials like geopolymers are being explored. Geopolymers, created from fly ash—a byproduct of coal combustion—offer an eco-friendly alternative to Portland cement. These materials produce fewer greenhouse gas emissions, utilize industrial waste, and require lower production temperatures, which makes them more energy-efficient and environmentally friendly. Geopolymers also provide excellent durability, fire resistance, and long-term cost savings, supporting sustainable development by reducing negative environmental impacts and promoting ecosystem sustainability.

2. METHODE

A literature review was the methodology employed in this investigation. The procedures entail gathering and analyzing research journal articles about the life cycle and environmental effects of geopolymer mortar. In addition, the parameters that exerted influence were determined and examined. To enable the extraction of conclusions from this literature review, the outcomes of the analysis of every parameter will be compiled from all existing studies.

This study assesses the life cycle effects of geopolymer concrete, OPC concrete, recycled aggregate concrete, and recycled aggregate-based geopolymer concrete using the midpoint method of the CML 2001 technique. The analysis shows that compared to OPC concrete, the global warming potential of geopolymer concrete can be lowered by as much as 53.7%. Moreover, photochemical oxidant production and acidification potential are reduced by geopolymer concrete.

This study thoroughly examines the environmental effects of the life cycle assessment technique used in the manufacturing of geopolymer concrete. The majority of conventional geopolymer concrete varieties have a somewhat smaller global warming impact during manufacture than normal Ordinary Portland Cement (OPC) concrete, according to the literature.

The purpose of this study is to assess the environmental effects of geopolymer concrete, a more environmentally friendly alternative to traditional cement concrete, that contains fly ash and silica fume. This study compares the environmental effects of three different geopolymer concrete mixtures using life cycle assessment: there are three types of fly ash geopolymers: fly ash and silica fume geopolymer with only sodium hydroxide, fly ash and silica fume geopolymer containing sodium silicate and sodium hydroxide. Utilizing the Ecoinvent 3.0 database and the ReCiPe method in UMBERTO NXT software, a life cycle evaluation was carried out.

3. RESULT and DISCUSSION

Study of Existing Journals

A Life Cycle Impact Assessment of Recycled Aggregate Concrete, Geopolymer Concrete, and Recycled Aggregate-Based Geopolymer Concrete

Imtiaz, L.; Javed, M.F.; Kashif-ur-rehman, S.; Musarat, M.A.; Alaloul, W.S.; Nazir, K.; Aslam, F.. 2021

The parameters of the Life Cycle Impact Assessment (LCIA)

Tabel 1. Concrete ingredient life cycle inventory

Ingredient	Cement	Coarse Aggregate	Fine aggregate	Recycled Aggregate
Total Energy (MJ/kg)	2.973	0.0154	0.0136	0.00833
Emissions (kg)				
CO_2	0.614	0.00173	0.00095	0.00124
SO_2	0.0014	6.976 x 10^{-6}	1.99 x 10^{-6}	2.091 x 10^{-6}
CO	0.0026	0.001437	3.46 x 10^{-6}	2.394 x 10-6
NOx	0.00141	1.128 x 10^{-5}	7.25 x 10^{-6}	8.202 x 10^{-6}
PM < 10	0.000267	1.281 x 10^{-5}	1.1 x 10^{-5}	7.097 x 10^{-6}
NMVOC	0.000161	6.455 x 10^{-7}	6.4 x 10^{-10}	4.320 x 10^{-7}
NH_3	1.893 x 10^{-5}	-	3.37 x 10^{-9}	-
N_2O	1.357 x 10^{-6}	2.813 x 10^{-8}	3.29 x 10^{-7}	1.535 x 10^{-8}
CH_4	0.000655	6.979 x 10^{-7}	1.88 x 10^{-8}	3.629 x 10^{-7}

Source: Imtiaz et al., 2021

Life Cycle Inventory Results Parameters

The total energy required for sand production and transportation is 0.0136 MJ/kg. The table below shows the energy data for each material as well as the energy used for transportation.

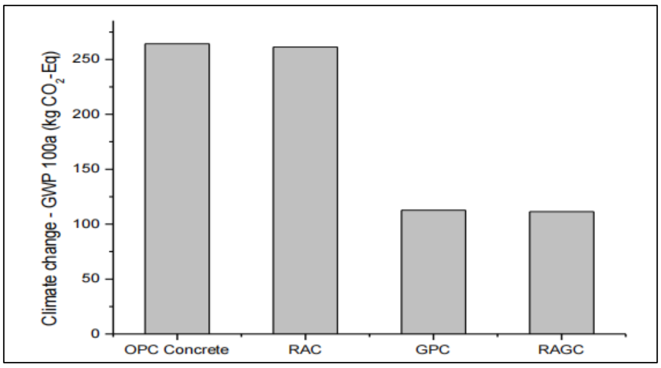
Table 1. Using a questionnaire survey, all substances'energy production

Ingredients	Production Energy (MJ/kg)	Transportation Energy (MJ/kg)
Fine Aggregates	0.00565	0.00795
Cement	2.918	0.055
Coarse Aggregates	0.00873	0.00630
Recycled Aggregates	0.00524	0.00309

Source: Imtiaz et al., 2021

Environmental Impact Analysis of Four Mixes Parameters

The analysis, which was conducted using Open LCA software, showed that using recycled aggregates or alternative binders can help lessen some environmental impacts. The effect category in the construction industry that



causes the most concern is the gobal warming wotential

Figure 1. Four combinations of GWP related to climate change (Imtiaz et al., 2021)

(GWP), which is primarily caused by greenhouse gas emissions and CO_2 production.

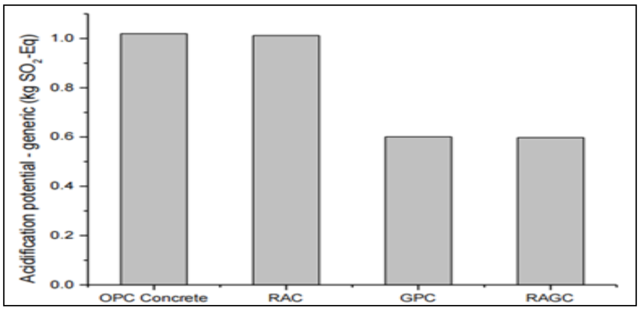


Figure 2. Four mixtures' potential for acidification (Imtiaz et al., 2021)

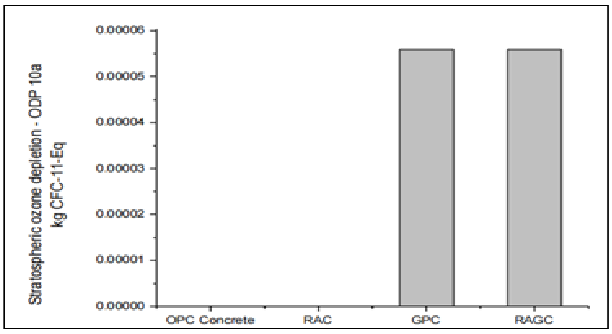


Figure 3. Four mixtures' potential to deplete the ozone layer (Imtiaz et al., 2021)

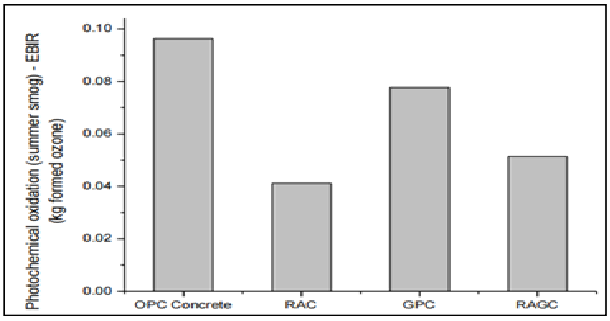


Figure 4. Four combinations undergo photochemical oxidation (Imtiaz et al., 2021)

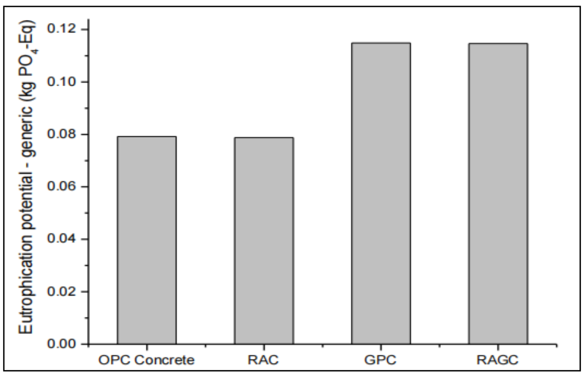


Figure 5. Four mixes' potential for eutrophication (Imtiaz et al., 2021)

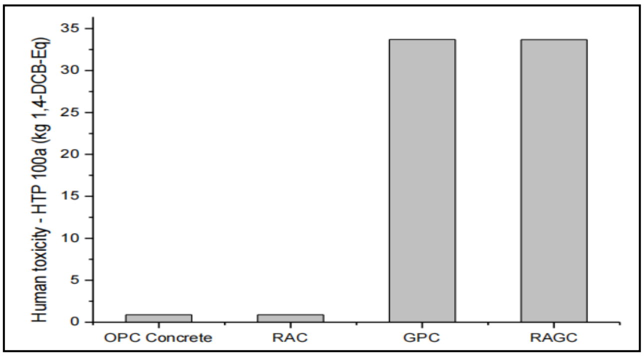


Figure 6. HTP of RAC, GPC, RAGC, and OPC concrete (Imtiaz et al., 2021)

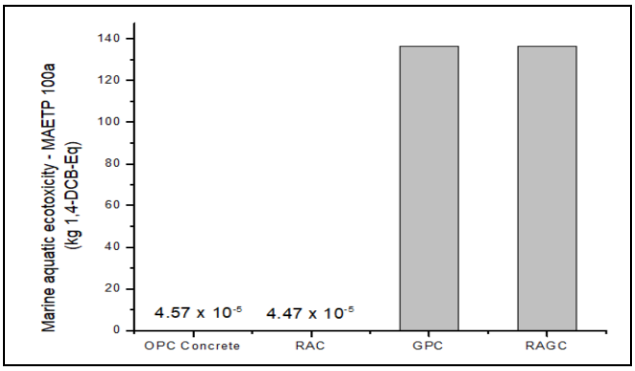


Figure 7. MAETP for RAC, GPC, RAGC, and OPC concrete (Imtiaz et al., 2021)

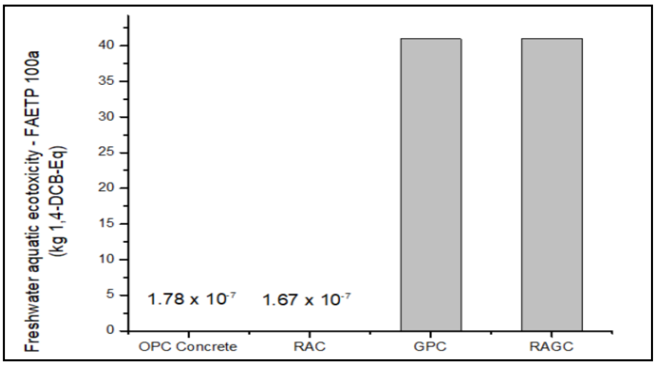


Figure 8. FAETP for RAC, GPC, RAGC, and OPC concrete (Imtiaz et al., 2021)

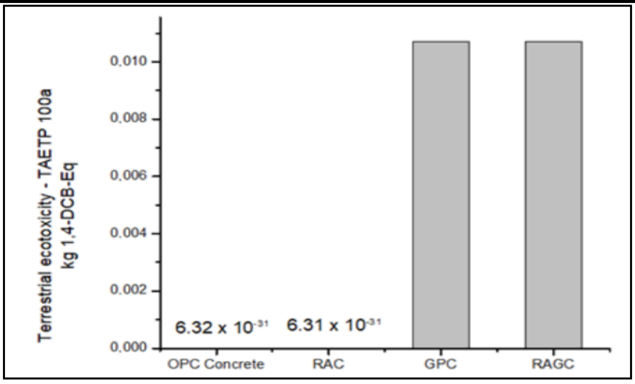


Figure 9. TAETP for RAC, GPC, RAGC, and OPC concrete (Imtiaz et al., 2021)

Based on the findings of this impact assessment analysis, OPC concrete has more potential impacts in the GWP, ADP, ETP, and POF categories than GPC and recycled blends. Comparing GPC with normal concrete can result in a considerable reduction of GWP of up to 57.34%. However, compared to ordinary concrete, GPC has greater impacts on other impact categories as FAETP, MAETP, stratospheric ozone depletion, HTP, and TAETP.

Reusing coarse aggregates in GPC and concrete can also lessen the overall environmental effect. Table 4.3 displays the impact potential values for each of the four combinations using the baseline CML approach.

Table 2 Category impacts using the CML baseline technique (Imtiaz et al., 2021)

Indicator	OPC Concrete	RAC	GPC	RAGC	Units
Climate Change – GWP	264.181	261.315	112.743	111.377	Kg CO_2-Eq
Acidification Potential – Generic	1.01904	1.01165	0.60119	0.59769	Kg SO_2-Eq
Freshwater Ecotoxicity	1.78 x 10^{-7}	1.677 x 10^{-7}	40.940	40.940	Kg 1,4-DCB-Eq
Eutropihcation Potential	0.07922	0.0788	0.11483	0.11463	Kg PO_2-Eq
Marine aquatic Ecotoxicity	4.575 x 10^{-5}	4.475 x 10^{-5}	136.45	136.45	Kg 1,4-DCB-Eq
Human toxicity	0.8952	0.8860	33.70	33.68249	Kg 1,4-DCB-Eq
Photocemical Oxidation	0.0963	0.0411	0.0777	0.0513	Kg ozone formed
Terrestrial Ecotoxicity	6.32 x 10^{-31}	6.30 x 10^{-31}	0.0107	0.0107	Kg 1,4-DCB-Eq
Stratospheric ozone depletion	0	0	5.59 x 10^{-5}	5.5 x 10^{-5}	Kg CFC-11-Eq

Source: Imtiaz et al., 2021

With an emphasis on possible environmental harm to the surrounding atmosphere, nine environmental indicators taken into consideration for this study were evaluated. In order of ranking, GWP came in first, then ODP, POF, HTP, ADP, EP, FAETP, MAETP, and TAETP. The most environmentally friendly mixture is RAGC, followed by GPC, RAC, and OPC mixtures based on the weighted average of all indicators across all mixtures. Table 5 displays the order of all mixes with respect to their environmental performance. This rating sheds light on the concrete mixtures that offer environmentally friendly options while effectively satisfying structural requirements. Depending on strength requirements, audiences can choose the appropriate aluminosilicate sources and activators, along with options for recycled or natural aggregates. According to the study's findings, RAGC is the best combination for addressing structural requirements and advancing sustainable development.

Table 4. Combinations ranked according to their performance in terms of environmental sustainability (Imtiaz et al., 2021)

Mixtures	Ranking
Recycled aggregate-based geoplymer concrete	1
Geoplymer concrete	2
Recycled aggregate concrete	3
Ordinary portland cement	4

Source: Imtiaz et al., 2021

Based on the findings of this impact assessment analysis, OPC concrete has more potential impacts in the GWP, ADP, ETP, and POF categories than GPC and recycled blends. Comparing GPC with normal concrete can result in a considerable reduction of GWP of up to 57.34%. However, compared to ordinary concrete, GPC has greater impacts on other impact categories as FAETP, MAETP, stratospheric ozone depletion, HTP, and TAETP. This is because GPC contains alkaline activators such as silicate sources. Reusing coarse aggregates in GPC and concrete can also lessen the overall environmental effect. Table 3 displays the impact potential values for each of the four combinations using the baseline CML approach.

A Review of Current Research Trends and an Environmental Assessment of the Production of Concrete Using Geoplymer

G. Habert.; N. Roussel.; J.B. d'Espinose de Lacaillerie. 2011

This study evaluates the environmental impacts of life cycle assessment techniques in geopolymer concrete production. Geopolymer concrete generally has a lower global warming impact compared to Ordinary Portland Cement (OPC) concrete, but it exhibits higher environmental impacts in other categories due to the significant effects of sodium silicate solution. Geopolymer concrete made from fly ash or granulated blast furnace slag (GBFS) has lower environmental impacts compared to those made from metakaolin, although their global warming impacts are similar to those of OPC concrete.

a. Environmental Impact Calculation Parameters

The CML01 method was used to assess environmental impacts across ten categories, including global warming and acidification. Results are shown in tables comparing the impacts of different concrete materials.

b. Environmental Analysis of Fly Ash-Based Geopolymer Concrete Compared to OPC Concrete

Fly ash-based geopolymer concrete can reduce global warming potential by up to 45% compared to OPC concrete. However, this reduction is not drastically different from current technology improvements in cement, indicating that while promising, it is not a breakthrough technology for CO2 reduction in concrete production.

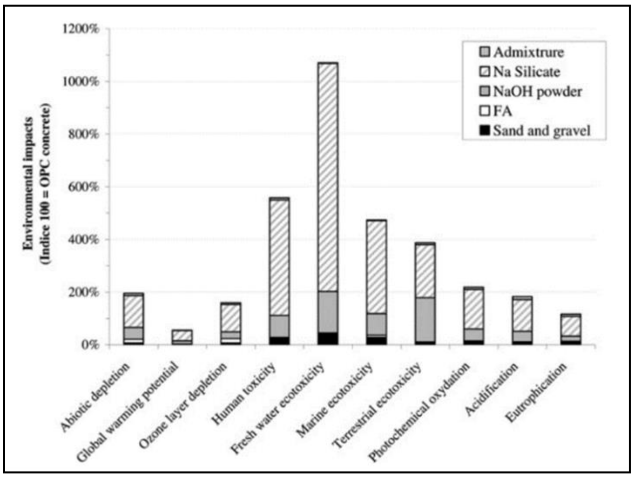


Figure 10. Fly ash-based geopolymer concrete's eco-profile in comparison to OPC-based concrete. While the existing concrete binder is manufactured with 70% CEM I and 30% fly ash, the pure OPC concrete binder is made completely with CEM I (Habert et al., 2011)

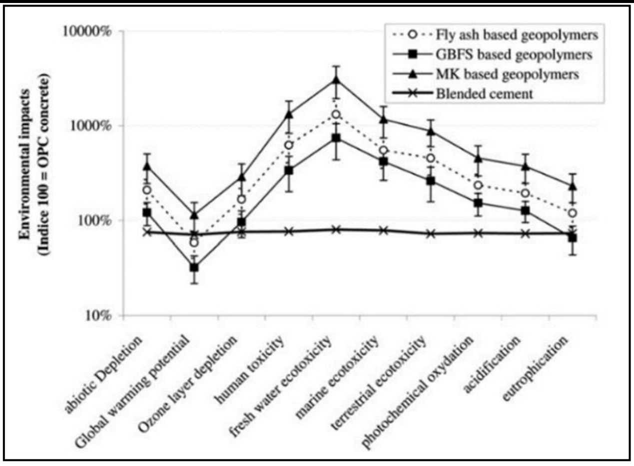


Figure 11. Various geopolymer concrete kinds' eco-profiles in comparison to OPC-based concretes. While conventional concrete binder is often created with 70% CEM I and 30% mineral addition, pure OPC concrete binder is made exclusively with CEM I (Habert et al., 2011)

c. Environmental Profile of Various Geopolymer Types

The study compared the environmental impacts of fly ash, GBFS, and metakaolin-based geopolymer concrete. Fly ash and GBFS-based geopolymers have lower global warming impacts compared to metakaolin, but GBFS-based concrete performs worse in acidification and ozone depletion compared to OPC.

d. Impact of Allocation Process on Geopolymer Concrete

The results indicate that geopolymer concrete generally has a higher environmental impact than blended concrete in categories like abiotic depletion and marine ecotoxicity. However, fly ash-based geopolymer concrete may have a lower impact on global warming if fly ash is considered a waste. GBFS-based geopolymers show varying impacts depending on the allocation method used.

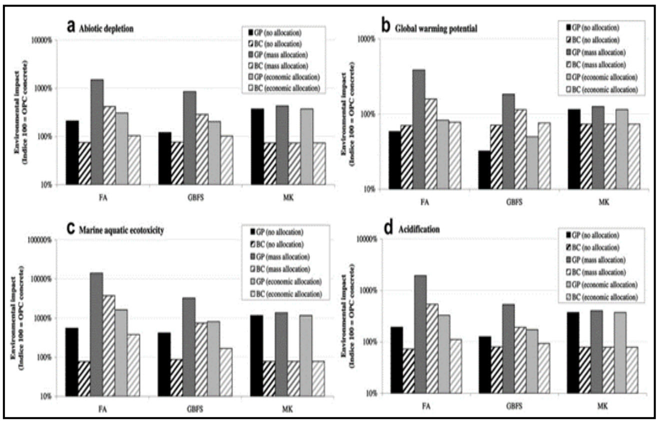


Figure 12. A comparison of the effects of different types of concrete a) Abiotic depletion, b) global warming potential, c) marine ecotoxicity, and d) acidification are the four main

issues. The three mineral additives under study are fly ash (FA), blast furnace slags (GBFS), and metakaolin (MK). (Habert et al., 2011)

Environmental Impact Assessment of Geopolymer Concrete Based on Fly Ash and Silica Fume

Anshuman Srivastava; Bajpai; Choudhary; Singh Sangwan; Manpreet Singh. 2020

The objective of this research is to evaluate the environmental impact of geopolymer concrete, which uses fly ash and silica fume as more eco-friendly alternatives to traditional cement concrete. The study uses life cycle assessment to compare three geopolymer mixtures: with sodium hydroxide, sodium silicate and sodium hydroxide, and fly ash and silica fume only. The Ecoinvent 3.0 database and ReCiPe method in UMBERTO NXT software were used. Findings alkaline activators and cement are major environmental concerns. Geopolymer concrete has a lower global warming potential compared to traditional cement concrete. The least harmful is the fly ash-silica fume geopolymer without sodium silicate. Transportation of raw materials increases environmental impact. Geopolymer concrete can reduce costs by 10.87% to 17.77%.

a) Assessment Parameters for End Points:

Concrete lifecycle impacts human health significantly. Conventional concrete (CC) has the highest impact due to greenhouse gas emissions and energy use in cement production.

Geopolymer concrete, using coal fly ash, has lower greenhouse gas emissions and addresses fly ash disposal issues. Substituting silica fume for sodium silicate reduces environmental impact.

Endpoint scores for CC, GC, G_SF_S, and G_SF are 68.52, 42.56, 39.02, and 36.58, respectively. This results in environmental effect reductions of 42.37%, 47.54%, and 51.10% for GC, G_SF_S, and G_SF compared to CC.

b) Contributing Elements to Environmental Effects:

For CC, cement is the main contributor to environmental damage.

For geopolymer concrete, chemical activators (NaOH and Na_2SiO_3) have significant impacts, especially on human health.

Disposal of geopolymer concrete slightly affects the environment more than CC, mainly due to alkaline contamination.

c) Midpoint Assessment Parameters:

Geopolymer concrete shows reduced impacts on particulate matter, fossil depletion, and climate change compared to CC.

G_SF has the lowest environmental impact across categories. Geopolymer mixes generally have less impact on climate change, fossil fuel depletion, and water depletion.

d) Transport Distance Impact:

Transportation of raw materials significantly affects the environmental impact of geopolymer concrete. G_SF_S has the highest variation (29.01%) in environmental impact due to transport, followed by G_SF (23.34%), GC (20.83%), and CC (9.71%).

Critical Transport Distances:

Geopolymer mixes have critical transport distances for raw materials to maintain lower GHG emissions compared to cement. The critical distances vary by component.

Table 5. The geopolymer mixes' critical transport distance (kilometers) for the constituents (Bajpai et al., 2020)

Concrete type	Silica fume	Fly ash	Na2SiO3	NaOH	Gravel	Sand
GC	-	3363.20	946.43	946.43	439.41	439.41
G_SF_S	3773.37	3279.04	922.74	922.74	428.21	428.41
G_SF	3704.58	3219.27	-	905.92	420.60	420.60

Sensitivity Analysis:

Transportation impacts geopolymer concrete more than CC, with a maximum relative increase in emissions of 3.48%. Local context can influence these impacts.

Table 6. Emissions' sensitivity to transportation distance (Bajpai et al., 2020)

	Concrete Type			
	GC	CC	G_SF	G_SF_S
Relative increase in emissions (%) (5% increase in average distances)	2.68	0.87	1.11	3.48

Self-Healing Geopolymer Concrete's Life Cycle Assessment

Arnel B. Beltran.; Raymond R. Tan.; Jerome Ignatius T. Garces.; Ithan Jessemar Dollente.; Michael Angelo B. Promentilla. 2021

This study evaluates the environmental impact of adding self-healing microcapsules to geopolymers, a sustainable alternative to ordinary Portland cement (OPC). The assessment shows that self-healing geopolymer concrete (SHGPC) has lower global warming potential than OPC but worse performance in other areas. Microcapsule and alkali activator production are major impact factors. Improvements are needed to enhance the environmental performance of self-healing geopolymers.

a. Results of Impact Assessment

The study compares environmental impacts of geopolymer concrete (GPC) and SHGPC using the CML-IA method. SHGPC shows higher impacts in most categories than GPC, especially ozone depletion potential (ODP), with microcapsules significantly increasing GPC's environmental burden.

Table 7. Impact assessment results (Garces et al., 2021)

Impact Category	GPC	OPCC	Microcapsules`	SHGPC
ADPF, MJ	2933.205	757.42	168.8375	6428.252
AP, kg SO_2 eq.	1.6067	0.8217	0.0299	2.2264
EP, kg PO_4 eq.	0.1337	0.1647	0.0043	0.2226
GWP100, kg CO_2 eq.	285.0813	454.5937	6.3807	417.1633
ODP, kg CFC-11 eq.	2.24×10^{-8}	4.66×10^{-9}	1.28×10^{-7}	2.66×10^{-6}
POCP, kg C_2H_4 eq.	0.0930	0.0449	0.0035	0.1649

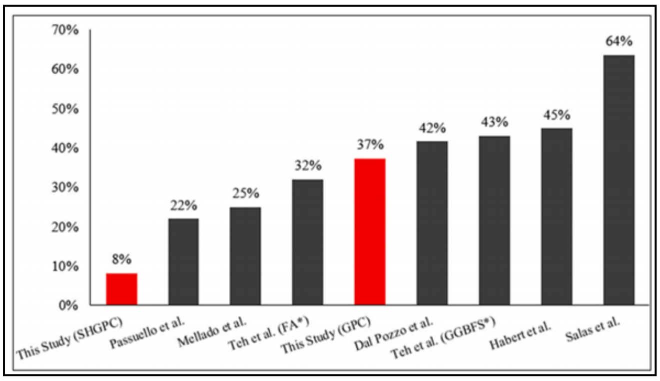


Figure 13. Comparison of various research' findings about the GWP decrease of geopolymer concrete (Garces et al., 2021)

b. Contribution Analysis

For ordinary Portland cement concrete (OPCC), cement is the largest contributor to environmental impacts, particularly in global warming potential (GWP). For GPC, alkali activators, especially sodium silicate, are the main contributors. Self-healing microcapsules also significantly impact the environment, particularly in ODP and abiotic depletion of fossil fuels (ADPF).

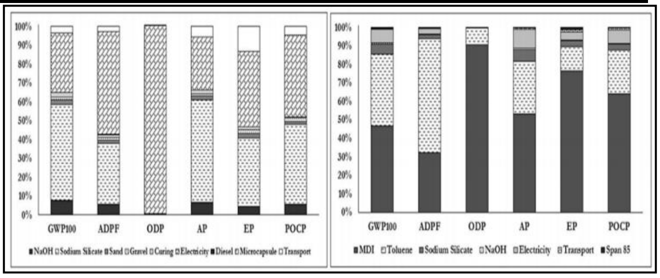


Figure 14. Analysis of contributions for both (a) SHGPC (b) and self-healing microcapsules (Garces et al., 2021)

c. Recommendations

Future research should focus on using high Si/Al ratio waste products and alternative production methods to reduce environmental impacts. Investigations into microcapsule production and self-healing performance are necessary to balance the initial environmental costs with long-term benefits such as reduced maintenance and increased durability.

Grouping and Analysis of Influencing Parameters

Environmental Impact Assessment Results

- Bajpai et al. (2020): GC, G_SF_S, and G_SF have lower environmental impacts compared to CC, with G_SF showing the most reduction.
- Garces et al. (2021): SHGPC increases environmental impacts in all categories compared to GPC, particularly ozone depletion and fossil fuel use.
- Imtiaz et al. (2021): Recycled materials and green technologies can significantly cut CO2 emissions and other environmental effects.
- Habert et al. (2011): Optimized geopolymer-based concrete can reduce GHG emissions and environmental impacts.

Environmental Impacts Due to Transportation Distance

- Bajpai et al. (2020): Transportation of raw materials like fly ash and silica fume affects GC, though overall concrete mix ratings remain unchanged.
- Garces et al. (2021): Transportation impacts are less significant than alkali activator production and microcapsule synthesis but still important.
- Imtiaz et al. (2021): Raw material transportation, especially over long distances, significantly adds to CO2 emissions.
- Habert et al. (2011): Reducing raw material transportation distances and sourcing locally can lower environmental impacts.

Material and Activity Effects

- Bajpai et al. (2020): Cement production is energy-intensive and generates greenhouse gases, making conventional concrete the most environmentally harmful. Geopolymer concrete (GC) has lower emissions with fly ash and silica fume.

- Garces et al. (2021): GPC has higher fossil fuel use and ozone depletion potential than OPCC but 37% lower global warming potential. Self-healing technology exacerbates these issues.
- Imtiaz et al. (2021): Using recycled materials and green technologies in concrete can reduce CO2 emissions.
- Habert et al. (2011): Reducing cement and using sustainable materials like slag and fly ash can mitigate environmental impacts.

Contributing Factors to Negative Impacts
- Bajpai et al. (2020): NaOH and Na_2SiO_3 in GC and cement in CC are major environmental concerns.
- Garces et al. (2021): Sodium silicate and microcapsule synthesis are key contributors to SHGPC's environmental impact.
- Imtiaz et al. (2021): Raw material production and manufacturing processes mainly impact CO2 emissions and energy use.
- Habert et al. (2011): Reducing cement use and optimizing waste material utilization can significantly cut negative impacts.

Midpoint Assessment Parameters
- Bajpai et al. (2020): GC is less harmful to climate change and fossil fuel depletion than CC but worse in human toxicity and freshwater ecotoxicity.
- Garces et al. (2021): GPC lowers global warming potential but increases fossil fuel consumption and ozone depletion, especially with self-healing microcapsules.
- Imtiaz et al. (2021): Emphasizes using recycled materials and low-energy technologies to reduce environmental impact.
- Habert et al. (2011): Efficient production of chemical activators can enhance the environmental benefits of geopolymer concrete.

Contribution Analysis
- Bajpai et al. (2020): Cement in CC and chemical activators in GC are primary environmental impact contributors. Reducing cement content and using aluminosilicate waste materials can mitigate impacts.
- Garces et al. (2021): Sodium silicate production and microcapsule synthesis are major environmental burdens for SHGPC. Greener alternatives can reduce these impacts.
- Imtiaz et al. (2021): Raw material production and manufacturing are major factors in environmental impact, especially for CO2 and energy use.
- Habert et al. (2011): Using alternative materials and reducing cement content in mixes can significantly cut environmental impacts.

4. CONCLUSION

Research on concrete types (Bajpai et al., 2020; Garces et al., 2021; Habert et al., 2011; Imtiaz et al., 2021) reveals:

1. Conventional Concrete (CC):
   Highly detrimental to the environment due to energy-intensive cement production and high greenhouse gas emissions.
2. Geopolymer Concrete (GC):
   More eco-friendly than CC, reducing greenhouse gases and fossil fuel use by substituting cement with fly ash and silica fume.
3. Chemical Activators:
   Despite GC's benefits, activators like NaOH and Na_2SiO_3 negatively affect health and ecosystems.
4. Self-Healing Geopolymer Concrete (SHGPC):
   Has lower global warming potential but higher impacts on fossil fuel consumption and ozone depletion due to sodium silicate and microcapsule production.
5. Raw Material Transportation:
   Impacts can be reduced by sourcing materials locally.
6. Health and Safety:
   Safer chemical activators are needed to address health and environmental risks.
7. Cost and Availability:
   The cost and availability of raw materials like fly ash are concerns, with ongoing research into alternatives.
8. Long-Term Durability:
   Geopolymers' performance over time under various conditions needs further study.
9. Mix Design Optimization:
   Finding the best mix for performance and environmental benefits is a challenge.
10. Scaling Up:
    Transitioning from lab to industrial production involves technical and logistical issues.
11. Standardization:
    Lack of standards and regulations limits the adoption of geopolymers in construction.

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