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# A Review on Geopolymer Interlocking Bricks: Sustainable Construction for Future

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**ABSTRACT:** The construction industry is undergoing significant transformation, with a growing focus on sustainability and the reduction of carbon footprints. Geopolymer interlocking bricks, made from industrial waste materials like fly ash, slag, and other alumino-silicate sources, are emerging as an eco-friendly alternative to conventional fired clay bricks and concrete. This review paper aims to provide a comprehensive analysis of geopolymer interlocking bricks, including their composition, manufacturing process, advantages, challenges, and their potential to contribute to sustainable construction practices.

**KEYWORDS:** Geopolymer, Interlocking Bricks, Sustainable Construction, Fly Ash, Alumino-silicate, Carbon Footprint, Construction Materials.

## I. INTRODUCTION

The construction industry is a major contributor to global environmental degradation, particularly due to the high consumption of energy and raw materials in the production of conventional construction materials like cement and clay bricks. As the world moves towards more sustainable practices, the need for innovative, low-carbon materials has become crucial. Geopolymers, which are synthetic alumino-silicate materials, have garnered attention due to their potential to replace traditional cement-based products. Geopolymer concrete and bricks, in particular, have emerged as a sustainable alternative.

Interlocking bricks, which do not require mortar for assembly, are a significant advancement in construction technology, offering both cost and time-saving benefits. When combined with geopolymer technology, interlocking bricks present a promising solution to many of the challenges faced by the construction industry, including environmental concerns, material shortages, and labour inefficiency.

This review focuses on geopolymer interlocking bricks, exploring their material properties, production processes, advantages, challenges, and their potential role in sustainable construction.

## II. LITERATURE SURVEY

Bashar s mohammed et al. (2018) stated that the study applied response surface methodology (RSM) via Design Experts software to optimize mix proportions, aiming for a specific compressive strength of 4 MPa. After testing 13 trial mixes, an optimal mixture was determined with an 18 M NaOH solution and an alkaline solution-to-fly ash ratio of 0.8. The bricks were then tested for properties including compressive strength, flexural strength, water absorption, initial rate of absorption, and efflorescence. Results indicated low compressive and flexural strength, a high-water absorption rate, and a non-effloresced classification, making the bricks suitable for non-load-bearing applications.

Priyanka kamtekar et al. (2022) stated that the the development of lightweight, sustainable geopolymer bricks made from fly ash, GGBS (ground granulated blast furnace slag), and quarry dust, activated with an alkaline solution (sodium hydroxide and sodium silicate). Unlike traditional clay or OPC (ordinary Portland cement) bricks, geopolymer bricks produce fewer CO<sub>2</sub> emissions, utilizing industrial by-products as alternative binders. The study evaluates the effect of alkaline solution ratios, curing conditions, and the inclusion of foaming agents on the brick's structural properties.

Experimental tests revealed that geopolymer bricks offer comparable or superior strength, reduced water absorption, and greater acid resistance than conventional bricks. These characteristics make them well-suited for environmentally sensitive and earthquake-prone regions, as well as sound-sensitive spaces like auditoriums. Additionally, economic analysis shows that geopolymer bricks offer financial advantages over traditional bricks. The findings suggest that geopolymer bricks could serve as an eco-friendly alternative to traditional bricks in construction, contributing to lower carbon emissions and sustainable building practices.

Dipak phapale et al. (2020) stated that the study explores the potential of geopolymer concrete (GPC) as an eco-friendly alternative to traditional Portland cement concrete. Testing methods include slump cone, compression, and water absorption tests. Findings indicate that GPC has properties similar to traditional concrete but with less shrinkage, a lower heat of hydration, and improved resistance to environmental damage, making it suitable for applications like precast concrete products, railway sleepers, retaining walls, and marine structures. Economically, GPC can be 10-30% cheaper than conventional concrete, and by reducing cement dependency, it also decreases greenhouse gas emissions. For brick applications, GPC interlocking bricks are lighter, stronger, and eliminate the need for mortar. The cost analysis reveals that GPC bricks can be produced for approximately Rs. 16 per unit, with further reductions possible by adopting hollow designs, which could lower weight and material use by 40%.

According to Niveditha balakrishnan et al. (2019) the use of fly ash-based alkali-activated geopolymer bricks as a sustainable alternative to traditional clay and cement bricks, with a focus on reducing fly ash disposal issues. In this study, geopolymer bricks (230 mm × 110 mm × 70 mm) were optimized by adjusting the sodium hydroxide molarity, extra water content, and curing conditions. Key parameters such as alkali-to-binder ratio (0.4) and sodium silicate to sodium hydroxide ratio (2.5) were maintained to achieve optimal properties. The compressive strength, water absorption, and durability of these optimized geopolymer bricks were compared with conventional cement and fired clay bricks. Economic considerations led to a mix design with a 1:6 fly ash-to-fine aggregate ratio and a sodium hydroxide molarity of 5M. Different fine aggregates (river sand, manufactured sand, and quarry dust) were assessed to identify the most cost-effective option.

S Elavarasan et al. (2021) explores the development of eco-friendly, energy-efficient earth bricks, stabilized with polypropylene fibers and metakaolin-based geopolymer binders, as a sustainable alternative to traditional fired clay bricks. Conventional brick production is energy-intensive and contributes to greenhouse gas emissions due to high-temperature firing. Earth bricks, with their minimal embodied energy, are highly energy-efficient and compatible with sustainable building practices. The use of polypropylene fibers (at 0.25%, 0.5%, 0.75%, and 1%) and a metakaolin geopolymer binder, a mix of metakaolin and an alkaline activator (sodium silicate and sodium hydroxide), to improve the structural integrity of earth bricks.

Kumutha Rathinam et al. (2023) stated that Geopolymer bricks incorporating fly ash, ground granulated blast furnace slag (GGBS), M-sand, and waste glass meet the density requirements outlined in IS 2185:2005 (Part I) for use as load-bearing units. Interlocking bricks formulated with a mix of 70% M-sand and 30% waste glass exhibit the highest compressive strength and low water absorption. Mixes M3 and M4, comprising 70% M-sand with 30% waste glass and 60% M-sand with 40% waste glass, respectively, achieve compressive strengths exceeding 3.2 N/mm<sup>2</sup>, classifying them under Grade C (4.0) according to IS 2185:2005 (Part I) standards. Additionally, interlocking brick prisms made with 70% M-sand and 30% waste glass demonstrate optimal load-bearing capacity and energy absorption. The observed compressive strength of interlocking prisms closely aligns with that of individual bricks, indicating a consistent strength trend across different structural configurations.

According to S. S. Vivek et al. (2023) the use of recycled and waste materials in Interlocking Concrete Block Pavements (ICBP) offers substantial environmental and economic benefits by conserving resources, reducing landfill pressure, and minimizing CO<sub>2</sub> emissions. This review highlights the performance, durability, and sustainability of ICBPs incorporating supplementary cementitious materials (SCM) from industrial (e.g., fly ash, blast furnace slag) and agricultural wastes (e.g., rice husk ash, palm waste). Research demonstrates that integrating waste materials, such as quarry dust and PET, in optimal proportions enhances cost-effectiveness, durability, and, in some cases, aesthetic appeal. However, the inclusion of plastic aggregates can reduce workability and strength due to weak bonding, although this may be beneficial in applications requiring flexibility. Additional studies are recommended to explore a wider variety of waste types and their mineralogic-petrographic impacts on ICBP. Future research should also examine

block–base interactions and structural behaviour under load to support cleaner production and sustainability in construction industries.

Gaurav udgata et al. (2024) explored the sustainable use of pond ash, fly ash, and quarry dust in the production of compressed interlocking bricks (PAICIB) to address the environmental challenges posed by industrial waste. With India generating over 200 million tonnes of coal ash annually, these materials represent a significant environmental burden. The PAICIB were created using a mix of 70% pond and fly ash (in equal proportions) and 30% quarry dust. Variations in lime and cement content were tested to optimize compressive strength and water absorption. The results showed that a cement-free brick with 10% hydrated lime achieved a compressive strength of 5.5 N/mm<sup>2</sup>, with acceptable water absorption properties. The study demonstrates that hydrated lime significantly improves the strength of PAICIB without the need for cement, thus reducing the environmental impact associated with cement production. These interlocking bricks, which do not require mortar, are also suitable for rapid and cost-effective construction, making them ideal for low-cost, temporary structures. Additionally, the initiative supports India's "fly ash management and utilization mission" by providing an eco-friendly use for waste pond ash, reducing its negative impact on water bodies and land use. This approach offers a viable path toward sustainable construction practices by reusing industrial by-products in a way that mitigates environmental hazards and promotes waste utilization.

Hongxiang gou et al. (2023) highlights the promising properties of lithium slag (LS) as a sustainable supplementary cementitious material (SCM) in concrete. LS exhibits a particle size distribution similar to fly ash (FA) and ground granulated blast furnace slag (GGBS), which contributes to densification and early hydration. With high SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> and low CaO content, LS behaves like FA, making it a low-calcium precursor. Increasing LS content shortens setting times, reduces flowability, and initially enhances mechanical properties, with diminishing returns beyond 30% LS. LS also improves chloride resistance and shrinkage performance over time. Its effectiveness in cementitious composites derives from three primary mechanisms: filling, pozzolanic, and nucleation effects. LS provides a cost-effective alternative to FA, with lower embodied CO<sub>2</sub> and energy than many SCMs, supporting its potential for waste recycling and sustainable concrete production.

Strength and microstructure of geopolymer recycled brick aggregate concrete after high temperatures by Yongqian zheng et al. (2024) examines the high-temperature behavior of geopolymer recycled brick aggregate concrete (GRBC), comparing it to ordinary recycled brick aggregate Portland cement concrete (ORBC) in terms of strength and microstructure. Tests varied temperature levels (20 °C to 800 °C) and RBA replacement ratios (0–100%) to assess compressive and tensile strength retention. GRBC showed better strength retention than ORBC at elevated temperatures, retaining 35.9–45.6% of its compressive strength and 41.5–44.2% of its tensile strength after exposure to 800 °C. Microstructural analysis revealed that the interfacial transition zone (ITZ) in GRBC was less affected by temperature than in ORBC, with the first weak zone in GRBC being the RBA itself, while ORBC's weak zone was the ITZ. The results suggest that GRBC's strength derives mainly from N-A-S-H and C-A-S-H gels, which remain stable under high heat, indicating potential for GRBC as a durable, eco-friendly construction material for high-temperature applications.

Micro-properties and mechanical behavior of high-ductility engineered geopolymer composites (EGC) with recycled concrete and paste powder as green precursor by Huixia wu et al. (2024) explored the feasibility of using recycled concrete powder (RCP) and recycled paste powder (RPP), derived from construction waste, as green precursors in high-ductility engineered geopolymer composites (EGC). Incorporating these recycled powders into EGC can reduce reliance on traditional mineral precursors such as fly ash and ground granulated blast furnace slag (FA-GGBS), contributing to sustainability. The recycled powders primarily contain C–S–H, SiO<sub>2</sub>, and CaCO<sub>3</sub>, with RPP showing higher alkali-activation activity than RCP. Optimal substitutions of RCP and RPP (25–50%) enhanced EGC's mechanical properties, with RCP improving ultimate stress and RPP enhancing strain capacity. However, 100% substitution reduced polymerization and strength. The fully recycled EGC exhibited high ductility, especially with RPP-based composites, and using recycled powder for FA replacement was more effective than replacing GGBS. This approach demonstrates environmental and economic benefits, supporting construction waste recycling and promoting sustainable EGC development.

Osama Zaid et al. (2024) examines the influence of various nanomaterials (NMs) on the engineering properties of geopolymer concrete (GPC), focusing on strength, durability, and microstructure. Key findings show that incorporating NMs such as nano-silica, nano-alumina, carbon nanotubes, and others at low dosages (typically less than 6% of binder

content) enhances GPC performance. Nano-silica, in particular, is widely used for its cost-effectiveness and ability to improve microstructure by forming additional calcium-silicate-hydrate (CSH) gel. NMs improve strength characteristics like compressive, flexural, and tensile strengths, especially at optimal dosages of 2-4%, and enhance durability by refining pore structure and preventing infiltration of harmful agents. Microstructural analysis, including SEM and FTIR, reveals that NMs promote gel formations that fill nano-level voids, accelerate hydration, and strengthen bond structures, resulting in a denser and more resilient GPC matrix.

George Uwadiegwu Alaneme et al. (2024) introduced a simplified framework for designing geopolymer concrete (GPC) mixtures, offering a structured guide to aid engineers in optimizing material selection, mix proportions, and testing protocols for GPC production. Key components of the approach include selecting appropriate raw materials, configuring the alkaline activator solution, and adjusting proportions based on desired properties, while also considering curing methods and quality control. Challenges noted include the dependency on source materials, limited applications due to heat curing requirements, and high costs associated with sodium silicate. By adapting principles from Portland cement concrete (PCC) mix design, this methodology aims to achieve desired compressive strength and workability in GPC, with the potential to reduce costs by substituting sodium silicate with alternative amorphous silica sources. Overall, this approach supports sustainable construction practices by promoting alternative binders, though further research is needed to enhance GPC's practical application and performance.

R.S.S. Ranasinghe et al. (2024) developed three deep learning algorithms—Deep Neural Network (DNN), Convolutional Neural Network (CNN), and Artificial Neural Network (ANN)—to predict the compressive strength of slag-ash-based geopolymer concrete. Results indicated that the DNN model outperformed the others, achieving high accuracy with  $R^2$  values of 0.977 for training and 0.972 for testing. Shapley additive explanations (SHAP) were used to interpret DNN predictions, identifying curing days and Ground Granulated Blast Furnace Slag as the most influential features, with Sodium Hydroxide Pellets showing minimal impact on strength. Additionally, a user-friendly software tool was developed to predict mix designs for target compressive strengths, underscoring the practical utility of deep learning in concrete engineering. This study highlights the potential of inverse modelling with deep learning for practical applications, recommending further exploration into its accuracy and efficiency for concrete strength predictions.

Yiming Zhou et al. (2024) examines the role of calcium in microbial-induced calcium carbonate precipitation (MICP) for repairing geopolymer concrete (GPC). Key findings show that calcium content significantly impacts healing, especially in internal methods, by enhancing calcium ion leaching, which improves crack healing. The study differentiates between external healing (e.g., bio-slurry application) and internal healing. For external methods, higher calcium content promotes stronger bonds in the healed area and increases resistance to water and chloride permeability, though crack penetration depth is unaffected by CaO content. External healing is suitable for specific applications, such as road repair, due to equipment needs and crack location requirements. For internal healing, a suitable bacterial carrier and increased CaO content improve healing efficacy, as seen in dynamic elastic modulus recovery. However, while higher alkali activator content increases concrete alkalinity, it slightly weakens MICP's healing effect. Calcium's role in interlayer structures is noted for contributing to calcium ion release, essential for healing. The study also highlights that chloride resistance depends on the interaction between pH and calcium carbonate's effects on Zeta potential, suggesting mix design optimization is crucial for chloride resistance. Future research should explore bacteria preservation in carriers, decalcification pathways in GPC, mix design effects on Zeta potential and chloride resistance, and the impact of internal carbonation from MICP on permeability performance in GPC.

Ujjwal Sharma et al. (2024) addresses the use of various fiber reinforcements in geopolymer composites to mitigate brittleness and enhance tension resistance. Fiber-reinforced geopolymer concretes (FRGCs) incorporate synthetic, organic, inorganic, and natural fibers, with hybrid fiber reinforcement emerging as an effective strategy to boost mechanical strength. Key findings show that steel fibers improve toughness, impact resistance, and durability, particularly under high temperatures up to 400°C. Glass fibers enhance ductility and crack resistance, though they reduce workability; higher NaOH molarity further improves strength. Polypropylene fibers help control crack propagation and shrinkage but lose effectiveness at elevated temperatures. Basalt fibers, known for their historical durability, improve strength and fracture resistance in geopolymers, with carbon-coated varieties offering superior performance. Overall, the selection and combination of fibers are essential to optimize geopolymer composite performance for diverse structural applications, from traditional construction to advanced thermal insulation and impact-resistant materials.

Rana Muhammad waqas et al. (2024) explores an innovative approach to geopolymer concrete (GPC) by replacing standard aggregates with quarry rock dust (QRD) from local sources and adding steel fibers to enhance the material's performance in structural applications. Key findings indicate that loading patterns greatly impact failure modes: concentric loads cause sudden, brittle failure, while eccentric loads lead to a gradual flexural failure. Steel fibers significantly improve the performance, increasing load capacity by 20-30% and enhancing ductility by 25-55% under various conditions. Fiber-reinforced GPC columns performed 6-8% better than traditional concrete (OPC) columns. Design codes (BS 8110 and ACI 318) underestimate real-world performance by up to 25%. This research highlights GPC's potential as a sustainable, high-performance alternative to conventional concrete, advocating for further studies on mix optimization and long-term performance to encourage its wider use.

Madhushan Rathnayaka et al. (2024) developed an advanced mix design procedure for geopolymer concrete (GPC) that predicts mix proportions for specific compressive strengths (25, 32, and 40 MPa) using artificial neural networks (ANN), data clustering, and parameter optimization. Experimental validation confirmed the model's accuracy, with deviations in strength prediction lower for Norochcholai fly ash than Port Augusta fly ash. Key features include data clustering to enhance parameter identification and dataset completeness, with the model self-generating data points in sparse regions for ongoing improvement. The inclusion of chemical oxide content, curing conditions, and activator properties significantly boosted accuracy (68.3% improvement in test performance), and using Bayesian Regularization in the ANN enhanced prediction reliability, particularly with unfamiliar fly ash sources. The user-friendly interface allows customization and supports users at different expertise levels, facilitating efficient, economical GPC mix designs.

Parmender Gill et al. (2023) examined the performance of geopolymer concrete (GPC) mixes with various additives, focusing on workability, strength, and durability under acidic conditions. The control GPC mix, M1, exhibited high workability with a slump value of 143 mm, a 28-day compressive strength of 46.56 MPa, and lost 35% of its compressive strength after 90 days in acidic conditions. Adding crumb rubber (CR) reduced both compressive and flexural strengths, with a 15% CR addition causing a 15.97% drop in compressive strength and a 9.8% decrease in slump. Acid exposure further weakened CR-modified GPC by 43%. The addition of OPC to a CR-modified mix improved strength, with a 15% OPC blend (RMC15) showing 21.62% and 16.33% increases in compressive and flexural strength, respectively. Despite improved strength, acid exposure caused a 38% strength loss due to  $\text{CaSO}_4$  formation. Glass fiber (GF) additions to RMC15 enhanced microstructure and acid resistance, with a 5.65% increase in compressive strength. The optimal mix, RMC\*G0.30, retained 65% compressive strength after acid exposure but had reduced workability due to increased fiber interactions. Steel fibers (SF) improved compressive strength to 60.87 MPa with 1% SF and increased flexural strength up to 1.5% SF. Both GF and SF acted as physical additives, improving durability without altering chemical composition.

Salini Theres N Kurian et al. (2024) investigated rubberized geopolymer concrete (GPC) made by combining sugarcane bagasse ash (SCBA), discarded rubber tires, and fly ash, using NaOH and  $\text{Na}_2\text{SiO}_3$  as activators. SCBA, typically disposed of in landfills, was explored as a sustainable building material additive to enhance waste recycling. Key findings show that adding rubber crumbs reduces the workability of fresh GPC, but superplasticizers can improve consistency. Compressive strength initially increases with up to 20% rubber addition but later decreases due to weak particle bonding. The highest strength, 41.27 MPa, was achieved for GPC with 8M SCBA. Flexural and split tensile strength also improve with increased rubber content in the presence of SCBA, peaking at 20% rubber. Curing methods affect strength significantly; oven curing enhances compressive strength compared to ambient curing.

Shyma Hameed Mohammad et al. (2024) developed foamed geopolymer materials using 6M NaOH and waste glass powder as activators, with or without 20 wt.% rice husk (RH) as a foaming agent, under heat treatment (550°C–850°C). Key findings include: foaming behaviour at 550°C for all formulas except MGR420-N6, with significant volume expansion at 650°C for MGR420-N6 and at 750°C for all pastes; weight loss ranged from 10%–27%, notably higher for MGR400-N6 and MGR600-N6. Compressive strengths varied, with MG-N6 pastes outperforming others after 7 and 28 days, but generally, compressive strength decreased with increased porosity from heat treatment. Due to their lightweight, high porosity, and low mechanical strength, these materials are well-suited for thermal and acoustic insulation applications.

Ramesh Kumar Chouhan et al. (2024) a novel ML superplasticizer designed to enhance the flow behaviour of geopolymer concrete without using commercial organic additives, while maintaining mechanical strength. Testing revealed that a 0.5% dosage of the superplasticizer (relative to fly ash content) provides the best combination of compressive strength and workability. Characterization techniques (XRD, FTIR, and SEM) showed that the

superplasticizer contains inorganic components like sodium silicate, synthesized from rice husk during alkaline treatment, and organic compounds such as cellulose,  $\beta$ -D-fructose, and phenol. These organic fractions help reduce the concrete's viscosity, improving workability by neutralizing charge effects within the geopolymer matrix.

Geeta Mehta et al. (2024) concluded that mix code 2.5FGC12 demonstrates compatible workability behaviour and high strength among all the mix codes tested, Therefore, a 12 M sodium hydroxide solution and a 2.5 sodium silicate to sodium hydroxide ratio can be recommended for self-compacting geopolymer concrete. Strength is mostly unaffected by increasing molarity and larger ratios of sodium silicate to sodium hydroxide, but workability is adversely affected. Additionally, concrete developed without cement and using Class F fly ash is contributing towards the reduction in CO<sub>2</sub> emissions and managing waste disposal which can further cause pollution.

Nugroho Adi Sasongko et al. (2024) investigates the properties of fly ash from coal power plants used in geopolymer concrete to strengthen alternative cement materials. Fly ash, a pozzolanic material high in reactive silica and alumina, reacts with calcium hydroxide in the presence of moisture to form cementitious compounds, producing C-S-H gel and Ca(OH)<sub>2</sub> that reinforce concrete. However, environmental factors like water, sulfates, and CO<sub>2</sub> can degrade Ca(OH)<sub>2</sub>, causing potential deterioration over time. Physically, fly ash particles are mainly spherical and contain crystalline solids such as quartz and hematite, which enhance hardness, fill pore spaces, and refine the microstructure of concrete. Spectral analysis highlights key reactivity peaks that reveal interactions critical to the geopolymerization process, where Si-OH and Al-OH groups help maintain mechanical strength. The Si/Al ratio significantly influences the polymer structure and properties of geopolymer concrete. Proximal analysis shows fly ash with low carbon (0.19%) and hydrogen (0.34%) content, high ash (99.29%), and low water content, reflecting stability and suitability for concrete. Classified as Class F per ASTM C618-15 standards, the fly ash displays pozzolanic properties with low CaO and a combined SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, and Fe<sub>2</sub>O<sub>3</sub> content exceeding 70%, making it well-suited for use in concrete applications.

### III. SUMMARY OF REVIEW

From the review of these studies, it's clear that geopolymer technology and recycled materials in construction offer significant environmental and economic advantages. Recycled powders, such as fly ash, GGBS, quarry dust, and even pond ash, are being effectively incorporated into bricks, concrete, and engineered geopolymer composites (EGC), reducing reliance on traditional cement and contributing to sustainable building practices. In specialized applications, geopolymer and recycled aggregate concretes retain their strength even under high temperatures, showcasing potential for use in areas requiring fire resistance. Interlocking brick designs made from recycled materials also provide economic benefits by reducing the need for mortar and cutting down on construction time.

In summary, using recycled materials and alternative binders like geopolymer technology contributes to sustainable construction by reducing environmental impacts and promoting resource efficiency. However, challenges such as optimizing mix proportions, curing conditions, and maintaining workability and strength with high levels of recycled content still need further research. This area holds great promise for developing eco-friendly building solutions aligned with global sustainability goals.

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