

A comparative study of the environmental impact of alkali activated and traditional materials

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ABSTRACT: Many construction materials carry significant environmental impacts because they require high energy input and non-renewable materials for production, contributing to material depletion and greenhouse gas emissions. In particular, Portland cement (PC), the binder most widely used, is often considered a main contributor to emissions. Most PC environmental impact is due to clinker production which requires burning rocks at 1400°C releasing abundant CO₂ from fuel combustion and rock decarbonization. Alkali-activated materials (AAMs) do not require clinker manufacturing but are produced at low temperature (ambient-100°C). Hence, they yield low emissions and have low embodied energy (EE). Most AAMs are made with waste which further lowers their EE and the raw materials and fuel consumption for their making. Savings up to 75% CO₂ emissions are reported compared with PC products, and additional environmental benefits (water consumption reduction and no requirement for superplasticizers). This paper calculates the EE and carbon footprint (EC) of AAMs made with wastes including slag (GGBS), fly ash (FA), bauxite and red mud (RM). The values are compared with equivalent CEM II products. Their environmental impact is set against their strength to assist the design of optimum mixes at lower impact. It is evidenced that the right activator procures a strength similar to CEM II at approximately half the EE and EC, while a wrong activator increases the environmental impact and lowers strength. Pyroprocessing waste at relatively low temperature slightly increases environmental impact but can greatly increase strength: sintering bauxite at 800°C enabled strength two times greater than the CEM II product.

KEY WORDS: fly ash; GGBS; red mud; bauxite; alkali activation; embodied energy; carbon footprint.

1 INTRODUCTION

The construction industry is one of the largest contributors to greenhouse gas emissions, and a great consumer of energy and non-renewable natural resources [1]. The fabrication of building materials such as aluminium, steel and PVC implies high energy consumption and environmental impact [2]. As a result of severe environmental problems, the construction industry needs to adapt. Using construction materials of low environmental impact worldwide would considerably lower the greenhouse gas emissions and improve the sustainability of construction. PC is the binder most widely used in construction. It is held responsible for major contributions to greenhouse gas emissions worldwide in multiple publications. Most of the environmental impact of PC is due to clinker production which requires burning rocks at c.1400°C releasing abundant CO₂ from the fuel combustion and the decarbonization of the carbonate rocks used as raw materials. Alkali-activated materials (AAMs) do not require clinker manufacturing but are produced at low temperatures, usually ranging from ambient to 100°C. Most alkali activated cements are produced at ambient temperatures, and others with a small energy input usually ranging from 60°C (curing) to 100°C (drying) or 400-600°C (thermal activation of certain wastes) [3-5]. Hence, they yield low carbon emissions and have low embodied energy (EE). Furthermore, most AAMs are made with industrial waste which further lowers their EE as well as the raw material and fuel consumption for their making. The reduction in emissions, and the use of waste for the production of AAMs, can elicit their wide uptake in the markets [6-9]. Industrial by products such as

GGBS and ash residues such as FA are used instead of clinker for the production of AAMs. These wastes contain abundant silicates and/or aluminates that can be activated with alkali metals. On successful activation, the wastes' active components generate Si⁴⁺, Al³⁺ and (sometimes) Ca²⁺ that become available to form cementing products [6-10].

Most authors agree that AAMs have lower EE and carbon emissions than their equivalent PC products. Duxon et al. [11] calculated the CO₂ emissions of AA FA and metakaolin cements using the CO₂ evolved during the production of Na₂O and SiO₂ in the alkali process as the primary inputs, and found savings of 80% in CO₂ emissions when compared to PC. However, there is a great divergence of results due to both a disparity in the data used and the different formulations. Wimpenny [12] and Provis and Deventer [13] state that the carbon footprint of AA binders is 30% of the PC print, but according to Zhang et al. [14], AA cement can be produced with 60% lower values of energy and CO₂ emissions than PC. Pacheco Torgal et al. [15] found several authors claiming 44-70% reductions in CO₂ emissions for several AAMs compared with similar PC mixes. Cunningham & Miller [16] account for AAMs having 10%–80% lower EE than their equivalent PC materials. Davidovits [17] states that geopolymers, a subset of AAMs where the binding phase is almost exclusively aluminosilicate, have 10-20% lower carbon footprint than PC, while other geopolymer formulations [18] have shown a 60% reduction in CO₂ emissions compared to their PC equivalents.

Using nine LCA (life cycle analyses) Lolli and Kurtis [19] conclude that AAMs show a 50% reduction in CO₂ production

when compared to PC and PC+SCM (supplementary cementitious material) binders, while providing the required compressive strength for pavement applications (30 MPa). The carbon emissions and EE of AAMs depend on their formulation. Ouellet-Plamondon and Habert [20] state savings up to 75% CO₂ emissions for certain formulations when compared with equivalent PC products. They also highlight further environmental benefits such as reducing water use and no requirement for superplasticizers. Ouellet-Plamondon and Habert [20] claim that sodium silicate activators can contribute up to 80% of the total impact of an AAM, while Anvekar et al. [21] report EE 48% greater than equivalent PC material due to the alkali activator energy demand. Several authors agree that the main source of CO₂ impact for AAMs is the production of sodium silicate activator from sodium carbonate [22-23]. However, the carbonate can be either mined from evaporite deposits or produced through the Solvay process. Mining implies 1/10 of the Solvay process CO₂ production, hence the impact of silicate activator is often overestimated [19].

Matheuet al [24] state that the global warming potential of AAMs is c. 25% lower than PC equivalents. They demonstrate that, in ten LCA categories (global warming potential, acidification, human health, air pollutants, ecotoxicity, smog, natural resource depletion, indoor air quality, water intake and ozone depletion) AAMs have less impact than PC materials. They found that, in seven categories, the AAMs impact was 40% lower than PC equivalents. In two categories PC material performed better: eutrophication and habitat alteration, due to the use of potassium-based activators. Potassium hydroxide can emit nutrients into waterways (eutrophication) and hence alter habitats. In this paper, potassium activator is replaced with sodium silicate/hydroxide.

As the environmental impact of AAMs depends on their formulation, not only is it important to use activators of low impact, but it is also important to use wastes that do not require calcination or any other high-energy processing to render them reactive. The processing of the wastes in this paper is minimal, based on previous work by the authors that determined the minimum processing that renders maximum reactivity [4-5, 25].

This paper calculates the embodied energy (EE) and carbon footprint (EC) of AAMs made with several industrial wastes including granulated blast furnace slag (GGBS), fly ash (FA), bauxite and red mud (RM) from Ireland and Saudi Arabia. These wastes have been successfully activated and used to produce AAMs by the authors. Most of the resultant AAMs showed satisfactory physical and mechanical properties, and others displayed outstanding mechanical strength and durability [26]. The outstanding performance of the AAMs in aggressive environments enhances their life cycle, hence reducing their environmental impact. Other authors have also found superior durability for certain AAM formulations including better corrosion resistance [7-9, 27]. The EC and EE of the AAMs produced is compared with equivalent PC materials made with CEM II A/L, a limestone cement of lower environmental impact than other members of the PC family.

2 MATERIALS AND METHODS

2.1 Materials

The AAMs were fabricated with wastes including GGBS, FA and RM sourced from Ireland and Saudi Arabia. A natural rock (bauxite), mined principally as an aluminium ore, was also used to fabricate some of the AAMs. The GGBS is a byproduct of the steel industry while the FA is a residue of burning coal in power stations. The RM is also a waste, generated during the refining of bauxite to produce aluminium

The wastes were used as precursors and activated with sodium hydroxide (NaOH) and sodium silicate (Na₂SiO₃), which dissolved the active components generating Si⁴⁺, Al³⁺ and Ca²⁺ that become available to form cementing products. The sodium hydroxide activator (NaOH) was used in pellet form with 98% purity. It was mixed with distilled water to attain different molarities to suit the different AAMs: a 6 molar (M) solution was used for the RM, 8 M solutions for the GGBS, and 8-10M solutions for the bauxite. The molarities are chosen according to previous research [4-5, 25]. The composition of the AAMs is included in tables 1-3. A sodium silicate activator (Na₂SiO₃) in liquid form was used, with a viscosity ranging from 800 to 1400 cps; PH 11-14, chemical composition of 14-17% Na₂O; 31-35% SiO₂ and silicate modulus (MS = SiO₂/Na₂O) of 2.20. The activators (NaOH, Na₂SiO₃) are used in liquid form, however they are included in the calculations as solids because water accounts for neither EE nor EC [28].

As aforementioned, wastes that rendered the maximum reactivity [4-5, 25] with minimum processing were selected. The bauxite required grinding to enhance fineness and specific surface area. The bauxite was mined from a deposit located in the region of Ha'il, central/northern Saudi Arabia. It was oven-dried at 105 °C for 24 hours and ground in a digital ball mill at 150 r.p.m with 20mm Ø stainless steel balls. Finally, it was calcined at c.800 °C to enhance reactivity [4]. For the same reason, the RM was calcined at c.400 °C [5]. The DOE software was used to develop an optimum mix for the AA bauxite materials. The GGBS and FA were unprocessed.

2.2 Mixing, curing and compaction

The mix design (Tables 1-3) was based on existing literature and previous research by the authors. The sand to precursor ratio is constant at 3:1. The precursors were dry mixed for 3 min and the activator solution added and mixed for a further 5 minutes. The sand was then added and mixed for 6 min. The mortars were cast into prismatic molds of 160*50*50 mm, vibrated for 1 min, and sealed with plastic sheets to prevent moisture loss during curing. The specimens were demolded after 24 hours. The software determined curing in isothermal chambers at 20 ± 2 °C for 28 days for the AA bauxite materials. Some of the AA GGBS materials were cured in an oven at 60 °C for 24 h. The CEM II A/L-based control materials were fabricated according to EN 196-1[29]. The percentage composition is calculated from the mass fitted in a 3-gang prismatic mold to attain densities between 1842 and 1966 g/m³ for the AA RM materials, 1676-1759 g/m³ for the AA GGBS materials and 1685-1895 g/m³ for the AA bauxite materials which is approximately 2 kg. As aforementioned, the activators are included in the calculations as solids because water accounts for neither EE nor EC.

2.3 Methods

Only the production stage is included in the calculations. Therefore, the life stages included in the EE and EC calculations are raw materials extraction, manufacturing and related transport, which in a LCA is equivalent to the cradle to gate system boundary. The scenarios for the production stage are usually defined in environmental product declarations (EPD). However, no EPDs were found for some AAM components. Therefore, some values are from the literature and others calculated with data provided by the producers-Table 4.

The EE and EC of the FA and GGBS are based on existing published data (Table 4). The EE and EC of the bauxite was calculated with the details of the mining process provided by the Ma'aden industries (Sidiya, Kaolin Processing and Management, Ma'aden 2021), and it is based on the quarrying of the Az Zabirah and Al Bai'tha mines. The Al Bai'tha supplies high-grade bauxite for aluminium production while the Az Zabirah mine supplies kaolin to the phosphate industry and low-grade bauxite to local cement companies. The environmental impact of quarrying this bauxite was calculated by Alelweet and Pavia [4] as summarized below. The primary energy used for quarrying is diesel, and the CO₂ emissions are estimated based on the quantity of diesel and the activity of the mine, amounting to 3.3 kg CO₂/t bauxite. This calculation considers a diesel consumption of 3144 l/day producing 8237.3 kg CO₂. The mining process starts with overburden stripping of a 0.5–1 m soil cap which is removed with a bulldozer. The strip waste is loaded into dump trucks and hauled to landfills outside the pit. Once exposed, the bauxite is ripped and piled in heaps with a bulldozer. The ore is then screened with wheel loaders and mobile screens and blended to meet customer requirements in terms of size and chemistry. The loaders collect the material passing the sieve and stockpile it as the final product. Auxiliary equipment includes one grader and one compactor for road maintenance. Finally, the product is loaded into trucks and dispatched to costumers. The red mud is produced as a waste during the refining of the quarried bauxite to produce aluminium. As a byproduct, the energy required for its manufacturing is zero. It is also produced locally; therefore, no transport is accounted for at the production stage.

Table 4. EE/ EC of the materials used to fabricate the AAMs.

	EE(MJ/kg)	EC(kgCO ₂ /kg)	Ref.
PC (CEM II A/L)	4.80	0.842	[30], [31]
PC (CEM I)	4.50	0.730	[32]
FA	0.10	0.008-0.010	[32-33]
GGBS	1.60	0.083	[32]
Bauxite	0.05	0.003-0.005	[4]
NaOH	3.50	0.632	[34]
Na ₂ SiO ₃	4.60	0.430	[35]
Water	0	0	[28]
Quartz sand	0.85	0.020	[36]
Fine aggregate	0.17	0.025	[37]
	0.004	0.081	[32]
Coarse aggregate	0.12	0.006	[30]
Compaction	0.009	0.001	[38]

The embodied energy was measured, as Mega-Joules (MJ) per unit area (m²) or per unit weight (kg or ton), according to

Anvekar *et al.* [21]. The embodied energy and carbon were calculated with equations 1 and 2 [39].

$$EE = \sum_{i=1}^n (EE_i \times m_i) \quad (1)$$

$$E_{CO_2} = \sum_{i=1}^n (E_{CO_2i} \times m_i) \quad (2)$$

Where: EE_i is the embodied energy of each material component (MJ/kg), E_{CO₂i} the embodied Carbon (kgCO₂/kg), and *m* the mass of each component.

As aforementioned, some of the components were processed (milled or heated). The impact of this processing appears in Table 5. According to Kim [40], ball milling is a grinding method of low environmental impact because it uses no chemical catalysts or any other substances. A ball mill of 0.15 kWh power capacity was used for grinding some of the wastes. The embodied energy of the grinding process *EE_{ball mill}* was calculated with equation (3) [41]:

$$EE_{ball\ mill} = \frac{(P_{kWh} \times t)}{m \times 1000} \quad (3)$$

Where: P_{kwh} is the power capacity of the ball mill, (*m*) the mass in kg, and (*t*) the time in hours.

The RM was ground for 3h, the EE_{ball mill} was 0.001 MJ/kg. The embodied energy of the grinding process for the bauxite EE_{ball mill} was greater (0.009 MJ/kg) because it was longer. The EE and EC of the heating and calcination processes were also calculated (Table 5) [42-43].

Table 5. EE and EC of the dry and calcined RM and bauxite.

Materials	T (°C)	Time (h)	EE (MJ/kg)	EC (Kg-CO ₂ /kg)
RM dry	105	24	0.14	0.017
RM sintered	400	3	0.94	0.118
Bauxite dry	105	24	0.14	0.017
Bauxite sintered	800	3	2.19	0.277
GGBS (G4-G6)	60	24	0.02	0.002

3 RESULTS AND DISCUSSION

The EE and EC calculations used the data in Tables 1–5 and equations 1-3. As aforementioned, the calculations refer to material production. Therefore, the life stages included are raw material extraction or supply, manufacturing and extraction-related transport which are usually included in EPD's. The EE and EC of the AAMs are reported as the arithmetic mean of all the mixes investigated. The strength of the resultant AAMs (tables 6-8) is set against their environmental impact to optimize their design for lower environmental impact.

The strength results of the alkali-activated RM and GGBS materials are experimental while the strength of the AA bauxite materials comes from both experimental data and an optimization of the mix design modelled with software. The strength values are the arithmetic mean of 6 tests each, and the results are reliable, showing a small dispersion, with COVs ranging from 0.04 (RMG1) to 0.23 (RMFA5). The COV of the

CEM II equivalent is 0.10. The alkali activators are the main responsible for the environmental impact of AAMs [44]. It can be seen from the results that rising the concentration and molar ratio of activator increases environmental impact. However, it doesn't significantly increase the strength, sometimes it even reduces it (Table 6).

In the AA RM materials, the results show that growing RM substitution with FA, from 6 to 10%, nearly doubles the 28-d compressive strength of the resultant AAMs without increasing their environmental impact (Table 6). The same effect is evident for GGBS replacement when the main activator is NaOH. However, with silica activator, the strength drops despite the increase of GGBS.

The AA GGBS materials including NaOH-rich activators can reach strengths comparable to their CEM II equivalents (~26-34MPa compared with 37MPa for CEMII)-Table7. However, their environmental impacts are considerably lower: The EE of the AA GGBS materials is 53.78 % lower that the CEM II and the ECO2 66.67 % lower (Table 8). Therefore, the right activator can provide a similar strength at half the emissions and half the EE than a similar CEM II mix.

Sintering the bauxite precursor at 800°C has slightly raised the environmental impact (Table 7-8) but has nearly doubled strength when compared to the equivalent CEM II product. The high strength of the GGBS blended bauxites (60MPa) is due to the combined reactions involving the pozzolanic transition aluminas in the bauxite, with the latent hydraulic phases of the GGBS, enhanced with the high surface areas of both precursors.

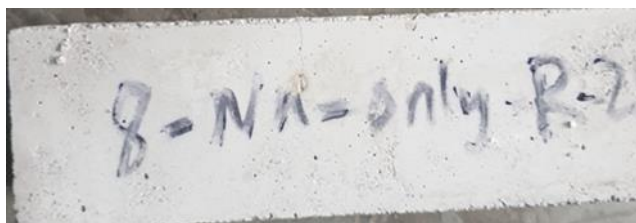


Figure 1. Typical appearance of AAGGBS materials studied.



Figure 2. Typical appearance of AA RM materials.



Figure 3. Typical appearance of AA bauxite materials

The results are comparable with others in the literature. Mathew et al. [45], calculated EE 40% under equivalent PC products for AAMs of formulation: 75%FA, 25%GGBS,

NaOH (15M), $\text{Na}_2\text{SiO}_3/\text{NaOH}=2.33$ and ratio activator / FA+GGBS = 0.42. Kalaw et al. [46] report the EE of AA FA/PC materials at 3.52 MJ/kg (for 25% PC replacement with FA) and 2.43 MJ/kg (50% replacement). Their environmental impact is higher than the mixes in this paper because their PC has a greater EE than CEM II. Faridmehr et al. [47] also state comparable values for AAM mixtures made with high-volume FA which emitted 45.5 kg CO_2/m^3 and consumed 881.2 MJ/ m^3 . They report GGBS mixes reaching higher values at 70.6 kg CO_2/m^3 and 1534.5 MJ/ m^3 . The impact of their AAMs is significantly lower than their benchmark mortars made with PC (CEM I) which carry 436.8 kg CO_2/m^3 emissions and 2793 MJ/ m^3 EE.

As aforementioned, most of the AAMs showed satisfactory properties and some displayed outstanding mechanical strength and durability [26]. Representative specimens appear in figures 1-3. Other authors have also found superior durability for certain AAM formulations including better corrosion resistance [2-4], [23]. An increased resilience enhances the life cycle of a material, hence reducing environmental impact.

4 CONCLUSION

The EE and EC of AAMs was calculated and compared with other materials. The results evidence that, in alkali activation technology, an appropriate design leads to lower environmental impact and superior strength.

From the AA GGBS material results, it was clear that the right activator procured a strength similar to the equivalent CEM II mixes at approximately half of their embodied energy and carbon emissions. Activators constitute the main environmental impact of AAMs. An excessive activator concentration or wrong molar ratio can increase the environmental impact while simultaneously lowering strength. Therefore, they must correctly selected and formulated.

In addition, sintering the bauxite at 800°C only slightly raised the environmental impact of the resultant material, but it nearly doubled the strength when compared to the equivalent CEM II product. Consequently, pyro-processing waste precursors at relatively low temperature can report great strength increase with a low increase in environmental impact.

The importance of blending waste precursors is also acknowledged: increasing FA in the AA RM materials, from 6 to 10%, nearly doubles the 28-day compressive strength without increasing the environmental impact.

Therefore, three design variables particularly impact the results including:

- 1- Using adequate blends of waste precursors.
- 2- Using the right activator formulation for a given waste precursor.
- 3- An adequate processing (activation) of waste precursors.

ACKNOWLEDGMENTS

The authors thank Ma'adem Industries, for valuable information and for providing materials for the investigation. The authors also thank the Government of Saudi Arabia, Technical & Vocational Training Corporation and the Saudi Arabian Cultural Bureau for their support and for financing the project. We thank our colleagues in the Civil Engineering laboratories: M. O'Shea, M. Grimes, M. Gilligan, P. Veale and Chief Technician D. McAuley for their assistance with testing.

REFERENCES

- [1] K. Ahmed Ali, M. I. Ahmad, and Y. Yusup, "Issues, impacts, and mitigations of carbon dioxide emissions in the building sector," *Sustainability*, vol. 12, no. 18, p. 7427, 2020.
- [2] Z. Zhongming, L. Linong, Y. Xiaona, Z. Wangqiang, and L. Wei, "Using materials efficiently can substantially cut greenhouse gas emissions," 2020.
- [3] T. Luukkonen, Z. Abdollahnejad, J. Yliniemi, P. Kinnunen, and M. Illikainen, "One-part alkali-activated materials: A review," *Cem. Concr. Res.*, vol. 103, no. October 2017, pp. 21–34, 2018.
- [4] O. Alelwee and S. Pavia, "Pozzolanic and hydraulic activity of bauxite for binder production," *J. Build. Eng.*, vol. 51, p. 104186, 2022.
- [5] O. Alelwee, S. Pavia, and Z. Lei, "Pozzolanic and Cementing Activity of Raw and Pyro-Processed Saudi Arabian Red Mud (RM) Waste," *lidsen*, no. 2689–5846, 2021.
- [6] C. Shi, D. Roy, and P. Krivenko, *Alkali-activated cements and concretes*. CRC press, 2003.
- [7] G. Habert, J. B. D'Espinose De Lacaillerie, and N. Roussel, "An environmental evaluation of geopolimer based concrete production: Reviewing current research trends," *J. Clean. Prod.*, vol. 19, no. 11, pp. 1229–1238, 2011.
- [8] R. Unless, P. Act, W. Rose, T. If, and W. Rose, "Advances in understanding alkali activated materials," 2015.
- [9] S. H. Teh, T. Wiedmann, A. Castel, and J. de Burgh, "Hybrid life cycle assessment of greenhouse gas emissions from cement, concrete and geopolimer concrete in Australia," *J. Clean. Prod.*, vol. 152, pp. 312–320, 2017.
- [10] F. Pacheco-Torgal, J. A. Labrincha, C. Leonelli, A. Palomo, and P. Chindaprasit, "Handbook of Alkali-Activated Cements, Mortars and Concretes," *Handbook of Alkali-Activated Cements, Mortars and Concretes*, pp. 1–830, 2014.
- [11] P. Duxson, J. L. Provis, G. C. Lukey, and J. S. J. van Deventer, "The role of inorganic polymer technology in the development of 'green concrete,'" *Cem. Concr. Res.*, vol. 37, no. 12, pp. 1590–1597, 2007.
- [12] D. Wimpenny, "Low Carbon Concrete – Options for the Next Generation of Infrastructure Concrete Solutions 09 Paper 4a-1," *Concr. Solut. 09*, no. February, pp. 1–10, 2009.
- [13] J. L. Provis and J. S. J. Van Deventer, *Geopolymers: structures, processing, properties and industrial applications*. Elsevier, 2009.
- [14] Z. Zhang, Y. Zhu, T. Yang, L. Li, H. Zhu, and H. Wang, "Conversion of local industrial wastes into greener cement through geopolimer technology: A case study of high-magnesium nickel slag," *J. Clean. Prod.*, vol. 141, pp. 463–471, 2017.
- [15] F. Pacheco-Torgal, J. Labrincha, C. Leonelli, A. Palomo, and P. Chindaprasit, *Handbook of alkali-activated cements, mortars and concretes*. Elsevier, 2014.
- [16] P. R. Cunningham and S. A. Miller, "Quantitative assessment of alkali-activated materials: environmental impact and property assessments," *J. Infrastruct. Syst.*, vol. 26, no. 3, p. 4020021, 2020.
- [17] J. Davidovits and S. France, "Properties of Geopolymer Cements," 2018, no. October 1994, pp. 131–149.
- [18] G. Habert, J. B. D'Espinose De Lacaillerie, E. Lanta, and N. Roussel, "Environmental evaluation for cement substitution with geopolymers," *2nd Int. Conf. Sustain. Constr. Mater. Technol.*, pp. 1607–1615, 2010.
- [19] F. Lolli and K. E. Kurtis, "Life Cycle Assessment of alkali activated materials: preliminary investigation for pavement applications," *RILEM Tech. Lett.*, vol. 6, pp. 124–130, 2021.
- [20] C. Ouellet-Plamondon and G. Habert, "Life cycle assessment (LCA) of alkali-activated cements and concretes," in *Handbook of alkali-activated cements, mortars and concretes*, Elsevier, 2015, pp. 663–686.
- [21] S. R. Anvekar, L. R. Manjunatha, S. R. Anvekar, S. Sagari, and K. Archana, "An Economic and Embodied Energy Comparison of Geopolymer, Blended Cement and Traditional Concretes," *J. Civ. Eng. Technol. Res.*, vol. 1, no. November, pp. 33–40, 2014.
- [22] H. H. Weldes and K. R. Lange, "Properties of soluble silicates," *Ind. Eng. Chem.*, vol. 61, no. 4, pp. 29–44, 1969.
- [23] U. A. Against et al., "Safety data sheet," *Science Lab.com*, 2014. [Online]. Available: <https://www.sciencecompany.com/Sodium-Silicate-Solution-16oz-P6375.aspx>.
- [24] P. S. Matheu, K. Ellis, and B. Varela, "Comparing the environmental impacts of alkali activated mortar and traditional portland cement mortar using life cycle assessment," in *IOP Conference Series: Materials Science and Engineering*, 2015, vol. 96, no. 1, p. 12080.
- [25] O. Alelwee and S. Pavia, "An Evaluation of the Feasibility of Several Industrial Wastes and Natural Materials as Precursors for the Production of Alkali Activated Materials," *Int. J. Civ. Environ. Eng.*, vol. 13, no. 12, pp. 741–748, 2019.
- [26] O. Alelwee and S. Pavia, "Durability of Alkali-Activated Materials Made with a High-Calcium, Basic Slag," *Recent Prog. Mater.*, vol. 3, no. 4, pp. 1–1, 2021.
- [27] and P. K. Shi, Caijun, Della Roy, *Alkali-activated Cements and Concretes*. 2003.
- [28] R. Jones, M. McCarthy, and M. Newlands, "Fly ash route to low embodied CO2 and implications for concrete construction," in *World of Coal Ash Conference, Denver, Colorado, USA*, 2011.
- [29] B. STANDARD, "BS EN 196-10:2016 Methods of testing cement. Determination of the water-soluble chromium (VI) content of cement." BSI, p. 37, 2016.
- [30] M. A. Nisbet, M. G. VanGeem, J. Gajda, and M. Marceau, "Environmental life cycle inventory of portland cement concrete," *PCA R&D Ser.*, no. 2137a, 2000.
- [31] MPA, "Fact Sheet 18 Embodied CO 2 e of UK cement , additions and cementitious material," 2019.
- [32] ICE, "Embodied Carbon-Inventory of Carbon and Energy (ICE)," 2014.
- [33] N. Hepworth and M. Goulden, "Climate change in Uganda: Understanding the implications and appraising the response.," 2008.
- [34] L. Thannimalay, S. Yusoff, and N. Z. Zawawi, "Life cycle assessment of sodium hydroxide," *Aust. J. Basic Appl. Sci.*, vol. 7, no. 2, pp. 421–431, 2013.
- [35] M. Fawer, M. Concannon, and W. Rieber, "Life cycle inventories for the production of sodium silicates," *Int. J. Life Cycle Assess.*, vol. 4, no. 4, pp. 207–212, 1999.
- [36] J. Chen, P.-L. Ng, R. Jaskulski, and W. Kubissa, "Use of Quartz Sand to Produce Low Embodied Energy and Carbon Footprint Plaster," *J. Sustain. Archit. Civ. Eng.*, vol. 21, no. 4, 2018.
- [37] R. Ranade, "Advanced cementitious composite development for resilient and sustainable infrastructure." University of Michigan, 2014.
- [38] L. K. Turner and F. G. Collins, "Carbon dioxide equivalent (CO2-e) emissions: A comparison between geopolimer and OPC cement concrete," *Constr. Build. Mater.*, vol. 43, pp. 125–130, 2013.
- [39] A. Adesina, "Performance and sustainability overview of alkali-activated self-compacting concrete," *Waste Dispos. Sustain. Energy*, pp. 1–11, 2020.
- [40] S. Kim, "Engineering Sustainability of Mechanical Recycling of Carbon Fiber Composite Materials." p. 6, 2014.
- [41] E. Petrakis and K. Komnitsas, "Effect of Grinding Media Size on Ferronickel Slag Ball Milling Efficiency and Energy Requirements Using Kinetics and Attainable Region Approaches," *Minerals*, vol. 12, no. 2, p. 184, 2022.
- [42] Engineeringtoolbox.com, "Carbon Dioxide - Specific Heat of Gas vs. Temperature," 2001. [Online]. Available: https://www.engineeringtoolbox.com/carbon-dioxide-d_974.html.
- [43] B. Sonesson, U., Janestad, H., & Raaholt, "Energy for preparation and storing of food: models for calculation of energy use for cooking and cold storage in households," *SIK Institutet för livsmedel och bioteknik.*, 2003. .
- [44] B. C. Mendes et al., "Application of eco-friendly alternative activators in alkali-activated materials: A review," *J. Build. Eng.*, vol. 35, p. 102010, 2021.
- [45] B. J. Mathew, M. Sudhakar, and C. Natarajan, "Strength , Economic and Sustainability Characteristics of Coal Ash – GGBS Based Geopolymer Concrete," *International Journal Of Computational Engineering Research*, vol. 3, pp. 207–212, 2013.
- [46] M. E. Kalaw, A. Culaba, H. Hinode, W. Kurniawan, S. Gallardo, and M. A. Promentilla, "Optimizing and characterizing geopolymers from ternary blend of philippine coal fly ash, coal bottom ash and rice hull ash," *Materials*, vol. 9, no. 7, 2016.
- [47] I. Faridmehr, M. L. Nehdi, M. Nikoo, G. F. Huseien, and T. Ozbakkaloglu, "Life-Cycle Assessment of Alkali-Activated Materials Incorporating Industrial Byproducts," *Materials (Basel).*, vol. 14, no. 9, p. 2401, 2021.

Table 1. Composition of the AA RM materials (3:1 – sand: RM/FA/GGBS).

	RM		FA		GGBS		sand		Density		water		NaOH (6M)		Na ₂ SiO ₃	
	(g)	(%)	(g)	(%)	(g)	(%)	(g)	(%)	(g)	(%)	(g)	(%)	(g)	(%)	(g)	(%)
RM-1	450	20.23	—	—	—	—	1350	60.68	1853.84	252.49	11.35	68.67	3.09	103.45	4.65	
RM-2	450	19.71	—	—	—	—	1350	59.13	1902.53	247.75	10.85	72.20	3.16	163.08	7.14	
RM-3	450	19.07	—	—	—	—	1350	57.21	1966.53	230.24	9.76	75.13	3.18	254.47	10.78	
RMFA1	315	14.24	135	6.10	—	—	1350	61.05	1842.78	244.60	11.06	66.53	3.01	100.21	4.53	
RMFA2	315	13.88	135	5.95	—	—	1350	59.50	1890.68	240.46	10.60	70.07	3.09	158.29	6.98	
RMFA3	315	13.44	135	5.76	—	—	1350	57.59	1953.58	223.85	9.55	73.04	3.12	247.41	10.55	
RMFA4	225	10.17	225	10.17	—	—	1350	61.05	1842.78	244.60	11.06	66.53	3.01	100.21	4.53	
RMFA5	225	9.98	225	9.98	—	—	1350	59.88	1878.86	233.19	10.34	67.95	3.01	153.49	6.81	
RMFA6	225	9.53	225	9.53	—	—	1350	57.21	1966.53	230.24	9.76	75.13	3.18	254.47	10.78	
RMG1	315	14.16	—	—	135	6.07	1350	60.68	1853.84	252.49	11.35	68.67	3.09	103.45	4.65	
RMG2	315	13.88	—	—	135	5.95	1350	59.50	1890.68	240.46	10.60	70.07	3.09	158.29	6.98	
RMG3	315	13.44	—	—	135	5.76	1350	57.59	1953.58	223.85	9.55	73.04	3.12	247.41	10.55	
RMG4	225	10.17	—	—	225	10.17	1350	61.05	1842.78	244.60	11.06	66.53	3.01	100.21	4.53	
RMG5	225	9.98	—	—	225	9.98	1350	59.88	1878.86	233.19	10.34	67.95	3.01	153.49	6.81	
RMG6	225	9.60	—	—	225	9.60	1350	57.59	1953.58	223.85	9.55	73.04	3.12	247.41	10.55	
CEM II	450	22.22	—	—	—	—	1350	66.67	1687.50	225.00	11.11	—	—	—	—	

Table 2. Composition of the AA GGBS materials (3:1 – sand: GGBS).

	GGBS		sand		Density	water		NaOH (8M)		Na ₂ SiO ₃	
	(g)	(%)	(g)	(%)	kg/m ³	(g)	(%)	(g)	(%)	(g)	(%)
G1	450	21.9	1350	65.69	1712.56	124.37	6.05	64.08	3.12	66.62	3.24
G2	450	22.37	1350	67.11	1676.25	100.46	4.99	111.04	5.52	—	—
G3	450	21.31	1350	63.92	1759.88	128.25	6.07	41.85	1.98	141.75	6.712
G4	450	21.90	1350	65.69	1712.56	124.37	6.05	64.08	3.12	66.62	3.24
G5	450	22.37	1350	67.11	1676.25	100.46	4.99	111.04	5.52	—	—
G6	450	21.31	1350	63.92	1759.88	128.25	6.07	41.85	1.98	141.75	6.712

Table 3. Composition of the AA bauxite materials (3:1 – sand: bauxite/FA/GGBS).

	Bauxite		FA		GGBS		sand		Density		water		NaOH (6M)		Na ₂ SiO ₃	
	(g)	(%)	(g)	(%)	(g)	(%)	(g)	(%)	Kg/m ³	(g)	(%)	(g)	(%)	(g)	(%)	(g)
Bauxite +GGBS	225.00	11.12	—	—	225.00	11.12	1350	66.74	1685.71	127.46	6.30	41.10	2.03	54.29	2.68	
Bauxite +FA	225.00	9.89	225.00	9.89	—	—	1350	59.36	1895.37	238.55	10.89	85.39	3.75	150.50	6.62	

Table 6. Compressive strength and environmental impact of the AA RM materials (3:1 – sand: RM/FA/GGBS). Arithmetic means of CS = 11.76 N/mm² at 28 days, COV's =0.04-0.21. COV of PC mix = 0.1.

	CS MPa	% RM	% FA	% GGBS	% NaOH	% Na ₂ SiO ₃	EE MJ/kg	EC kgCO ₂ /kg
RM-1	4.53	20.23	—	—	3.09	4.65	1.43	0.18
RM-2	4.68	19.71	—	—	3.16	7.14	1.71	0.21
RM-3	1.69	19.07	—	—	3.18	10.78	1.88	0.20
RMFA1	6.87	14.24	6.10	—	3.01	4.53	1.27	0.16
RMFA2	10.85	13.88	5.95	—	3.09	6.98	1.55	0.19
RMFA3	5.74	13.44	5.76	—	3.12	10.55	1.72	0.18
RMFA4	9.90	10.17	10.17	—	3.01	4.53	1.18	0.15
RMFA5	11.54	9.98	9.98	—	3.01	6.81	1.43	0.17
RMFA6	8.90	9.53	9.53	—	3.18	10.78	1.66	0.17
RMG1	13.21	14.16	—	6.07	3.09	4.65	1.50	0.17
RMG2	9.52	13.88	—	5.95	3.09	6.98	1.75	0.20
RMG3	8.02	13.44	—	5.76	3.12	10.55	1.92	0.19
RMG4	27.48	10.17	—	10.17	3.01	4.53	1.52	0.16
RMG5	33.65	9.98	—	9.98	3.01	6.81	1.77	0.19
RMG6	12.59	9.60	—	9.60	3.12	10.55	1.97	0.18
CEM II	37.18	—	—	—	—	—	3.31	0.45

Table 7. Compressive strength and environmental impact of the alkali-activated GGBS and bauxite materials (3:1 – sand: GGBS/bauxite/FA/GGBS). COV's AA GGBS=0.01-0.48; COV's AA bauxites = 0.41-0.63.

	GGBS (%)	Bauxite (%)	FA (%)	Curing t (°C)	NaOH (6M) (%)	Na ₂ SiO ₃ (%)	CS (MPa)	EE (MJ/kg)	Eco ₂ - (kgCO ₂ /kg)
G1	21.90	—	—	20	3.12	3.24	25.70	1.48	0.14
G2	22.37	—	—	20	5.52	—	17.56	1.34	0.14
G3	21.31	—	—	20	1.98	6.71	5.21	1.75	0.16
G4	21.90	—	—	60	3.12	3.24	33.69	1.49	0.14
G5	22.37	—	—	60	5.52	—	12.03	1.35	0.14
G6	21.31	—	—	60	1.98	6.71	2.92	1.76	0.16
Bauxite + GGBS	11.12	11.12	—	20	2.03	2.68	60.41	1.52	0.16
Bauxite + FA	—	9.89	9.89	20	3.75	6.62	33.12	1.78	0.22
CEM II	—	—	—	20	—	—	37.18	3.31	0.45

Table 8. Summary of environmental impact vs strength results (MPa). EE (MJ/kg), EC (kgCO₂/kg). E COV's = 0.06 – 0.62. % Δ -Arithmetic mean of the percentage variation compared with CEM II equivalent.

%Δ	AA RM materials			AA GGBS materials			AA Bauxite + GGBS			AA Bauxite + FA			PC equivalents		
	EE	ECO ₂	CS	EE	ECO ₂	CS	EE	ECO ₂	CS	EE	ECO ₂	CS	EE	ECO ₂	CS
	1.62	0.18	11.76	1.53	0.15	16.19	1.52	0.16	60.41	1.78	0.22	33.12	3.31	0.45	37.18
	-50	-22	-65	-54	-67	-55	-54	-64	+40	-46	-53	0			

O. Alalweat, S. Pavia (2022) A comparative study of the environmental impact of alkali activated and traditional materials. Civil Eng. Research Ireland. Holmes, De Paor, West Eds. ISBN 978-0-9573957-5-6. Publ. by Civil Eng. Research Association of Ireland. p. 613-618.