

Eco-Friendly Composites—Environmental Assessment of Mine Tailings-Based Geopolymers [†]

Kinga Korniejenko ^{*}, Beata Figiela , Michał Łach  and Barbara Kozub 

Faculty of Materials Engineering and Physics, Cracow University of Technology, 24 Warszawska Street, 31-155 Cracow, Poland; beata.figiela@pk.edu.pl (B.F.); michal.lach@pk.edu.pl (M.Ł.); barbara.kozub@pk.edu.pl (B.K.)

^{*} Correspondence: kinga.korniejenko@pk.edu.pl; Tel.: +0048-609974988

[†] Presented at the 2nd International Conference on Raw Materials and Circular Economy “RawMat2023”, Athens, Greece, 28 August–2 September 2023.

Abstract: Resource efficiency is one of the basic principles of a circular economy (CE). It can be achieved by finding replacements for natural raw materials using anthropogenic raw materials, including by-products from industrial processes and waste materials. In the case of the Polish economy, one possible source is the mining tailings from hard coal exploration and also the waste material from post-mining heaps. The main objective of this work is to present the results of an environmental analysis of geopolymers based on mine tailings. Two geopolymer materials were compared using life cycle assessment (LCA) methodology principles. One of them was based on metakaolin, and the second on industrial waste, mainly from coal shale, as a waste product of hard coal mining. The results show that replacing the original material with alternatives such as metakaolin from mine tailings, reduces the environmental impact, including CO₂ emissions. The main findings can be helpful in the implementation of CE, especially the development of sustainable materials, which is one of the crucial elements of introducing closed loops into practice.

Keywords: geopolymer; mine tailing; environmental assessment; circular economy; sustainable development



Citation: Korniejenko, K.; Figiela, B.; Łach, M.; Kozub, B. Eco-Friendly Composites—Environmental Assessment of Mine Tailings-Based Geopolymers. *Mater. Proc.* **2023**, *15*, 94. <https://doi.org/10.3390/materproc2023015094>

Academic Editors: Antonios Peppas, Christos Roumpos, Charalampos Vasilatos and Anthimos Xenidis

Published: 4 December 2024



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1. Introduction

One of the important elements related to the implementation of a circular economy (CE) is saving natural resources [1,2]. This task is mainly connected with finding replacements for natural raw materials using anthropogenic raw materials, including by-products from industrial processes and waste materials [1,3]. This kind of solution is especially important for the construction industry, where the use of waste products to produce construction materials is a required development track. It is applied, for example, to the possibility of using fly-tipped waste for concrete [4] or working on alternative materials made from industrial waste [5,6]. Among the alternative materials, the most suitable for a CE purpose seems to be geopolymers [5,6]. Firstly, they can be used for the production of different kinds of by-products and waste materials; secondly, they have a low environmental burden, including low gas emissions during their production and a low energy consumption [7,8]. One of the possibilities is the usage of mine tailings in the geopolymerization process [9,10]. These kinds of materials have reasonable mechanical properties and effectively close material loops in the recycling process. Moreover, for some by-products, such as coal shale, it is possible to use them for the production of insulation materials with high fire resistance for the construction industry, which means there is a possible way to up-cycle, with the correct geopolymerization process [11].

A quick review was carried out using the Scopus database and searching for the following keywords combined together: “geopolymer” and “LCA”. “LCA” was selected as the most popular and complex method of assessment of the environmental influence

of certain materials. The search results in the Scopus database provided 88 documents (Figure 1). Based on the search results, the most relevant publication was analyzed as a gap in the literature.

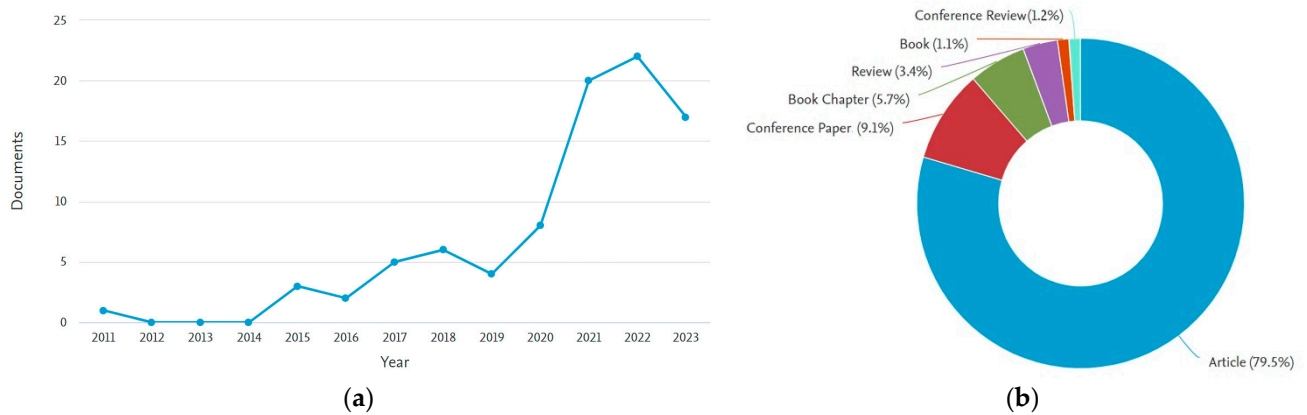


Figure 1. Results of the search in the Scopus database: (a) published documents by year; (b) published documents by type [12].

The analysis of the search results shows that this research topic is very new. The first publications were in 2015, excepting one in 2011 (Figure 1a). Most of them were original research (Figure 1b) and less than 5% were review articles indexed in the Scopus database in this research area.

Among the search results, the most recent publications are summarized in Table 1. Most of them show the positive influence of replacement concrete, based on ordinary Portland cement but using geopolymer concrete [7,13–19].

Table 1. Summary of environmental assessment of geopolymer concrete.

Functional Unit	Data Source	Impact Considered	Conclusion	Reference
1 m ³ high-strength self-compacting geopolymer concrete composites	The literature and calculations	Energy, greenhouse gas (GHG) emissions, and cost	GHG emissions can be reduced by between 5 and 10%, compared to emissions from Ordinary Portland Cement (OPC) concrete.	[7]
1 m ³ of construction and demolition waste (CDW)-based GP structure	ISO 14040 and 14044, GaBi software, the literature, and calculations	CO ₂ footprint	GP-based 3D-printed construction resulted in the lowest global warming potential of 488 [kg CO ₂ eq] compared to 595.6 [kg CO ₂ eq] for OPC-based structures and 533.7 [kg CO ₂ eq] for conventional GP-based structures.	[13]
1 m ³ GP concrete	Ecoinvent, Simapro LCA, and IMPACT 2002+ [®]	Mainly energy	50–60% reduction in environmental impacts, as compared to OPC concrete	[14]
1 m ³ concrete	The literature and calculations	Energy, GHG emissions, and cost	In greenhouse applications, GP concretes are more efficient than OPC concretes	[15]
1 m ³ GP binder	GaBi software and the literature	Global warming potential, acidification potential, eutrophication potential, ozone layer depletion potential, ecotoxic air	The global warming potential for the geopolymer binder produced is 21% less than that of OPC. The source of electricity plays an important role in this analysis.	[16]

Table 1. Cont.

Functional Unit	Data Source	Impact Considered	Conclusion	Reference
1 m ³ concrete	ELCD, ecoinvent, and the literature	Global warming potential and economic assessment	The LCA showed a lower environmental impact of GP concrete in comparison to traditional concrete.	[17]
1 m ³ concrete	ISO 14040 and 14044, Ecoinvent, GaBi software, the literature, and calculations	CO ₂ footprint	The pretreatment of industrial waste has a slight environmental impact, but their usage significantly reduces the potential for global warming.	[18]
1 m ³ concrete of 40 MPa and 60 MPa	The literature and calculations	Energy, CO ₂ footprint	The ingredients of the activating solution have a significant impact on energy and CO ₂ emissions	[19]

However, the scale of this influence is strictly dependent on local factors [16,19] and applied technology [13]; the previous investigation shows that, from an environmental point of view, this research topic should be in development. Overall, the small number of indexed publications, based on mainly original research, shows that this topic is worth investigating. Moreover, it is worth noting that environmental assessments of geopolymers can have significantly different results and strongly depend on the locally available materials. The presented research is a trial of the environmental assessment of two geopolymers—one of them was based on metakaolin and the second on industrial waste, mainly from coal shale, as a waste product of hard coal mining.

2. Materials and Methods

Two geopolymer materials were compared, taking into consideration their energy consumption and GHG emissions. One of them was based on metakaolin and the second on industrial waste, mainly from coal shale, as a waste product of hard coal mining. Data taken from previous literature, supported by some calculations, were used for the estimation of the environmental influence. The analysis took into consideration the cradle-to-gate model.

The estimated values for a range of ingredients are presented in Table 2.

Table 2. Energy consumption and GHG emissions.

Material	Energy Consumption [GJ/t]	GHG Emission—CO ₂ eq [t CO ₂ /t]	Source of Data
Metakaolin	2.5	0.33	[19,20]
Mine tailings	1.26	0.08	Own calculation ¹
River sand	0.00085	0.02	[21]
Sodium hydroxide	20.5	1.915	[19]
Sodium silicate	5.371	1.222	[19]

¹ Parameters: distance from mining: 100 km, energy in crushing and milling, energy for calcination 4 h in 750 °C.

The geopolymers were made with quartz sand. As activators, approximately 10 M sodium hydroxide and an aqueous sodium silicate solution were used. Moreover, tap water was also used to prepare the solution. For both geopolymers, the proportions were the same (Table 3).

The energy consumption during the preparation of the cast elements was related to the mixing process—this lasted about 15 min, with an energy consumption of 60 kWh—and the curing process, which occurred in an oven at 75 °C for 8 h, with an energy consumption of 192 kWh. The total energy consumption for material preparation was 252 kWh (9.072×10^5 kJ). The energy consumption per 1 kg was 907.2 kJ/kg (or 0.9072 GJ/t). The emission of GHGs for this level of energy consumption was estimated using the average GHG emission levels for energy consumption in Poland, derived mainly from fossil fuels [22].

Table 3. Mixture proportions for geopolymers [kg/m³].

Material	Metakaolin-Based Geopolymer	Mine Tailing-Based Geopolymer
Metakaolin	870	0
Mine tailings	0	870
River sand	870	870
Sodium hydroxide	50	50
Sodium silicate	487	487
Water	159	159

3. Results and Discussion

The energy consumption of two types of geopolymers is compared in Figure 2. The analysis shows that geopolymers based on mine tailings have lower embodied energy. This is because the mine tailing is a by-product of the mining industry and factors related to excavations were not taken into account. The main component responsible for energy consumption is sodium silicate. To reduce this value, the method of material activation should be modified [18].

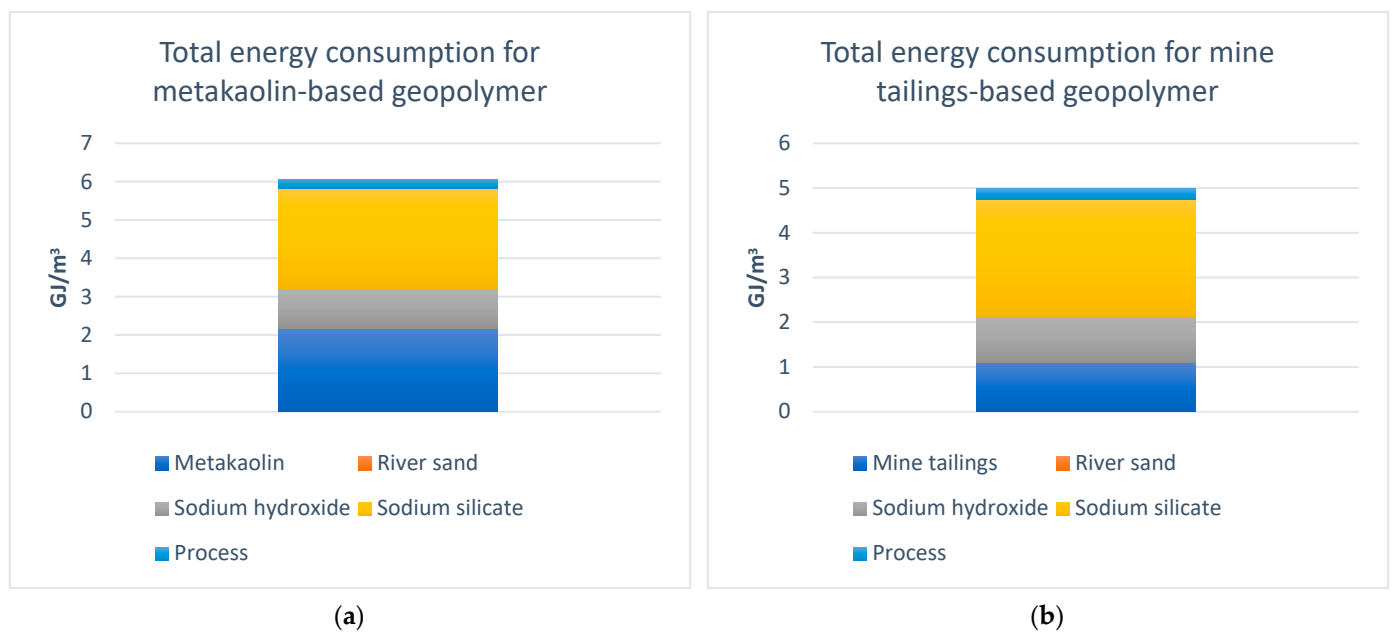


Figure 2. Total energy consumption: (a) metakaolin-based geopolymer; (b) mine tailing-based geopolymer.

The GHG emissions for two types of geopolymers are presented in Figure 3. However, the GHG emissions are lower for the mine tailing-based geopolymer; the most important factor in this case is the energy used in the process of geopolymerization. The environmental influence can be reduced by changing the source of this energy to a renewable source [16].

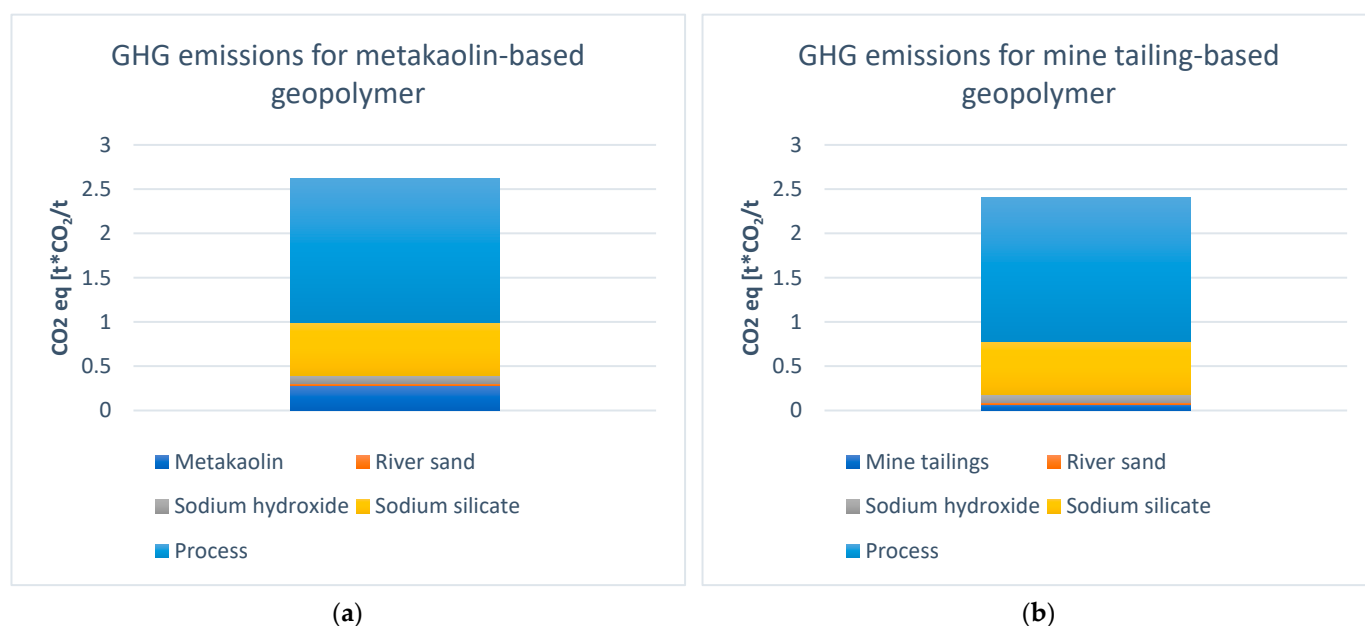


Figure 3. GHG emissions: (a) metakaolin-based geopolymer; (b) mine tailing-based geopolymer.

4. Conclusions

The results show that replacing the original material with alternatives such as metakaolin or mining tailings reduces the environmental impact of these materials. However, while the replacement of raw materials with industrial by-products reduces energy consumption and GHG emissions, it does not play crucial role in reducing the environmental burden. In the case of energy consumption, the most important role is played by the activator. The replacement of silica silicate or the reduction of the amount used can significantly reduce energy consumption levels. In the case of GHG emissions, the most important factor is the level of energy consumption during the process and the energy sources used. Changing the energy source from fossil fuels to renewable sources can significantly decrease GHG emissions. The presented conclusions are helpful for the effective design of more environmentally friendly materials.

Author Contributions: Conceptualization, K.K. and B.K.; methodology, B.F.; software, K.K.; validation, B.K. and M.L.; formal analysis, M.L.; investigation, K.K. and B.F.; writing—original draft preparation, K.K. and B.F.; writing—review and editing, B.K. and M.L.; visualization, K.K.; supervision, K.K.; project administration, K.K.; funding acquisition, K.K. All authors have read and agreed to the published version of the manuscript.

Funding: The works were carried out as part of the project: “Geopolymer foams with low thermal conductivity produced on the basis of industrial waste as an innovative material for the circular economy”, which is financed by the National Center for Research and Development under the LIDER X program. Grant No.: LIDER/31/0168/L-10/18/NCBR/2019.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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