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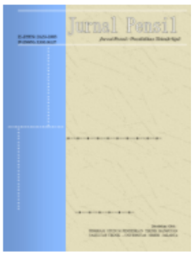

THE EFFECT OF ALKALI ACTIVATOR MOLARITY ON THE MECHANICAL PERFORMANCE OF GEOPOLYMER PAVING BLOCKS BASED ON WASTE GLASS POWDER AND FLY ASH

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Abstract

The effect of concentration of sodium hydroxide (NaOH) on physical and mechanical properties of geopolymer paving blocks consist of fly ash type F and glass powder. A quantitative experimental method was used both the NaOH molarity (1M, 2M, 4M, 6M, 8M and 10M) was studied and the compressive strength, flexure strength and water absorption were taken as key parameters. The ratio of alkali activator to binder was 0.35, and the ratio of Sodium Silicate/NaOH was 1.5. The best performance at 4M molarity yielded compressive strength of 35.60 MPa and flexural strength of 4.29 MPa, due to optimal geopolymerization and denser microstructure. The mechanical performance of the geopolymer paving blocks was compromised at NaOH molarities higher than 4M due to the emergence of a micropore, which increased the porosity and water absorption from 6.55% at 1M to 9.14% at 10M. These results confirm that increasing NaOH molarity is vital for producing geopolymer paving block with high performance. Hence, this study contributes to sustainable construction by using waste products of industries for producing construction and building materials.

Keywords: Fly ash, Geopolymer Paving Block, Glass Powder, NaOH

Introduction

Portland cement manufacture contributes between 5 - 7% to global CO_2 emissions, making the construction industry among the biggest single contributors. These facts constitute a major challenge for climate change mitigation, as almost 0.9 tons of CO_2 is emitted for each ton of cement produced (Davidovits, 2015; Gholampour et al., 2019). The cement is an essential construction component for the modern civilization as it is used on a large scale in the global cement industry, which keeps growing owing to increasing demand for infrastructure and urbanization, especially in developing areas of the world (e.g., Sub-Saharan Africa and Central Asia) (Aziz et al., 2024; Chen et al., 2023; Xi et al., 2016). Global cement production grew from 0.6 Gt in 1970 to 4.2 Gt in 2020 Nevertheless, its production process turned to be an important contributor to the emissions of air pollutants, which influences the atmospheric environment in the region (Klimont et al., 2017; Liu et al., 2015; Q. Zhang et al., 2007). Global cement demand is expected to keep rising along with the economic growth of developing countries (Cheng et al., 2023). In addition, cement production spills a lot of natural resources, which is harmful to ecological sustainability.

Geopolymers as more environmentally friendly alternative materials, can provide a solution. The burning of solid fuels such as coal produces air pollution, as well as byproducts like fly ash (when the fuel is burned), which comes from the non-flammable mineral residue in the fuel. However, energy generation from coal, heavy oil and biomass generates fly ash, which should be managed accordingly to avoid environmental impacts. Not only does fly ash reuse be an environmentally friendly and economical approach, but it is particularly important because the global coal consumption remains on a high level (Luo et al., 2021; Nath, 2020; Srividya et al., 2022). Fly ash, with a small particle size (1–500 µm), is exhausted with flue gases and is often captured by electrostatic precipitators (Lanzerstorfer, 2018). This ash contains elements such as silicon, aluminum, iron, and other trace elements, with compositions depending on the fuel, technology, and combustion conditions (Ahmaruzzaman, 2010; Belviso et al., 2015; Zhao et al., 2020).

Granular types such as cenospheres have high application potential due to their chemical and mechanical properties (Ranjbar & Kuenzel, 2017; Żyrkowski et al., 2016). The construction industry has witnessed the extensive utilization of fly ash in concrete and geopolymers (Ahmaruzzaman, 2010; Yao et al., 2015), which is consistent with circular economy principles. Investigations of fly ash play an important role in the development of its applications through pozzolanic reactivity, which in turn can result in more resistant and durable concretes (Kusuma et al., 2014; Xu & Shi, 2018). Its use also decreases the consumption of natural resources and CO_2 emissions. For instance, 45% cost reduction and 55% reduction in CO_2 emissions was reported when contributing fly ash to Engineered Cementitious Composites (Xu & Shi, 2018). Moreover, it is possible to use fly ash in the production of CO2 sorbents, mineral sequestration, zeolites or recovery of strategic metals, which remains in favour of environmental and economic sustainability (Uliasz-Bocheńczyk & Mokrzycki, 2020).

Apart from fly ash, waste glass is another potential material that has been used as a replacement. It can be processed into waste glass powder (WGP) which has pozzolanic properties akin to those of fly ash. WGP reacts with calcium hydroxide released due to cement hydration, producing calcium silicate hydrate (C-S-H) gel, which causes the improvement in the strength and long-term performance of Portland Cement (PC) (Gomes Silveira et al., 2022; Jiang et al., 2022; Matos et al., 2024). Besides, WGP can enhance the working property and flowability of PC, and its fine spherical particles can refine pore structures as well as decrease the risk of water penetration and improve the damage resistance for sulfate attack and alkali-silica reaction (Abed et al., 2024; Omran et al., 2018). WGP has an environmental advantage over cement production with a high carbon perspective which is a major concern in industrial production; WGP is based on industrial glass waste (Bostanci, 2020; Gao et al., 2022). Due to its wide availability and being inexpensive, WGP may be used for replacement material of cement (Matos et al., 2024). The addition of such

WGP partially replacement of cement and enhanced the compressive strength, flexural strength, and durability and minimized the cement content (Li et al., 2021). On the other hand, a combination of WGP as a cement replacer and crushed waste glass (CWG) as coarse aggregate has been reported on a new hybrid approach required to improve the properties of PC, thus significantly mitigating its environmental impact (Ju et al., 2023; S. N. Mahdi et al., 2022; Shen et al., 2020; Tchakouté et al., 2016).

In geopolymer applications, sodium hydroxide (NaOH) is considered one of the major alkaline activators in the geopolymerization process. Alkaline activator acts as an accelerator in the geopolymeric reaction between the silica-alumina source materials and alkaline solutions resulting in a stable geopolymer structure (Marathe et al., 2024). Optimized concentration of NaOH could achieve superior mechanical strength and durability of geopolymers, which can create an eco-friendly substitute (Fareeddahmeddmemon, 2013; Joseph Davidovits, 1994; H. Y. Zhang et al., 2019). Furthermore, NaOH also promotes the addition of other industrial wastes like fly ash and slag in smart and sustainable materials development. A vast body of literature has shown that the concentration of sodium hydroxide, NaOH, has a major effect on the setting time, compressive strength, and workability of geopolymers (Sunarsih, As'ad, Mohd. Sam, et al., 2023). Setting times increases with lower molarities, while compressive strengths decrease; Higher molarity give optimal compressive strength, while experiencing less workability (Sunarsih, As'ad, Sam, et al., 2023). The combination of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) has also been found to enhance the mechanical properties of geopolymers when used in certain proportions (F. Mahdi et al., 2010). Geopolymer paving blocks have been shown to be more resistant to long-term freezing-thawing cycles than conventional cement-based paving blocks (Jonbi & Fulazzaky, 2020).

The novelty of this research lies in the synthesis of geopolymer paving blocks using fly ash and waste glass powder, addressing an existing gap in sustainable construction identified by previous studies. Nath (2020), for example, studied only fly ash in the creation of geopolymer fly ash paving blocks, and did not consider other waste products. Similarly, (Shen et al., 2020) studied the use of crushed waste glass in concrete, but not in geopolymers. In contrast to these studies, this study encompasses fly ash and waste glass powder and aims to markedly improve the mechanical behavior and green performance of the studied binder, exploiting their interactive pozzolanic behavior. This study is unique because it details how molarity of sodium hydroxide (NaOH) affects the mechanical characteristics of geopolymer paving blocks. Although previous studies, including those by Sunarsih, As'ad, Mohd. Sam, et al. (2023), although they did not study the interaction of blended waste material like glass powder and fly ash, they studied the effect of NaOH molarity on compressive strength and workability in geopolymer mortars. This study further builds on this by optimizing NaOH molarity towards achieving an optimized balance of geopolymerization reactions alongside a reduction in the formation of micropores; a common bottleneck in high molarity systems (S. N. Mahdi et al., 2022). The outcomes not only contribute to the development of eco-friendly construction materials but also pave the way for sustainable practices by transforming industrial waste into high-value construction products. This investigation thus bridges gaps in existing research by combining innovative material usage with an in-depth study of alkali activator effects on paving block performance.

Research Methods

Investigate the influence of alkaline activator molarity variations (1M, 2M, 4M, 6M, 8M, and 10M) against the mechanical properties of geopolymer paving blocks based on 30% waste glass powder and fly ash type F with a quantitative experimental method, pretest and post-test design. The laboratory study was carried out in three months (August 2024–October 2024), where curing of paving blocks was done in the oven at a temperature of ±80oC in 24 hours and conducted at the Civil Engineering Materials Laboratory of Universitas 17 Agustus 1945 Jakarta. The study aims to improve the mechanical performance and durability of geopolymer paving blocks made from fly ash and glass powder. The test specimens of the samples were 108, including three main parameters, including the compressive strength, flexural strength, and water absorption for each molarity group.

The experimental procedure included the production of paving blocks with uniformized material compositions, interference of NaOH molarity as the treatment, and testing of each parameter with six samples per molarity group. In this research, the alkali activator to binder ratio was 0.35, the ratio of Sodium Silicate/Sodium Hidroxide was 1.5. The compressive strength testing consisted of determining the maximum pressure before the test object experienced failure, and was performed following the guidelines outlined in SNI 03-0691-1996. Flexural strength was measured in accordance with ASTM C78 specification, which involved loading until fracture occurred to measure flexural strength. The percentage of water absorbance of the paving blocks were measured by the immersion method according to ASTM C140. Universal compression testing machine, flexural strength testing machine, and water absorption testing device were used as research instruments, controlling laboratory conditions to ensure consistent data. The retrieved data were then analyzed and plotted to illustrate the correlation between changes in molarity and the mechanical behavior of paving blocks, offering thus optimal suggestions for the design of sustainable construction materials.

Research Results and Discussion

In this study, the impact of using varying molarity of the alkaline activator on the mechanical characteristics of ambient-cured geopolymer paving blocks based on waste glass powder and fly ash is investigated. This research variable evidence is the NaOH molarity (1M, 2M, 4M, 6M, 8M and 10M) as the activator, while the tested parameter includes compressive strength, flexural strength and water absorption. The most striking of the findings among the obtained results is a close correlation of the alkali concentration with the mechanical properties and durability of geopolymer materials. The ensuing explanation correlates the findings with geopolymerization theory to yield some better understanding.

The Effect of NaOH Molarity on the Compressive Strength of Paving Blocks

Compressive strength is a key characteristic parameter indicating the mechanical performance of paving blocks, in that it represents the capacity of the material to resist compressive load up to the point of rupture. Geopolymer paving blocks compressive strength is highly dependent on geopolymerization, where an alkaline solution is used as an activator for the dissolution of silica-alumina sources in fly ash and glass powder. This reaction creates a very dense and homogeneous microstructure, which is one of the main factors for the load-bearing capacity of a material. This parameter stands as a significant factor in determining the effects of varying NaOH molarity on geopolymer paving blocks both in terms of quality and performance.

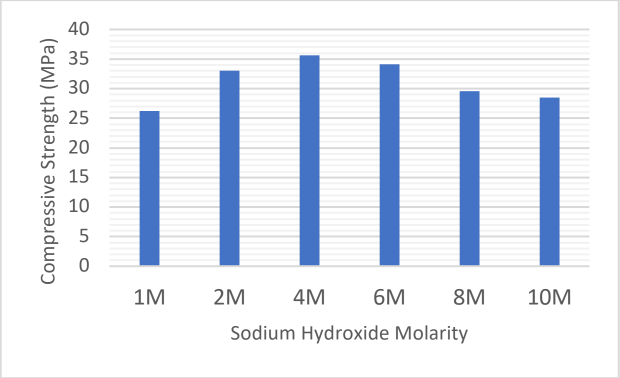

Figure 1. Effect of NaOH Molarity on the Compressive Strength of Paving Blocks

The average compressive strength of geopolymer paving blocks with NaOH molarity variations of 1M, 2M, 4M, 6M, 8M and 10M was 26.20 MPa, 33.07 MPa, 35.60 MPa, 34.13 MPa, 29.53 MPa, and 28.47 MPa respectively. The compressive strength test shows that there is a positive linear correlation of increase in the NaOH molarity and the compressive strength of the paving blocks up to 4M, which shows that increasing alkali concentration in the experimental range enhances the chemical reaction of the constituent materials, forming a more dense and stable material structure. max for 4M molarity where conditions are favorable for the geopolymerization reaction. The hydroxyl (OH^-) ions that are present in the alkaline solution catalyze the dissolution of silica-alumina components in the fly ash and glass powder. During the dissolution, a solution rich in silicates and aluminates is formed which undergoes polycondensation to result in a complex 3-dimensional N-A-S-H gel (Sodium Aluminosilicate Hydrate). This structure serves the dual purpose of being the mechanical backbone of the paving block as well as providing it with high resistance to compressive loads. Similar findings were reported by Davidovits (2015) where the formation of N-A-S-H gel was identified as a critical factor in enhancing the mechanical properties of geopolymers.

The optimal compressive strength can be attributed to chemical reaction balance and particle distribution of the material matrix, thereby giving 4M molarity its best results. This concentration of OH^- ions is sufficient to dissolve the precursor materials while preventing unwanted side reactions—the formation of alkali residues or gases that could disrupt structure. This ensures that a continuous geopolymatix is generated without the formation of any microstructural defects, vital for retaining the integrity of the mass under high loads applied. Gholampour et al. (2019) also observed that optimal molarity levels lead to a denser and more homogenous microstructure, contributing to higher compressive strength in geopolymer materials. But beyond NaOH molarity of 4M, the compressive strength reduces. This is due to excessive reactions from alkali ions leading to the formation of a porous microstructure for 8M and 10M molarity. This excess of OH^- ions can accelerate dissolution and polycondensation, but if this concentration is exceeded, the opposite effect is observed. Hydroxide is then released, whereas high levels of OH^- ions can cause gas bubbles during the process, which, since they wish to rise up into the atmosphere, get caught in the material matrix and create pores that weaken the density of the material. This phenomenon aligns with findings by S. N. Mahdi et al. (2022) who noted that excessive alkali concentrations result in pore formation, reducing the mechanical integrity of geopolymers. Not only do these pores decrease the material's ability to resist compressive loads, they also make it more prone to the formation of microcracks, which can lead to structural failure. Also, excess alkali ratio will unbalance the reactions at high molarities, where some precursors will be only partially reacted. This yields unbonded alkali or silica-alumina residues in the geopolymer network, mitigating their contributions to the mechanical strength. These residues can also act as a weak point within the material, which results in low performance of paving blocks in terms of compressive loads. Sunarsih, As'ad, Mohd. Sam, et al. (2023) highlighted similar challenges, where high molarity NaOH led to unreacted precursors, weakening the material structure. These results show that careful control of alkali concentrations in the geopolymer paving block production process is important so that the composites produced have a good microstructure and a consistent mechanical performance.

Therefore, this study demonstrates that even if NaOH is the primary agent of geopolymerization, its usage should be as much as the optimal range requires. A suitable NaOH molarity would optimize the efficiency of the reaction while avoiding material structure defects that would reduce mechanical capacity. As an example, the compressive strength obtained with the 4M molarity treatment in this research (35.60 MPa) satisfies the minimum compressive strength requirement in SNI 03-0691996 for Class A paving blocks. These findings support the need for a science-based algorithm regarding the design of geopolymer material, where each processing parameter, needs to be individually optimized in order to maximize the best balance between chemical adhesion and structural integrity.

The Effect of NaOH Molarity on the Flexural Strength of Paving Blocks

One of the most significant determined parameters for the pavement blocks is the flexural strength. This parameter indicates the integrity of the material matrix in resisting loads potentially causing cracks or fractures.

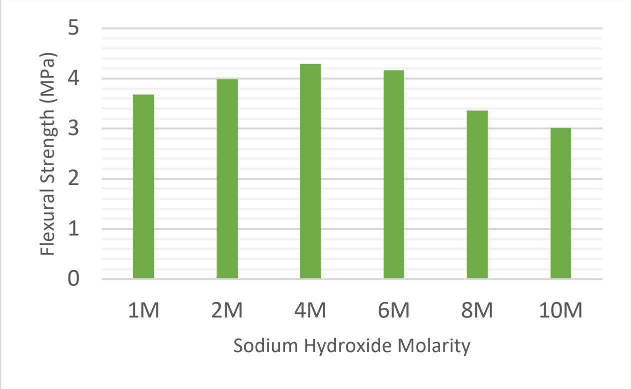

Figure 2. The Effect of NaOH Molarity on the Flexural Strength of Paving Blocks

According to the data in Figure 2, the flexural strength of geopolymer paving blocks based on NaOH molarity variations of 1M, 2M, 4M, 6M, 8M, and 10M had average results of 3.68 MPa, 3.99 MPa, 4.29 MPa, 4.16 MPa, 3.36 MPa, and 3.02 MPa, respectively. Flexural strength tests are showing an increase, reaching its maximum at the 4M NaOH molarity, and then decreasing for higher molarities. The flexural strength of 2 M, 3 M and 5 M is less than that of 4 M, showing that 4 M of alkali can promote dissolution of silica-alumina, tube wall density and uniformity of material matrix. Under these conditions, a microstructure was developed (in 7.5 - 17.5 wt%) to uniformly distribute the load, enabling the resistance of flexural forces in the material.

Although the flexural strength is slightly decreased at 6M molarity. Although this decrease is negligible, it could also be due to limitations in the active site performance as alkali concentrations approach saturation thresholds. This results in inhomogeneous distribution of OH^- ions, limiting the polycondensation process. The is observed for a sharp drop in flexural strength at molarities 8 M and 10 M. The decrease can be attributed to micro-pores formation as excess OH^- ions cause disruption of the material’s microstructural stability. An excessive amount of alkali may also hasten the primary reaction, leading to the lack of uniform distribution of precursor materials in the matrix. This aligns with findings by Gholampour et al. (2019) who observed that uneven precursor distribution in geopolymers results in weaker structural bonds and reduced flexural strength. As a result, the material's ability to resist flexural forces is reduced, and microcracks are formed and propagated more easily under load.

The degree of decline at the higher molarities shows that too much alkali does not help but instead appears to reduce the quality of the material. Thus, for the flexural strength parameter of geopolymer paving blocks, an NaOH molarity of 4M can be valued as the optimal value. This concentration hits equilibrium in the geopolymerization reaction that creates a well-building material because of the enhanced mechanical thermodynamic integrity that shows resistance to flexural loads. The flexural strength achieved at 4M molarity in this study (4.29 MPa) meets the requirements for paving blocks, as outlined in ASTM C936-19, which specifies a minimum flexural strength of 4 MPa for interlocking concrete pavers. These results contribute to the understanding on geopolymer-based paving blocks design, characterized by stringent control of the alkali concentration required for producing mechanically robust and long-term stable materials.

The Effect of NaOH Molarity on the Water Absorption of Paving Blocks

Water absorption is an important factor in assessing the quality of paving blocks, which reflects the material's capacity to absorb water from the environment.

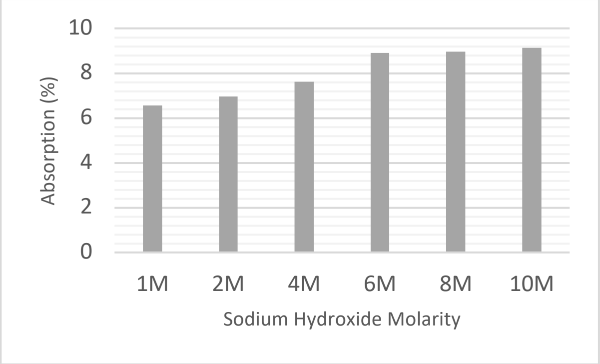

Figure 3. The Effect of NaOH Molarity on the Water Absorption of Paving Blocks

The average water absorption for geopolymer paving blocks with NaOH molarity variations of 1M, 2M, 4M, 6M, 8M, and 10M was 6.55%, 6.96%, 7.63%, 8.89%, 8.97%, and 9.14% respectively as seen in Figure 3. The test results showed a tendency towards absorption with higher NaOH molarity. According to SNI 03-0691-1996, the maximum water absorption value for paving blocks in Class A is 6% for areas with heavy traffic and 10% for general applications. The values obtained in this study fall within the acceptable range for general applications. This indicates that the material has relatively low porosity and enhances the idea that during geopolymerization the dissolution of precursor materials facilitates porosity but it is possible that such pores do not stabilize; thus they should be in a continuing process of formation.

However, at lower molarities, relatively low absorption values show that due to effective geopolymerization, a denser microstructure is being developed. Within this range, the OH^- ions from NaOH solution assist to dissolve the precursors (fly ash and glass powder) and create a matrix (with a more homogeneous distribution of particles). This makes it more challenging for water to penetrate the structure, as microvoids or pores in the material are limited. This finding aligns with the study by (Xu & Shi, 2018), which highlighted that optimal geopolymerization reactions lead to a denser matrix with minimal porosity, thereby reducing water absorption. As a result, this generates a material with inherently low water uptake that is an attractive feature for use in applications where the materials are exposed to high water contents. But NaOH molarity > 4M absorbance values increase so much. This rise shows that high concentrations of alkali ions are starting to influence the microstructure formation in the material. The geopolymerization reaction might produce excess OH^- ions, which will lead to gas production or unreacted alkali residues at this time. These effects create micro-pores or voids in the matrix and contribute to the overall porosity of the material. This added porosity translates to the material's ability to absorb more water.

The upward trend implies the critical fluctuation in NaOH molarity for geopolymer paving blocks production as the result of absorption. At particularly high molarities, the geopolymerization will occur more quickly, but the structure of the material is less compact and more prone to water ingress. This can reduce the material's life, particularly in the case of paving blocks used in damp or waterlogged areas. This concern is consistent with findings by Jonbi & Fulazzaky (2020), who emphasized that high water absorption negatively impacts the durability of geopolymer paving blocks, especially in freeze-thaw conditions. One should also keep in mind that high water absorption can contribute to damage to the material over time -- be it through freeze-thaw cycles or chemical reactions that water can have with substances that have dissolved in it. NaOH molarity optimization is, therefore, of great importance while designing geopolymer paving blocks. It helps gather that ideal NaOH molarity is lower than 4M which will not affect elasticity/efficiency of geopolymerization reaction due to less porosity.

Conclusion

Experimental work has been performed to understand the influence of NaOH molarity on the mechanical and physical properties of geopolymer paving blocks. The molarity of 4M showed the highest efficiency of geopolymerization reaction in terms of maximum compressive and flexural strength. At elevated molarities (>4M), mechanical performance worsened owing to micro-pores and increased porosity of the material. It is also in line with the trend of water absorption, which is maximal at 10M molarity due to the less compact structure of the material. The novelty of this research originates from addressing the combined use of fly ash and waste glass powder as geopolymer precursors, which has not been studied nor explored in previous works. Moreover, this study also goes into optimizing NaOH molarity to neutralize geopolymerization in order to obtain a higher microstructure density and reduce the challenge of micropore formation in high-molarity systems. This study shows that with respect to mechanical performance and durability 4M molarity provides the most beneficial ratio that can be used as a tool for the development of sustainable geopolymer paving blocks. Such results stress the importance of tight control of the alkali molarity in the geopolymer application process and plays a decisive role in the geopolymer paving block optimization in terms of reactivity, final volume and strength indices. Meanwhile, the synergism and forthwith trend of the mechanical durability and water resistance enable the above 4 M molarity geopolymer paving blocks to be the best performing paving blocks with excellent mechanical durability and water resistance, thus making it suitable to be used in construction applications.

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References

Abed, H. S., Al-Saffar, Z. H., & Hamad, A. J. (2024). Synergistic effect of the silica fume and glass powder as pozzolanic materials in cement mortar. *International Journal of Sustainable Building Technology and Urban Development*, *15*(1), 43–56. https://doi.org/10.22712/susb.20240004

Ahmaruzzaman, M. (2010). A review on the utilization of fly ash. *Progress in Energy and Combustion Science*, *36*(3), 327–363. https://doi.org/10.1016/j.pecs.2009.11.003

Aziz, A., Mehboob, S. S., Tayyab, A., Khan, D., Hayyat, K., Ali, A., & Latif Qureshi, Q. B. I. (2024). Enhancing sustainability in self-compacting concrete by optimizing blended supplementary cementitious materials. *Scientific Reports*, *14*(1), 12326. https://doi.org/10.1038/s41598-024-62499-w

Belviso, C., Cavalcante, F., Di Gennaro, S., Palma, A., Ragone, P., & Fiore, S. (2015). Mobility of trace elements in fly ash and in zeolitised coal fly ash. *Fuel*, *144*, 369–379. https://doi.org/10.1016/j.fuel.2014.12.037

Bostanci, L. (2020). Effect of waste glass powder addition on properties of alkali-activated silica fume mortars. *Journal of Building Engineering*, *29*, 101154. https://doi.org/10.1016/j.jobe.2019.101154

Chen, P., Zhang, S., Meng, J., Lei, T., Li, B., & Coffman, D. (2023). Technological Solutions to China's Carbon Neutrality in the Steel and Cement Sectors. *Earth's Future*, *11*(9). https://doi.org/10.1029/2022EF003255

Cheng, D., Reiner, D. M., Yang, F., Cui, C., Meng, J., Shan, Y., Liu, Y., Tao, S., & Guan, D. (2023). Projecting future carbon emissions from cement production in developing countries. *Nature Communications*, *14*(1), 8213. https://doi.org/10.1038/s41467-023-43660-x

Davidovits, J. (2015). *Geopolymer Institute Library. Technical paper #24, False-CO2-values.* http://www.materialstoday.com/polymers-soft-materials/features/environmental-implications-of-geopolymers/

Fareed Ahmed Memon. (2013). *Effect of Sodium Hydroxide Econcentration on Fresh Properties and Compressive Strength of Self-Compacting Geopolymer Concretee* (Vol. 8)

Gao, X., Yao, X., Xie, R., Li, X., Cheng, J., & Yang, T. (2022). Performance of fly ash-based geopolymer mortars with waste cathode ray tubes glass fine aggregate: A comparative study with cement mortars. *Construction and Building Materials*, *344*. https://doi.org/10.1016/j.conbuildmat.2022.128243

Gholampour, A., Ho, V. D., & Ozbakkaloglu, T. (2019). Ambient-cured geopolymer mortars prepared with waste-based sands: Mechanical and durability-related properties and microstructure. *Composites Part B: Engineering*, *160*, 519–534. https://doi.org/10.1016/j.compositesb.2018.12.057

Gomes Silveira, N. C., Figueiredo Martins, M. L., Bezerra, A. C. da S., & Gabriel da Silva Araújo, F. (2022). Ecological geopolymer produced with a ternary system of red mud, glass waste, and Portland cement. *Cleaner Engineering and Technology*, *6*. https://doi.org/10.1016/j.clet.2021.100379

Jiang, X., Xiao, R., Bai, Y., Huang, B., & Ma, Y. (2022). Influence of waste glass powder as a supplementary cementitious material (SCM) on physical and mechanical properties of cement paste under high temperatures. *Journal of Cleaner Production*, *340*, 130778. https://doi.org/10.1016/j.jclepro.2022.130778

Jonbi, J., & Fulazzaky, M. A. (2020). Modeling the water absorption and compressive strength of geopolymer paving block: An empirical approach. *Measurement: Journal of the International Measurement Confederation*, *158*. https://doi.org/10.1016/j.measurement.2020.107695

Joseph Davidovits. (1994). *Environmental implications of Geopolymers - Materials Today.* https://www.materialstoday.com/polymers-soft-materials/features/environmental-implications-of-geopolymers/

Ju, M., Rashid, K., Zafar, I., & Ltifi, M. (2023). Developing FA-based cementless binder composite by opting sustainable technology: Application of brick and paving block. *Engineering Science and Technology, an International Journal*, *48*. https://doi.org/10.1016/j.jestch.2023.101580

Klimont, Z., Kupiainen, K., Heyes, C., Purohit, P., Cofala, J., Rafaj, P., Borken-Kleefeld, J., & Schöpp, W. (2017). Global anthropogenic emissions of particulate matter including black carbon. *Atmospheric Chemistry and Physics*, *17*(14), 8681–8723. https://doi.org/10.5194/acp-17-8681-2017

Kusuma, A., Steenie, P., Wallah, E., & Dapas, S. O. (2014). KUAT TARIK BELAH BETON GEOPOLYMER BERBASIS ABU TERBANG (FLY ASH). *Jurnal Sipil Statik*, *2*(7), 330–336.

Lanzerstorfer, C. (2018). Fly ash from coal combustion: Dependence of the concentration of various elements on the particle size. *Fuel*, *228*, 263–271. https://doi.org/10.1016/j.fuel.2018.04.136

Li, A., Qiao, H., Li, Q., Hakuzweyezu, T., & Chen, B. (2021). Study on the performance of pervious concrete mixed with waste glass powder. *Construction and Building Materials*, *300*, 123997. https://doi.org/10.1016/j.conbuildmat.2021.123997

Liu, F., Zhang, Q., Tong, D., Zheng, B., Li, M., Huo, H., & He, K. B. (2015). High-resolution inventory of technologies, activities, and emissions of coal-fired power plants in China from 1990 to 2010. *Atmospheric Chemistry and Physics*, *15*(23), 13299–13317. https://doi.org/10.5194/acp-15-13299-2015

Luo, Y., Wu, Y., Ma, S., Zheng, S., Zhang, Y., & Chu, P. K. (2021). Utilization of coal fly ash in China: a mini-review on challenges and future directions. *Environmental Science and Pollution Research*, *28*(15), 18727–18740. https://doi.org/10.1007/s11356-020-08864-4

Mahdi, F., Abbas, H., & Khan, A. A. (2010). Strength characteristics of polymer mortar and concrete using different compositions of resins derived from post-consumer PET bottles. *Construction and Building Materials*, *24*(1), 25–36. https://doi.org/10.1016/j.conbuildmat.2009.08.006

Mahdi, S. N., Babu R, D. V., Hossiney, N., & Abdullah, M. M. A. B. (2022). Strength and durability properties of geopolymer paver blocks made with fly ash and brick kiln rice husk ash. *Case Studies in Construction Materials*, *16*. https://doi.org/10.1016/j.cscm.2021.e00800

Marathe, S., Sadowski, Ł., & Shree, N. (2024). Geopolymer and alkali-activated permeable concrete pavements: Bibliometrics and systematic current state of the art review, applications, and perspectives. In *Construction and Building Materials* (Vol. 421). Elsevier Ltd. https://doi.org/10.1016/j.conbuildmat.2024.135586

Matos, A. M., Milheiro-Oliveira, P., & Pimentel, M. (2024). Eco-efficient high performance white concrete incorporating waste glass powder. *Construction and Building Materials*, *411*, 134556. https://doi.org/10.1016/j.conbuildmat.2023.134556

Nath, S. K. (2020). Fly ash and zinc slag blended geopolymer: Immobilization of hazardous materials and development of paving blocks. *Journal of Hazardous Materials*, *387*. https://doi.org/10.1016/j.jhazmat.2019.121673

Omran, A., Soliman, N., Zidol, A., & Tagnit-Hamou, A. (2018). Performance of Ground-Glass Pozzolan as a Cementitious Material—A Review. *Advances in Civil Engineering Materials*, *7*(1), 237–270. https://doi.org/10.1520/ACEM20170125

Ranjbar, N., & Kuenzel, C. (2017). Cenospheres: A review. *Fuel*, *207*, 1–12. https://doi.org/10.1016/j.fuel.2017.06.059

Shen, P., Zheng, H., Liu, S., Lu, J.-X., & Poon, C. S. (2020). Development of high-strength pervious concrete incorporated with high percentages of waste glass. *Cement and Concrete Composites*, *114*, 103790. https://doi.org/10.1016/j.cemconcomp.2020.103790

Srividya, T., Kannan Rajkumar, P. R., Sivasakthi, M., Sujitha, A., & Jeyalakshmi, R. (2022). A state-of-the-art on development of geopolymer concrete and its field applications. *Case Studies in Construction Materials*, *16*. https://doi.org/10.1016/j.cscm.2021.e00812

Sunarsih, E. S., As'ad, S., Mohd. Sam, A. R., & Kristiawan, S. A. (2023). The effect of sodium hydroxide molarity on setting time, workability, and compressive strength of fly ash-slag-based geopolymer mortar. *Journal of Physics: Conference Series*, *2556*(1). https://doi.org/10.1088/1742-6596/2556/1/012019

Sunarsih, E. S., As'ad, S., Sam, A. R. M., & Kristiawan, S. A. (2023). Properties of Fly Ash-Slag-Based Geopolymer Concrete with Low Molarity Sodium Hydroxide. *Civil Engineering Journal (Iran)*, *9*(2), 381–392. https://doi.org/10.28991/CEJ-2023-09-02-010

Tchakouté, H. K., Rüscher, C. H., Kong, S., Kamseu, E., & Leonelli, C. (2016). Geopolymer binders from metakaolin using sodium waterglass from waste glass and rice husk ash as alternative activators: A comparative study. *Construction and Building Materials*, *114*, 276–289. https://doi.org/10.1016/j.conbuildmat.2016.03.184

Uliasz-Bocheńczyk, A., & Mokrzycki, E. (2020). The potential of FBC fly ashes to reduce CO2 emissions. *Scientific Reports*, *10*(1), 9469. https://doi.org/10.1038/s41598-020-66297-y

Xi, F., Davis, S. J., Ciais, P., Crawford-Brown, D., Guan, D., Pade, C., Shi, T., Syddall, M., Lv, J., Ji, L., Bing, L., Wang, J., Wei, W., Yang, K.-H., Lagerblad, B., Galan, I., Andrade, C., Zhang, Y., & Liu, Z. (2016). Substantial global carbon uptake by cement carbonation. *Nature Geoscience*, *9*(12), 880–883. https://doi.org/10.1038/ngeo2840

Xu, G., & Shi, X. (2018). Characteristics and applications of fly ash as a sustainable construction material: A state-of-the-art review. *Resources, Conservation and Recycling*, *136*, 95–109. https://doi.org/10.1016/j.resconrec.2018.04.010

Yao, Z. T., Ji, X. S., Sarker, P. K., Tang, J. H., Ge, L. Q., Xia, M. S., & Xi, Y. Q. (2015). A comprehensive review on the applications of coal fly ash. *Earth-Science Reviews*, *141*, 105–121. https://doi.org/10.1016/j.earscirev.2014.11.016

Zhang, H. Y., Yan, J., Kodur, V., & Cao, L. (2019). Mechanical behavior of concrete beams shear strengthened with textile reinforced geopolymer mortar. *Engineering Structures*, *196*. https://doi.org/10.1016/j.engstruct.2019.109348

Zhang, Q., Streets, D. G., He, K., Wang, Y., Richter, A., Burrows, J. P., Uno, I., Jang, C. J., Chen, D., Yao, Z., & Lei, Y. (2007). NO x emission trends for China, 1995–2004: The view from the ground and the view from space. *Journal of Geophysical Research: Atmospheres*, *112*(D22). https://doi.org/10.1029/2007JD008684

Zhao, L., Dai, S., Finkelman, R. B., French, D., Graham, I. T., Yang, Y., Li, J., & Yang, P. (2020). Leaching behavior of trace elements from fly ashes of five Chinese coal power plants. *International Journal of Coal Geology*, *219*, 103381. https://doi.org/10.1016/j.coal.2019.103381

Żyrkowski, M., Neto, R. C., Santos, L. F., & Witkowski, K. (2016). Characterization of fly-ash cenospheres from coal-fired power plant unit. *Fuel*, *174*, 49–53. https://doi.org/10.1016/j.fuel.2016.01.061