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Potential Use of Construction Waste for the Production of Geopolymers: A Review †

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Abstract: In recent decades, geopolymer concrete has often been viewed as an alternative to traditional concrete. Although its comparatively lower production of greenhouse gas emissions during a lifecycle is usually mentioned at the top of the list of benefits, the possibility of using various waste materials in its production is a clear advantage as well. This literature review summarizes and analyses the existing information on the different available construction wastes for the production of geopolymer and foamed geopolymer concrete and analyzes the curing conditions, constituents in the aluminosilicate precursor, mechanical properties, and the activator type. As part of the literature review, the use of autoclaved aerated concrete and brick wastes has been evaluated. Autoclaved concrete has been chosen because it is a typical low-strength, cement-based construction material and demolition waste that is currently disposed of in landfills, making it quite a challenge for direct use as a supplementary cementitious material. On the other hand, brick waste, one of the most common construction wastes, can be feasibly used in the form of brick dust. This literature review uses data from randomly selected studies.

Keywords: construction waste; geopolymer; porous geopolymers; waste clay bricks; autoclaved aerated concrete waste

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1. Introduction

The construction industry is the single largest energy consumer in the European Union (EU), as well as one of the largest carbon dioxide (CO_2) emitters (mainly from construction, demolition, and renovation) [1]. Over the past two decades, countless studies have been conducted on ways to improve the current situation. One of the researched areas relates to the development of alternatives for traditional concrete, which is a widely used material for construction. Demand for ordinary Portland cement-based concrete (hereafter referred to as OPC-based concrete) is continuously increasing [2]. Unfortunately, OPC-based concrete requires a considerable amount of ingredients and resources which are acquired through mining and exhaustive processing, causing immense quantities of greenhouse gas emissions to be sent into the atmosphere [3,4]. This review examines geopolymer as a promising alternative because it not only allows for a reduction in CO_2 emissions and water consumption in comparison with OPC-based concrete production (the former by 80% [5]), but it can also be produced effectively using various waste materials [6]. A majority of studies about geopolymer concrete focus on using high amorphous precursors, such as fly ash, silica fume, and ground granulated blast-furnace slag [2,7], which are industrial byproducts. These are abundantly available in some countries. However, in many, they are either unavailable or available only in small, limited quantities [8]; therefore, it is always useful to search for new, suitable, and preferably local materials for geopolymer production. By analyzing the literature, regulatory acts, and studies, it was found that there is a large amount of construction waste in the European Union (and also in Latvia) which is currently being disposed of in landfills or reused only in small quantities. Therefore, within the framework of this review, much attention is paid to widely available and local construction waste (clay brick waste and aerated concrete waste) in order to evaluate the possibilities of their use for the production of geopolymers.

2. Review Methodology

Data from peer-reviewed journal articles were mainly used to analyze the existing information on the production of geopolymers using various construction wastes, including their mechanical and thermal properties and the porosity of samples. The related literature was searched for in Scopus and Web of Science databases using the search keywords "autoclaved aerated concrete waste", "clay brick waste", and "construction waste". Once the search results were obtained, only the articles from the last 6 years were selected for use. The articles, which were used in the introduction section, had no restrictions related to their publication date.

3. Autoclaved Aerated Concrete Waste

Autoclaved aerated concrete (AAC) is a combination of silica sand, lime, cement, water, and an expansion agent. It is relatively lightweight and has lower thermal conductivity and lower shrinkage in comparison to traditional concrete [9]. Disposal of AAC waste to landfills may cause contaminating leaching and pH changes in the water and surrounding soil [10]; therefore, instead of hiding AAC waste from our sight and pretending that the problem is fixed, an approach where AAC waste is reused and recycled should be chosen.

It is important to understand that AAC waste is produced not only during the demolition and construction works, but also during AAC production and transportation, as it is easily damaged [9,11]. In their article, He X. et al. reported that 3–5% of the entire AAC production is waste [12], while Zou D., using the situation in China as an example, wrote that AAC waste will account for about 40% of the various types of building material waste by 2025 [13].

In terms of production volumes, according to the European Autoclaved Aerated Concrete Association, there are more than 100 AAC manufacturing plants in 18 countries, which are producing 15 million cubic meters of AAC every year, while the global AAC market was valued at more than 4445 million EUR in 2021 and is expected to reach more than 8255 million EUR by 2030 [13]. This means that the wider production will be followed by an increasingly large amount of waste, and that the conventional disposal of AAC waste, including backfilling and stacking, will not meet the increasing demand for AAC waste disposal [12]. Additionally, landfill capacities are limited, therefore it is expected that landfill fees will increase, which could lead to the development of more complex and cost-intensive recycling processes [14].

Recycling of AAC Waste

In order to eliminate the above-mentioned environmental problems, several scientists have studied AAC waste-recycling methods. Extensive research has been conducted on AAC waste as an adsorbent material that can solidify harmful chemical components due to its porous structure [13,15] and its incorporation into the mortar, which is one of the most widely used building materials [16]. Because AAC waste is rich in silicate, it may partially replace sand, which is necessary for making mortar; thus, not only does it reduce AAC waste, but it also saves the natural river sand resources. According to Lam's study [17], AAC waste can replace up to 25% of natural sand in new AAC fabrication, yielding materials whose main properties (compressive strength, bulk density volume, and drying shrinkage) meet the technical requirements of ASTM C 1693—standard specification for autoclaved aerated concrete.

Several researchers have been focusing on the chemical properties of AAC waste. They have reported that this type of waste could produce sodium aluminosilicate, aluminosilicate zeolites, or replace cementitious materials. However, the preparation procedures require not only a specific environment, but also a special chemical treatment, which significantly limits this type of AAC waste utilization [11,12].

Scientists' interest in using AAC waste as a supplementary cementitious material is significant. This can be explained by the low strength and reactivity of hydrated AAC particles, though there may be some residual unhydrated phases inside the AAC waste [18]. Within the framework of the study, He X. et al. attempted to find a possible approach to using AAC waste as a cement substitute in building materials. He used a mechanical grinding of the AAC waste in the water environment to promote particle refinement and ion dissolution promotion. This experiment showed that AAC waste could be efficiently used as an alternative cementitious material in cement and concrete after the wet-milling treatment, which notably improved the particle fineness, distribution homogeneity, pH value, and other properties of the AAC waste slurry [12].

Although there are studies on the use of AAC waste for the replacement of sand, which is also a component of geopolymers, or on the development of alternative cementitious materials, during the preparation of this review, no articles were found on the possibilities of using AAC waste in the production of geopolymers.

High amorphous precursors, such as fly ash, silica fume, and ground granulated blast-furnace slag, are unavailable locally in Latvia; therefore, it was essential to evaluate the possibilities of using locally available construction and demolition waste for the production of geopolymers. The literature analysis revealed that clay brick waste (CBW) is much more promising for this purpose.

4. Clay Brick Waste

CBW constitutes a major part of the solid waste generated by construction and demolition activities worldwide. Its disposal results in both the pollution of the environment and the occupation of large areas of land. However, the actuality of the problem can be entirely understood when considering the following data: firstly, construction and demolition (hereafter C&D) activities in the Europe Union are responsible for generating more than 850 million tons of C&D waste per year [19]. In China, this amount exceeds 1.5 billion tons of C&D waste per year, which has led to severe environmental and social problems [20]. In the United States of America, 600 million tons of C&D debris was generated in 2018, which is more than twice the amount, and is generated as municipal solid waste [21].

Secondly, research data indicate that CBW accounts for an average of 30% of total C&D waste in the EU [22]. According to Zhu L. and Zhu Z. [23], CBW from demolished brick walls accounted for approximately 54% of C&D waste in Spain; however, it must be understood that CBW is obtained not only as a result of the demolition, as a large amount of broken clay bricks is obtained after the firing activities, transportation, and also construction with this material.

In their article [24], L. M. Beleuk a Moungam et al. mentioned a brick factory in Cameroon where the annual volume of bricks produced is almost 4000 tons; however, 17% of the production is broken. Thirdly, a significant part of CBW is deposited in landfills or reclamation sites, which are expensive and inefficient. The distances between demolition sites and disposal areas are increasing, negatively affecting transportation costs. In addition, landfills and reclamation sites are limited; however, CBW occupies significant areas, damaging the soil structure [21,23]. Therefore, many scientists are looking for alternatives, both in terms of providing effective waste management practices, thus ensuring a cleaner and greener environment, and also searching for different ways to successfully reuse and recycle the already existing CBW [25–27].

4.1. Geopolymer Production Using CBW

Considering the various studies conducted on the methods of using CBW to produce new building materials, as well as the limited volume of reviews, the use of CBW is analyzed only for geopolymers, without mentioning other building materials.

The most extensively investigated precursor materials are slag, fly ash, silica fume, and metakaolin [2,28,29]. However, recent studies [22,30] have confirmed the feasibility of using low-amorphous aluminosilicates for the synthesis of geopolymers. Waste clay bricks, on the other hand, are excellent low-amorphous aluminosilicates for geopolymer production due to their chemical and mineralogical properties, allowing one to obtain samples with sufficient strength [8]. Clay, obtained from CBW, has the natural advantage of being already calcined at up to a high temperature of 950 °C [31] during the manufacturing process. The combined water in clay minerals evaporates, creating disordered amorphous phases of alumina and silica, which, in turn, allows us to look at CBW as an environmentally friendly and low-cost raw material for the production of geopolymers [8]. In addition, CBW can be used to produce geopolymers with or without widely used precursor materials such as fly ash and slag. More information on CBW as a precursor material and relevant studies is summarized in Table 1. It also provides information about components, the curing conditions, activator type, and compressive strength.

Table 1. CBW-based geopolymer material properties and curing conditions.

Constituents in Aluminosilicate Precursor	Activator Type	Curing Conditions, °C	Compressive Strength, MPa	Ref.
CBW (with the addition of a reduced amount (30%) of PC)	NaOH	25 ± 3, 80% humidity	2 ± 0.5 (7 days) 7 ± 0.5 (28 days)	[32]
CBW only	Na_2SiO_3	25 ± 3	3.3 (7 days)	[2]
			5.4 (28 days) 10.5 (90 days)	
CBW + metakaolin	NaOH + Na_2SiO_3	40 for 20 h, later—ambient temperature	7 ± 0.75	[33]
CBW + fly ash	Na_2SiO_3	25 ± 3	7.5 (7 days)	[2]
			22.4 (28 days)	
CBW + dolomite-concrete powder	NaOH	80 for 24 h, later—40, >95% humidity	15.0	[34]
CBW + Natural Pozzolana	NaOH + Na_2SiO_3	80	37.0 ± 3 (7 days)	[22]
CBW + metakaolin	NaOH + Na_2SiO_3	Ambient cond. for 24 h, then 4–5 h 60	39.0 (7 days) 43.0 (28 days)	[35]
Waste brick powder	NaOH + Na_2SiO_3	20	41.9 (28 days)	[36]
C&D-based masonry waste (CBW, roof tile, hollow brick), glass	NaOH	95–115	42.0 (2 days) 45.0 (3 days)	[37]
CBW + slag	Na_2SiO_3	25 ± 3	68.3 (7 days)	[2]
			81.8 (28 days) 88.5 (90 days)	
Waste brick powder	NaOH + Na_2SiO_3	60 and 80, 50% humidity	-	[38]

Upon analyzing the information available in Table 1, it can be seen that more strength is obtained for geopolymers that use CBW in combination with slag. High-strength samples cannot be obtained using only CBW at ambient conditions, as the compressive strength of the samples, in this case, does not exceed 7 MPa, even after 28 days. The activator type for geopolymers, which are produced using CBW, does not differ from activators which are used in other geopolymers. In most cases, it is NaOH together with Na_2SiO_3; however, in some studies, they have been used alone. These conclusions are also confirmed by J. Migunthanna, who states in her study [2] that CBW-only one-part geopolymers and CBW-only two-part geopolymers are not capable of achieving high compressive strength in ambient curing conditions. She evidences this with the low degree of reaction of CBW, suggesting that elevated curing temperatures are more suitable for 100% CBW-based geopolymers [2,22]. It should be noted that Table 1 includes information on only a few studies wherein CBW has been used to produce geopolymers. Due to the limited volume of the review, its purpose was to show the vast possibilities of how this kind of C&D waste, alone or in combination with other raw materials, can be used in the production of geopolymers. Secondly, Table 1 deliberately includes studies with different curing temperatures to show that the creation of geopolymers is possible not only at temperatures of 60 °C and higher, but also in ambient conditions.

Many studies have determined the best production conditions of geopolymers, thus providing good geopolymerization [35]. Nonetheless, this analysis is complicated by the fact that, not only must the aforementioned curing conditions be observed, but also different precursor materials and activators, alkaline solution concentration [39], and particle size. Therefore, more information on the curing temperature and activator type is provided in Sections 4.2 and 4.3.

4.2. Curing Temperature

Curing conditions have a significant impact on the process of geopolymerization, which is a process of forming an amorphous or semi-crystalline polymeric structure consisting of sialate (Si-O-Al) and siloxo (Si-O-Si) bonds as a result of heterogeneous reactions of powder aluminosilicate oxides dissolved in a high-alkaline solution medium. It is reported that the curing temperature from 25 °C to 145 °C and curing time from 2 h to 24 h highly affects the dissolution of the precursor material [35]. According to Udawattha et al. [40], the recommended curing temperature is 50–80 °C. It is also confirmed by Chen K. et al. in their study [32], showing that the dissolution rate and geopolymerization increase with an increase in temperature. This is explained by the fact that an increase in temperature also increases the average kinetic energy of reactant molecules. Chen K. with his colleagues further emphasized that the control of the temperature may not only significantly affect the geopolymerization process, but might also affect the hardened characterizations of geopolymers [39,40]. Moreover, the results of Yener's and Karaaslan's research on the curing time and temperature effect on the properties of pumice-based geopolymers has shown that a curing treatment at 60 °C and 75 °C up to 168 h increased the strength of the geopolymer samples by almost two-fold compared to the 24-h heat-curing time and approximately 13 times compared to ambient curing [35].

However, one of the biggest disadvantages of geopolymers is the fact that, in the case of fly ash-based and other geopolymers, curing must be conducted at a relatively high temperature due to the poor hydration reactivity. The heat-curing process leads to high costs and energy consumption. It creates a barrier for the broad application of fly ash-based geopolymers in building processes due to the formulation of in situ cast concrete [41]; therefore, during the development of the review, special attention was paid to the possibility of using ambient conditions during the curing time. Despite the apparent advantages of using a relatively high temperature, several studies have confirmed that the curing of a fly ash-based geopolymer at an ambient temperature could be significantly accelerated after adding a small proportion of slag [42] or OPC with high CaO content [41]. Moreover, J. Migunthanna et al. have proven in their research [2] that geopolymers from binary blends of CBW with other aluminosilicate precursors such as slag and fly ash show good compressive strength also at ambient curing conditions. Of course, a more thorough analysis of the existing research is needed. However, it is already clear that geopolymers containing CBW can be successfully manufactured even if curing temperatures are not elevated.

4.3. Activator Type

Such alkaline activators as sodium hydroxide, sodium silicate, KOH, potassium silicate, and sodium metasilicate are widely used to produce geopolymers [43,44]. There are two types of activators, namely, solid and liquid. Liquid activators are usually used in two-part geopolymers, whereas solid activators are usually used in one-part geopolymers. The use of solid activators lowers the cost of materials and environmental footprint, and transportation becomes easier [45].

Unfortunately, the aqueous activators, which are used in two-part geopolymer production, are highly corrosive and hazardous, therefore it is difficult to use them on an industrial scale [2].

The information gathered in Table 1 confirms a general trend that NaOH, sodium silicate Na_2SiO_3, and their combination are mainly used as activators for geopolymers in the production in which CBW is used. It should be noted that Na_2SiO_3 is produced via the direct fusion of pure silica with soda ash in a furnace at a temperature of approximately 1400 °C [2]. This process is highly energy consuming, and CO_2 is emitted not only when furnaces are fired using oil and gas, but also during the chemical reaction. Of course, this activator is not used in large quantities, therefore the environmental impact is small; however, this is a factor to consider when choosing a suitable activator.

5. Conclusions Remarks and Research Perspective

The conducted review provides clear evidence of how urgent the problem of C&D waste is and confirms the interest of researchers in the development of various building materials using such widespread wastes as CBW and AAC waste. Although, during the planning of the review, the possibility of using both AAC waste and CBW for the production of geopolymers was foreseen, a thorough analysis of the literature allowed CBW to be prioritized.

Even though scientists have studied geopolymers for more than two decades, many factors must be evaluated and analyzed when designing geopolymer compositions. It is necessary to choose suitable curing conditions, precursor materials and activators, and an alkaline solution concentration when trying to reduce the necessary resources and environmental impact.

Particular attention should be paid to the effect of CBW particle size, as the results widely vary. Some articles provide information that the compressive strength of geopolymers, produced using only CBW or CBW in combination with fly ash, is only slightly affected by the particle size change. At the same time, other studies indicate more than a 70% increase in compressive strength after decreasing CBW particle size. In contrast, while using CBW with slag, CBW particle size significantly affected the properties of the geopolymers.

Future research will focus on developing geopolymers using CBW and slag and on providing ambient curing conditions. This direction seems promising and not so resource intensive. This is not only an opportunity to develop geopolymers and reduce the C&D waste simultaneously, it is also a way to reduce the necessary amount of high amorphous precursors such as fly ash, silica fume, and ground granulated blast-furnace slag that are unavailable locally in Latvia.

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References

1. An Official European Commission Website. In Focus: Energy Efficiency in Buildings. Available online: https://commission.europa.eu/news/focus-energy-efficiency-buildings-2020-02-17_en (accessed on 11 December 2022).
2. Migunthanna, J.; Rajeev, P.; Sanjayan, J. Investigation of waste of clay brick as partial replacement of geopolymer binders for rigid pacement application. *Constr. Build. Mater.* **2021**, *305*, 124787. [CrossRef]
3. Shah, K.W.; Huseien, G.F.; Xiong, T. Functional nanomaterials and their applications toward smart and green buildings. In *New Materials in Civil Engineering*; Pijush, S., Dookie, K., Nagesh, R.I., Sandeep, C., Eds.; Butterworth-Heinemann: Oxford, UK, 2020; Chapter 11; pp. 154–196.
4. Saez-Perez, M.; Duran-Suarez, J.A.; Castro-Gomes, J.P. Improving the behavior of green concrete geopolymers using different hemp preservation conditions (fresh and wet). *Minerals* **2022**, *12*, 1530. [CrossRef]
5. Davidovits, J. Geopolymer cement to minimize carbon-dioxide greenhouse-warming. *Ceram. Trans.* **1993**, *37*, 165–182.
6. Akbari, H.; Heller, T.; Shin, S.; Yang, X.; Kolay, P.K.; Kumar, S.; Mohanty, M. Geopolymer based concrete to reduce carbon footprint of the construction industry. *Min. Eng.* **2013**, *65*, 57–62.
7. Figiela, B.; Brudny, K.; Lin, W.T.; Korniejenko, K. Investigation of mechanical properties and microstructure of construction and demolition waste-based geoopolymers. *J. Compos. Sci.* **2022**, *6*, 191. [CrossRef]
8. Migunthanna, J.; Rajeev, P.; Sanjayan, J. Waste clay bricks as a geopolymer binder for pavement construction. *Sustainability* **2022**, *14*, 6456. [CrossRef]
9. Rahman, R.A.; Fazlizan, A.; Thongtha, A.; Asim, N.; Noorashikin, M.S. The physical and mechanical properties of autoclaved aerated concrete (AAC) with recycled AAC as a partial replacement for sand. *Buildings* **2022**, *12*, 60.
10. Straits Research. Autoclaved Aerated Concrete Market Growth, Trends and Forecast to 2030. Available online: https://straitsresearch.com/report/autoclaved-aerated-concrete-market (accessed on 10 December 2022).
11. Iucolano, F.; Campanile, A.; Caputo, D.; Liduori, B. Sustainable management of autoclaved aerated concrete wastes in gypsum composites. *Sustainability* **2021**, *13*, 3961. [CrossRef]
12. He, X.; Zheng, Z.; Yang, J.; Su, Y.; Wang, T.; Strnadel, B. Feasibility of incorporating autoclaved aerated concrete waste for cement replacement in sustainable building materials. *J. Clean. Prod.* **2020**, *250*, 119455. [CrossRef]
13. Zou, D.; Que, Z.; Cui, W.; Wang, X.; Guo, Y.; Zhang, S. Feasibility of recycling autoclaved aerated concrete waste for partial sand replacement in mortar. *J. Build. Eng.* **2022**, *52*, 104481. [CrossRef]
14. Zou, D.; Que, Z.; Su, D.; Liu, T.; Zhou, A.; Li, Y. Sustainable use of recycled autoclaved aerated concrete waste as internal curing materials in ultra—High performance concrete. *J. Clean. Prod.* **2022**, *373*, 133910. [CrossRef]
15. Volk, R.; Steins, J.J.; Stemmermann, P.; Schultmann, F. Comparison of different post-demolition autoclaved aerated concrete (AAC) recycling options. *IOP Conf. Ser. Earth Environ. Sci.* **2022**, *1078*, 012074. [CrossRef]
16. Castellar, J.A.; Formosa, J.; Chimenos, J.M.; Canals, J.; Bosch, M.; Rosell, J.R.; Silva, H.P.D.; Morató, J.; Brix, H.; Arias, C.A. Crushed autoclaved aerated concrete (CAAC), a potential reactive filler medium for enhancing phosphorus removal in nature-based solutions-preliminary batch studies. *Water* **2019**, *11*, 1442. [CrossRef]
17. Lam, N.N. Recycling of AAC waste in the manufacture of autoclaved aerated concrete in Vietnam. *Int. J. GEOMATE* **2021**, *20*, 128–134. [CrossRef]
18. Qin, L.; Gao, X. Recycling of waste autoclaved aerated concrete powder in Portland cement by accelerated carbonation. *Waste Manag.* **2019**, *89*, 254–264. [CrossRef] [PubMed]
19. Saez, P.V.; Osmani, M. A diagnosis of construction and demolition Waste generation and recovery practice in the European Union. *J. Clean. Prod.* **2019**, *241*, 118400. [CrossRef]
20. Huang, B.; Wang, X.; Kua, H.; Geng, Y.; Bleischwitz, R.; Ren, J. Construction and demolition waste management in China through the 3R principle. *Resour. Conserv. Recycl.* **2018**, *129*, 36–44. [CrossRef]

21. An Official Website of the United States Government—EPA, United States Environmental Protection Agency. Sustainable Management of Construction and Demolition Materials. Available online: https://www.epa.gov/smm/sustainable-management-construction-and-demolition-materials (accessed on 9 December 2022).
22. Silva, G.; Castaneda, D.; Kim, S.; Castaneda, A.; Bertolotti, B.; Ortega-San-Martin, L.; Nakamatsu, J.; Aguilar, R. Analysis of the production conditions of geopolymer matrices from natural pozzolana and fired clay brick wastes. *Constr. Build. Mater.* **2019**, *215*, 633–643. [CrossRef]
23. Zhu, L.; Zhu, Z. Reuse of clay brick waste in mortar and concrete. *Adv. Mater. Sci. Eng.* **2020**, *2020*, 6326178. [CrossRef]
24. Beleuk a Moungam, L.M.; Mohamed, H.; Kamseu, E.; Billong, N.; Melo, U.C. Properties of geopolymers made from fired clay bricks wases and rice husk ash (RHA)—Sodium Hydroxide (NaOH) activator. *Mater. Sci. Appl.* **2017**, *8*, 537–552.
25. Olofinnade, O.M.; Ede, A.N.; Booth, C.A. *Sustainability of Waste Glass Powder and Clay Brick Powder as Cement Substitute in Green Concrete*; Hussain, C.M., Ed.; Handbook of Environmental Materials Management; Springer: Cham, Switzerland, 2018; pp. 1–22.
26. Scheinherrova, L.; Dolezelova, M.; Vimmrova, A.; Vejmelkova, E.; Jerman, M.; Pommer, V.; Cerny, R. Fired clay brick waste as low and eco-friendly pozzolana active filler in gypsum-based binders. *J. Clean. Prod.* **2022**, *368*, 133142. [CrossRef]
27. Abdellatief, M.; Elermam, W.E.; Alanazi, H.; Tahwia, A.M. Production and optimization of sustainable cement brick incorporating clay brick wastes using response surface method. *Ceram. Int.* 2022. *in press*. Available online: https://www.sciencedirect.com/science/article/pii/S0272884222041645 (accessed on 9 December 2022).
28. Luhar, I.; Luhar, S.A. Comprehensive review of fly ash—Based geopolymer. *J. Compos. Sci.* **2022**, *6*, 219. [CrossRef]
29. Wu, X.; Shen, Y.; Hu, L. Performance of geopolymer concrete activated by sodium silicate and silica fume activator. *Case Stud. Constr. Mater.* **2022**, *17*, e01513. [CrossRef]
30. Abadel, A.A.; Albidah, A.S.; Altheeb, A.H.; Alrshoudi, F.A.; Abbas, H.; Al-Salloum, Y.A. Effect of molar ratios on strength, microstructure & embodied energy of metakaolin geopolymer. *Adv. Concr. Constr.* **2021**, *11*, 127–140.
31. Hanein, T.; Thienel, K.C.; Zunino, F.; Marsh, A.T.; Maier, M.; Wang, B.; Canut, M.; Juenger, M.C.; Ben Haha, M.; Avet, F.; et al. Clay calcination technology: State-of-the-art review by the RILEM TC 282-CCL. *Mater. Struct.* **2022**, *55*, 3. [CrossRef]
32. Robayo-Salazar, R.A.; Meia-Arcila, J.M.; de Gutierrez, R.M. Eco-efficient alkali-activated cement based on red clay brick wastes suitable for the manufacturing of building materials. *J. Clean. Prod.* **2017**, *166*, 242–252. [CrossRef]
33. Rovnanik, P.; Rovnaniková, P.; Vysvaril, M.; Grzeszczyk, S.; Janowska-Renkas, E. Rheological properties and microstructure of binary waste red brick powder/metakaolin geopolymer. *Constr. Build. Mater.* **2018**, *188*, 924–933.
34. Ouda, A.S.; Gharieb, M. Development the properties of brick geopolymer pastes using concrete waste incorporating dolomite aggregate. *J. Build. Eng.* **2020**, *27*, 100919.
35. Yener, E.; Karaaslan, C. Curing time and temperature effect on the resistance to wet-dry cycles of fly ash added pumice based geopolymer. *J. Cem. Based Compos.* **2020**, *2*, 19–25. [CrossRef]
36. Fort, J.; Vejmelkova, E.; Konakova, D.; Alblova, N.; Cachova, M.; Keppert, M.; Rovnanikova, P.; Cerny, R. Application of waste brick powder in alkali activated aluminosilicates: Functional and environmental aspects. *J. Clean. Prod.* **2018**, *194*, 714–725.
37. Ulugöl, H.; Kul, A.; Yıldırım, G.; Şahmaran, M.; Aldemir, A.; Figueira, D.; Ashour, A. Mechanical and microstructural characterization of geopolymers from assorted construction and demolition waste-based masonry and glass. *J. Clean. Prod.* **2021**, *280*, 124358.
38. Fort, J.; Novotny, R.; Vejmelkova, E.; Trnik, A.; Rovnanikova, P.; Keppert, M.; Pommer, V.; Cerny, R. Characterization of geopolymers prepared using powdered brick. *J. Mater. Res. Technol.* **2019**, *8*, 6253–6261.
39. Chen, K.; Cheng, Y.; Yu, M.; Liu, L.; Wang, Y.; Zhang, J. Predicting the Geopolymerization Process of Fly-Ash-Based Geopolymer Using Machine Learning. *Buildings* **2022**, *12*, 1792.
40. Udawattha, C.D.; Lakmini, A.V.R.D.; Halwatura, R.U. Fly ash-based geopolymer mud concrete block. In Proceedings of the Moratuwa Engineering Research Conference (MERCon)/4th International Multidisciplinary Engineering Research Conference, Katubedda, Sri Lanka, 30 May–1 June 2018; pp. 583–588.
41. Zhao, J.; Wang, K.; Wang, S.; Wang, Z.; Yang, Z.; Shumuye, E.D.; Gong, X. Effect of elevated temperature on mechanical properties of high-volume fly ash-based geopolymer concrete, mortar and paste cured at room temperature. *Polymers* **2021**, *13*, 1473. [CrossRef] [PubMed]
42. Fang, G.; Ho, W.K.; Tu, W.; Zhang, M. Workability and mechanical properties of alkali-activated fly ash-slag concrete cured at ambient temperature. *Constr. Build. Mater.* **2018**, *172*, 476–487.
43. Hajimohammadi, A.; Ngo, T.; Mendis, P. Enhancing the strength of pre-made foams for foam concrete applications. *Cem. Concr. Compos.* **2018**, *87*, 164–171. [CrossRef]
44. Kyung, W.K.; Hyung, M.L.; Seog-Young, Y.; Hyunseok, K. Fast-curing geopolymer foams with an enhanced pore homogeneity derived by hydrogen peroxide and sodium dodecyl sulfate surfactant. *Minerals* **2022**, *12*, 821.
45. Ghazy, M.; Abd Elaty, M.; Mostafa, S. Properties of one-part versus two-part geopolymers composites-a review. *Am. J. Eng. Res.* **2022**, *11*, 1–14.