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Thermo-Mechanical and Thermal Performance of Rice Husk Ash-Based Lightweight Geopolymer Concrete Activated by a Dual-Alkali System Incorporating Expanded Perlite and Pumice Aggregates

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ABSTRACT

This study describes the development of lightweight, thermally efficient geopolymer concrete using rice husk ash (RHA) as the main binder, activated with a dual-alkali system of sodium hydroxide (NaOH) and sodium aluminate ($NaAlO_2$). Pumice and expanded perlite (EP) were employed as lightweight aggregates with different volume ratios to assess their impact on the important characteristics of concrete. A fixed binder content of 450 kg/m³, an activator dosage of 150 kg/m³, and water-to-binder ratio of 0.35 were used to prepare all the mixes. The concrete samples were ambient-cured for 28 d after being heat-cured for 24 h at 60℃. The compressive strength, density, water absorption, and thermal conductivity of the samples were determined. The results showed that the compressive strength ranged from 18.6 to 31.2 MPa, the dry density varied from 1354 to 1689 kg/m³, the water absorption ranged from 10.1% to 18.4%, and the thermal conductivity ranged from 0.189 to 0.331 W/m·K. NASH gel synthesis was improved using a dual alkali activator, while the durability, strength, and mechanical properties were further improved. This technology, created from volcanic and agricultural wastes, provides an eco-friendly approach that reduces the emission of CO_2 by as much as 80% compared to that released by systems utilizing Ordinary Portland Cement (OPC). This information verifies the viability of producing low-carbon lightweight geopolymer concrete.

1. INTRODUCTION

Notably, its dependency on Ordinary Portland Cement (OPC) accounts for approximately 8% of CO_2 emissions worldwide [1], and the cement industry is faced with increasing pressure for environmentally sustainable construction practices. In response to such a demand, Geopolymer concrete (GPC) has emerged as a sustainable alternative to concrete structures for their durability and sustainability. In its current form, GPC can be said to consist of a binding matrix formed through aluminosilicate precursors, which have been activated through an aqueous solution of alkali and have a drastically lower emission rate of CO_2 by as much as 95% in comparison to Portland concrete [2]. Among the various precursors used in GPC, rice husk ash (RHA) stands out as one of the most preferred, owing to its superiority in terms of environmental adaptability and costs. Because it is usually a by-product of most rice milling industries, the precursor contains up to 90% amorphous silicon, which is sufficient to make it highly reactive in GPC [3, 4]. The precursor not only promotes sustainable use in the industry but also makes significant contributions towards reducing the environmentally damaging effects related to the production process of concrete materials. The use of lightweight particles has also gained popularity in the development of low-density thermally insulating concrete. The two most widely used naturally occurring lightweight particles in building construction with low density, high porosity, and thermally insulating properties are expanded perlite (EP) and pumice stones. Their concrete integration lowers the structural dead load [5-7] and increases the workability and energy efficiency through structural improvements. In this study, geopolymerization was initiated using an alkaline activator composed of sodium hydroxide (NaOH) and sodium aluminate ($NaAlO_2$). This combination not only increased the rate and amount of geopolymer gel development but also aided the dissolution of reactive silica and alumina from RHA. $NaAlO_2$ enables a denser and more stable sodium aluminosilicate hydrate (N-A-S-H) gel network and provides an additional supply of Al^{3+} ions, thereby achieving high mechanical strength and durability. By combining RHA with EP and pumice aggregates, a new lightweight concrete composite with a low unit weight, improved insulating performance, and sufficient structural capacity can be developed. Previous research indicates that such concretes are suitable for energy-efficient construction because they can reduce density by up to 30%, compressive strengths over 40 MPa, and thermal conductivities less than 0.35 W/m·K [8]. Crucially, the use of RHA- and $NaAlO_2$-based activators also helps reduce CO_2 emissions by up to 80% relative to OPC-based systems, thereby providing a scalable and low-carbon option for the construction sector [9].

Many studies have been conducted on RHA-based geopolymers or on the effects of lightweight aggregates alone. However, the effects of the combination of EP and pumice within an RHA geopolymer matrix activated by a NaOH-$NaAlO_2$ binary system have not been systematically explored. The interaction effects of the two types of lightweight aggregates and the effects of this interaction on the formation of the interfacial transition zone (ITZ) are unclear.

The addition of $NaAlO_2$ to the alkaline activator was anticipated to introduce additional Al^{3+} ions, which would influence the Al/Si ratio and the N-A-S-H gel matrix microstructure. It is anticipated that this would not only influence the cross-linking and matrix densification, but also the interfacial bond between the aggregate and matrix. This interfacial bond plays a crucial role in determining the thermomechanical properties of lightweight GPC. However, the role of $NaAlO_2$ in controlling the chemistry and ITZ zone formation in RHA geopolymer systems using mixed lightweight aggregates has not been properly identified.

This study aims to address a particular knowledge gap through a comprehensive investigation of the combined effects of blends of expanded perlite/pumice and the dual-alkali activation method (NaOH + $NaAlO_2$) on the density, mechanical properties, water absorption capacity, and thermal conductivity of RHA-based lightweight GPC.

2. MATERIALS AND METHODOLOGY

The purpose of this study was to develop a lightweight GPC. RHA was used as a binder in this experiment. RHA was activated using solutions of NaOH and $NaAlO_2$. The proportion of the mixture of EP to the pumice used as the lightweight aggregate was changed to achieve a concrete mix that was thermally insulating, durable, and environmentally friendly. Based on controlled rice husk burning followed by high fineness to enhance the pozzolanic activity, RHA was used in this study as the sole geopolymer precursor. According to the ASTM C618 standard for pozzolanic materials, the RHA used in this study contained approximately 85% amorphous silica. The chemical composition of the RHA is summarized in Table 1. The number of binders used in the concrete mixture was kept constant at 450 kg/m³ to conduct a comparative study between the mixtures. The NaOH used in this study was an analytical grade chemical used to prepare the alkaline solution, which was mixed in a total amount of 150 kg/m³ in all mixtures. NaOH was dissolved in water to prepare a 10 M solution. $NaAlO_2$ powder was mixed with RHA in a dry mixer and then added to the alkaline solution. Precursor materials improve the mechanical strength, and 10 M is often found to be the best concentration that provides a good balance between reactivity and workability (e.g., compressive strength increments with the concentration of NaOH were observed in fly ash geopolymers when comparing 10 M with 14 M NaOH concentrations) [10]. A comprehensive analysis of alkali-activated materials indicates that high molar concentrations can cause difficulties in workability and microstructure formation because of the high viscosity or fast setting [11].

In addition, the optimization of aluminate distribution through the dry blending process of $NaAlO_2$ with the solid precursor was successful in controlling the reaction kinetics during the early stages of the reaction, thereby improving the homogeneity of the matrix, as supported by previous studies [11, 12]. This combination improves the dissolution of silica and alumina in solution, promotes the creation of a dense, strong sodium-alumino-silicate-hydrate (N-A-S-H) gel framework, and enhances the geopolymerization reaction. The study used a 10 M NaOH solution in the RHA geopolymer formulation to avoid several disadvantages, such as high viscosity, rapid setting time, efflorescence, and high alkalinity at higher concentrations. The formulation can provide an optimal balance between the reactivity, workability, and handling characteristics of the powder at this formulation level in NaOH solution in GPC formulation. The reasons for using $NaAlO_2$ to make more homogenous precursor solutions for Al^{3+} ions in this study were to prevent high pH concentration gradients due to $NaAlO_2$, to prevent direct $NaAlO_2$ reaction to form flash set geopolymer, to enhance handling characteristics related to powder mixture in geopolymer powder activator in this study, and to enhance the rapid formation of an N-A-S-H framework, in turn, to improve geopolymer powder. To provide consistent rheological properties, NaOH pellets were dissolved in deionized water and stirred to a concentration of 10 M. This mixture was allowed to cool to room temperature before being mixed with a dry RHA/$NaAlO_2$ powder blend. These choices reflect prior geopolymer work on alumina-rich geopolymer synthesis routes and concentration optima for enhanced microstructure consolidation and polymerization [2, 7].

Table 1. Chemical composition of rice husk ash (RHA)

Oxide Component	Content (% by weight)
SiO_2	87.5
Al_2O_3	0.9
Fe_2O_3	0.7
CaO	1.5
MgO	0.6
Na_2O	0.4
K_2O	2.3
SO_3	0.2
Loss on Ignition	5.9

Note: Silicon Dioxide (SiO_2); Aluminum Oxide (Al_2O_3); iron (III) oxide/ferric oxide (Fe_2O_3); Calcium Oxide (CaO); Magnesium Oxide (MgO); Sodium Oxide (Na_2O); Potassium Oxide (K_2O); Sulfur Trioxide (SO_3); Loss on Ignition (LOI).

All mixes exhibited sufficient workability based on maintaining the water-to-binder ratio of 0.35 and assisted in the process of polymerization. Perlite and pumice are lightweight aggregates that have expanded owing to their low densities and natural properties. EP is a thermally expanded volcanic glass (bulk density of 100 kg/m³) that appears white and granular. Pumice is another lightweight volcanic rock that was preferred on account of its moderate strength and insulation properties, and has slightly higher densities of approximately 650-700 kg/m³. Table 2 shows the volumetric proportions of the different components used to produce the various lightweight geopolymer concrete mixtures. Therefore, five mixes were prepared: M1 consisting of 100% EP; M2 consisting of 75/25 EP and Pumice; M3 consisting of 50/50 EP and Pumice; M4 consisting of 25/75 EP and Pumice; and M5 consisting of 100% pumice. These percentages are based on equal volumes. Varying the proportions of these binder mixes makes it feasible to study various principles. The purpose of varying the binder mixes is to study and derive the principles of various combinations. To achieve an optimal balance in the density, workability, and overall performance, all the lightweight aggregates used in the study were produced in a size grading of 5-25 mm. The lightweight coarse aggregates used in this study were perlite and pumice with a particle size distribution in accordance with ASTM C33. This refers to the size of aggregates between 5-25 mm. Sieve analysis of the aggregates used in this study showed the following: 100% of particles passed through 25.0 mm; 98%, 19.0 mm; 45%, 12.5 mm; 22%, 9.5 mm; 5%, 4.75 mm; and 2%, 2.36 mm. This sieve analysis was kept identical for all mixtures to ensure uniform aggregate gradation. Therefore, any variations in density, mechanical properties, and thermal conductivity can be attributed solely to changes in the perlite-to-pumice ratio. This size grading was selected because Abdulrehman et al. [13] found that size grading results in a more homogeneous matrix, higher packing density, and enhanced mechanical properties in lightweight GPC. The size grading of the aggregates results in a more homogeneous microstructure, which results in a stronger and less porous material. Size grading also eliminates the size factor, which may act as a variable, and ensures that the variation in the mechanical, physical, and thermal properties is a function of the ratio and not the size. This methodology agrees with recent research on lightweight GPCs (2022-2024), which indicated that the use of gradation control greatly impacts the concrete density values, ITZ, and overall strength and durability of the concrete. The balance between the structural and thermal requirements was obtained by adjusting the size range of the aggregate; hence, the concrete produced was capable of satisfying the requirements of structural and nonstructural energy-efficient structures. First, the dry pan materials were well mixed in a pan mixer for two minutes. To obtain a workable and homogeneous paste, the prepared alkali activator was gradually added during mixing and blended thoroughly for 3–4 min. The fresh concrete mixtures were then compacted using light vibration and cast into pre-prepared cubic molds with dimensions of 150 mm × 150 mm × 150 mm. The specimens were wrapped and placed in an oven at 60 ± 2°C for 24 h to initiate geopolymerization. The samples stood under lab conditions (23 ± 2°C) after removal from the molds until the end of the 28th day, when the samples were subjected to rigorous testing to set the performance standards. Characteristic value testing for compressive strength involved the use of calibrated universal testing machines in accordance with EN 12390-3. The bulk density was measured based on the ratio of the dry weight to the volume of the hardened specimens. The open porosity and water absorption values were measured according to ASTM C642 standards. The thermal conductivity was measured using a guarded hot-plate apparatus according to ASTM C177. The structural, insulating, and durable properties of the concrete matrix were tested.

Table 2. Physical properties of rice husk ash (RHA), expanded perlite (EP), and pumice

Property	Rice Husk Ash (RHA)	Expanded Perlite (EP)	Pumice
Color	Gray	White	Light gray
Specific Gravity	2.10	0.10–0.15	0.65–0.70
Bulk Density (kg/m³)	550	100–120	650–700
Fineness (passing 45 µm sieve, %)	96	—	—
Surface Area (BET) (m²/g)	27	—	—
Particle Shape	Irregular/angular	Spherical/porous	Angular/porous
Porosity (%)	Moderate	Very high	High
Water Absorption (%)	~10	~25–30	~15–20

Table 3. Mix proportions for rice husk ash (RHA)-based lightweight geopolymer concrete (GPC)

Mix ID	RHA (kg/m³)	$NaOH + NaAlO_2$ (kg/m³)	Expanded Perlite (vol%)	Pumice (vol%)	Water-to-Binder Ratio
M1	450	150	100	0	0.35
M2	450	150	75	25	0.35
M3	450	150	50	50	0.35
M4	450	150	25	75	0.35
M5	450	150	0	100	0.35

3. EXPERIMENTAL TESTS

To determine the effects of EP and pumice lightweight aggregates on the mechanical strength, density, water absorption, and conductivity of GPC, RHA geopolymer concrete mixtures consisting of a fixed quantity of RHA (450 kg/m³) were designed and fabricated. An alkaline activator combination of NaOH and $NaAlO_2$ was applied at a rate of 150 kg/m³. The changes in the volume ratio of EP to pumice are presented in Table 3. A series of experiments was conducted to investigate the impact of the aggregate type and proportion on the significant performance parameters by maintaining the extent of the binder, activator dosage, and water-to-binder ratio constant. This study was conducted to determine a lightweight mix of aggregates that could ideally be strong and thermally efficient, without being detrimental to workability or durability. All combinations were maintained at a water-to-binder (w/b) ratio of 0.35, such that uniform hydration and geopolymerization occurred. M1-M5 Mixed five mix designs were run. Mix M5 had 100% pumice; Mix M1 utilized 100%

EP as the aggregate. The intermediate mixes M2, M3, and M4 contained 75, 50%, and 25% EP, respectively, with pumice filling the remaining volume. This gradual change allowed the estimation of the difference in the performance of denser and highly porous aggregate systems.

EN 12390-3 compressive strength test was conducted on cubic GPC specimens with standard dimensions of 150 mm × 150 mm × 150 mm. After an initial heat-curing period of 60°C for 24 h to facilitate geopolymerization, all specimens were demolded 24 h post-casting, followed by ambient curing at the time of testing. They were tested over 28 days to determine the mechanical performance and growth of the binder of the different aggregate blends. A uniaxial compressive force was applied using calibrated universal testing equipment under laboratory-controlled conditions. This was done using a constant and shock-free load until failure at a steady rate of 0.5 MPa/s. Each mix design (M1-M5) with various volume proportions of EP and pumice was tested on three samples, and the overall compressive strength was recorded to ensure statistical consistency and reproducibility. This testing procedure was used to determine the load-bearing capacity of the RHA-based geopolymer matrix for various types of lightweight aggregates, including 100% EP and 100% pumice aggregates. These results can be used for comparison purposes to identify the relative integrity of all mixes, offering a perspective on how well such low-density concrete systems work in a structure.

In this study, the hardened density of RHA-based GPC mixtures was measured using ASTM C642 to evaluate the effect of the ratio of expanded pumice to RHA on the density and mass-to-volume ratio of the resulting concrete. Hardened density tests of the concrete mixtures in this study were conducted using cubic specimens with dimensions of 150 mm × 150 mm × 150 mm. Conventional curing, comprising heat curing at 60 ± 2°C for 24 h and natural environmental curing at a temperature of 23 ± 2°C for 28 days, was performed on the concrete specimen prior to testing.

Water Absorption Capability

The water absorption capability of various GPC mixtures was determined in accordance with ASTM C642 to assess the effect of the aggregate type on the capability of the concrete to withstand water absorption. This study presents new and interesting data on the pore characteristics and lifespan of lightweight concrete mixtures containing EP and pumice. The cubic specimens of size 150 mm × 150 mm × 150 mm were first dried at 105 ± 5°C for 24 h to remove all moisture in the specimen and then allowed to cool in a desiccator to avoid the possibility of the surrounding air reabsorbing the moisture. The dry weight (Wdry) of each specimen was determined using a computer-precision balance. The dried specimens were then immersed in water at room temperature for 48 h. Immersion measurements were performed using the saturated weight (Wsat).

To eliminate variations in the experimental results, three specimens were tested for each mix type (M1–M5) by changing the volumetric proportions of EP and pumice, and the average value of water absorption was obtained. This test aimed to identify the factors affecting the water absorption behavior of the RHA-based geopolymer matrix (in terms of aggregate porosity and packing efficiency). Given that both EP and pumice have natural porous structures, the results can serve as a guiding factor for how effectively the binder matrix can close such open porosity and provide water-resistance properties, as needed for applications under exposed conditions.

Thermal conductivity measurements were performed to ascertain the insulating properties of the GPC mixes with EP and pumice. Where appropriate, or more specifically, in thermal envelope systems, it plays a fundamental role in determining the appropriateness of lightweight concrete used in energy-saving designs. The test was conducted with a guarded hot plate apparatus to monitor the constant heat flow through the concrete sample, using a concrete sample with dimensions of 300 mm × 300 mm × 50 mm. The recommended procedure was to cast the concrete sample into slabs and cure the sample following the normal procedure for 24 h of heat curing at 60°C with ambient curing at 23°C for 28 days. A temperature- and humidity-controlled environment was used to condition all specimens to a uniform mass prior to the thermal analysis to exclude the effect of moisture on the thermal performance. Heat transfer was recorded at the thickness of the sample, and a progressive temperature gradient was imposed on the surfaces of the specimen during the test. Thermal conductivity (W/m·K) was measured according to the ASTM standard. With respect to the heat flow rate, the thickness of the specimen and the temperature difference (K) were calculated. Three samples were tested for each mix (M1–M5), and the average thermal conductivity was calculated. Increased levels of EP (particularly M1 and M2) led to lower thermal conductivity values, which were attributed to the high air content and low thermal mass of perlite. Nevertheless, owing to the denser and less porous structure of pumice, mixes with higher pumice contents (M4 and M5) had higher conductivity values. Most importantly, this testing stage revealed the trade-offs between the aggregate type and thermal performance, thus enabling the determination of optimal aggregate combinations for use in lightweight, thermally insulating, and structurally sound GPC applications. Three samples were prepared for each experiment. The values presented are the mean of three experiments to ensure that the results are credible and reproducible.

4. RESULTS AND DISCUSSION

The results presented in this section are the mean values of the three samples. The observed pattern was very regular with a small amount of scatter on the graph, indicating that the experimental results were reliable and accurate.

As the complete substitution of EP by pumice in the lightweight GPC mix design progressed, the data on the compressive strength in Table 4 and Figure 1 showed an increase in the values. The lowest value of the compressive strength measured in Mix M1 with 100% perlite is significant at 18.6 MPa, showing how perlite cannot withstand any amount of load as a coarse aggregate material.

Table 4. Mechanical and physical results of the geopolymer concrete (GPC) mixtures incorporating expanded perlite (EP) and pumice

Mix ID	M1	M2	M3	M4	M5
Compressive Strength MPa	18.6	22.1	25.7	28.5	31.2
Density (kg/m³)	1354	1457	1566	1622	1689
Water Absorption (%)	18.4	15.9	13.4	11.8	10.1
Thermal Conductivity (W/m·K)	0.189	0.225	0.266	0.292	0.331

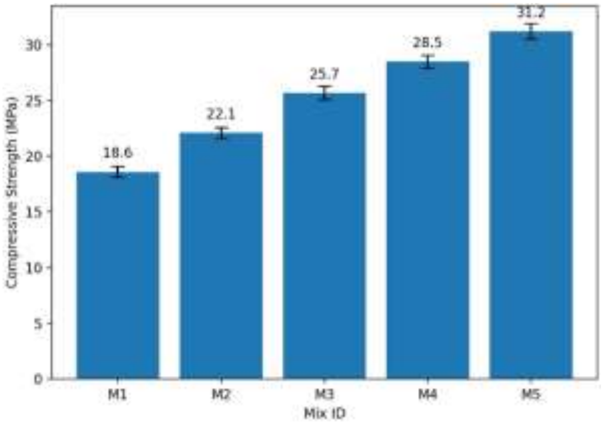

Figure 1. Compressive strength of rice husk ash (RHA)-based lightweight geopolymer concrete (GPC) mixes with varying ratios of pumice to expanded perlite (EP)
Note: Error bars represent ±1 standard deviation (n = 3).

Porous perlite, an expansive perlite with a very loose structure, has a better insulating capacity than its compressive strength [14]. It has less mechanical interlocking with a low compressive strength and is an expansive perlite with a looser structure.

The compressive strength values were observed to fall drastically as the percentage of pumice increased, with the maximum value at 31.2 MPa for Mix M5 with 100% pumice. This tendency conforms to the known mechanical behavior of pumice-based lightweight aggregates, which exhibit greater angularity, better aggregate interlock than perlite [15], and greater strength. Stronger bonding with the geopolymer gel, made possible by the rough surface texture of the pumice, also helps obtain denser and more coherent microstructures [16]. Furthermore, the strength growth critically depends on the binder matrix. Effective dissolution of the high silica content of RHA was made possible by a binary alkaline activator system (NaOH + $NaAlO_2$), which helped generate a strong sodium–alumino–silicate–hydrate (N-A-S-H) gel [2]. Additional Al^{3+} ions from $NaAlO_2$ improve crosslinking in the gel network, thereby producing a denser and more mechanically stable structure [2]. Several studies have found that the Si/Al ratio plays an important role in the formation of the structure and properties of geopolymer gels. Chen et al. [17] and El Alouani et al. [18] have particularly described the controlled synthesis of N-A-S-H gels of different Si/Al ratios and their thermodynamic properties and found a strong correlation between the properties of the gels and the available Al content. The addition of $NaAlO_2$ as an additional source of alumina has also been found to significantly alter the chemistry of the gels in a major way by increasing the concentration of Al in the gels. This, in turn, increased the three-dimensional connectivity of the N-A-S-H geopolymer structure. The dense three-dimensional structure of the geopolymer matrix makes it easier to bind with reactive siliceous aggregates. Recent studies on the mechanism of geopolymerization have also emphasized the importance of the formation of Si-O-Al bonds in the process of polycondensation in determining the structure and mechanical properties of geopolymer gels [17, 19]. In mixes with pumice, which already supported better physical bonding, the interaction at the aggregate–binder interface was enhanced. These findings are consistent with those of previous studies on lightweight geopolymers made from porous pebbles. Federowicz et al. [20] discovered that the compressive strength of lightweight concrete systems can be significantly enhanced by replacing lightweight weakening aggregates with lightweight structurally resilient aggregates, including pumice. Correspondingly, Almadani et al. [21] demonstrated that the type of aggregate and its combination with the binder matrix directly influence the mechanical strength of geopolymer composites, and this effect emerges in systems where the geopolymer gel benefits from both silica and alumina sources. Similar trends were recently reported by these studies [22, 23] for aerated polystyrene-based lightweight concretes, showing that the properties of lightweight aggregates and their compatibility with the binder play a significant role in the development of their strength and structural properties. Although mixes with a high concentration of perlite (M1 and M2) showed lower strength values, they still met the lowest structural requirements for lightweight applications, as stipulated in ACI 213R (> 7 MPa). These combinations are appropriate for non-load-bearing and thermally efficient parts. Although maintaining the advantages of being lightweight and providing better thermal insulation, the pumice-dominated mixtures (M4 and M5) had favorable mechanical properties, which can also find applications in other structural areas. Finally, especially when the alkaline activator solution was at an optimal ratio, the trend clearly indicated that pumice was more effective than perlite in improving the compressive strength of RHA GPC. These results confirm the applicability of this hybrid form to the structural conditions found in buildings.

The unique physical and chemical properties of pumice gave it greater compressive strength, which was noted in mixes with pumice, especially in M4 and M5. The angular particle shape and rough surface texture resulted in a denser and more cohesive microstructure, enhanced mechanical interlocking, and formed stronger bonds in the ITZ. In addition, the reactive aluminosilicate phases present in the pumice can contribute to secondary geopolymerization, which provides more support to the matrix. However, perlite is more porous and smoother; therefore, the bonding is poorer, and the stress transfer at the ITZ is low, reducing the compressive strength. The tendencies of the thermal conductivity also had a strong resemblance to the aggregate porosity and ITZ properties. Because of the higher air trapping in the highly porous perlite particles and surrounding matrix, which reduced the rate of heat transfer, mixtures with higher perlite contents (M1 and M2) had lower thermal conductivities. However, the pumice-based mixes (M4 and M5) had slightly better thermal conductivities owing to the better packing of the particles and reduced porosity, which allowed heat to be conducted by the continuous solid structure. This is supported by the findings of previous studies [24], which showed that the aggregate porosity and densification of the ITZ are relevant for equalizing the mechanical and thermal properties of lightweight GPCs. These results underscore the need to balance the increased ratio of perlite to pumice depending on the nature of the intended structural or nonstructural use to obtain the best balance between mechanical integrity and thermal insulation efficiency.

As the percentage of pumice replaced the EP, the hardened density values presented in Table 4 and Figure 2 indicate a continuous increase in the bulk density of the geopolymer concrete (GPC) mixtures. Mix M1 has the lowest density figure recorded—1354 kg/m^3—which can be ascribed to the exclusive use of EP, a very porous and ultra-lightweight volcanic aggregate with a bulk density of roughly 145 kg/m^3

[24]. The density was also increased by the addition of pumice, which is denser than perlite. Mix M5, with a composition of 100% pumice, had a density of 1689 kg/m³. From the graph, the type of aggregate is shown to affect the general mass-density relationship for GPC. Although pumice offers superior compactness and packing efficiency owing to its more solid matrix and granular texture [25], the cellular structure of EP significantly reduces the bulk mass but enhances void content. The slow change from M1 to M5 shows consistent densification of the matrix; each step produces a more solid structure without appreciably changing the binder phase. According to ASTM C330, with a maximum density of 1850 kg/m³, all measured densities fall within the approved limits for lightweight structural concrete. This validates the appropriateness of all mixes, particularly M2–M5, for structural use, where a low dead load is a major design issue. Zahabi and Said [26] stated that concrete with a density of less than 2000 kg/m³ is light and may offer both performance and durability benefits, particularly in high-rise and seismic zone structures. Furthermore, these findings are consistent with those of previous studies on RHA-based geopolymers. Particularly in the case of low-density pozzolanic binders, such as RHA, Chanda and Guchhait [27] found that aggregate density and pore structure have a significant effect on hardened density in alkaline-activated materials. The results of this investigation demonstrate that although EP is still the best choice in terms of saving weight and providing superior insulation, the addition of pumice produces concrete with a higher density, which performs better in terms of mechanical integration. In GPC, the type of aggregate must ultimately be a balance between density, strength, and thermal efficiency, depending on its use. The results showed that GPCs with customized density profiles could be produced using a targeted combination of EP and pumice, depending on the structural or envelope purpose of their application in sustainable buildings.

As the percentage of EP decreased and the pumice content increased in the concrete mixes, it was clear from the water absorption results presented in Table 4 and Figure 3 that there was a trend of decreasing absorption capacity in the concrete. With 100% EP, Mix M1 exhibited the highest water absorption value of 18.4%. Mix M5, which is made completely of pumice, recorded the lowest absorption rate at 10.1% instead. This is a significant decrease, which emphasizes the direct influence of the aggregate type on the pore structure and moisture transport behavior of lightweight GPC. Owing to the highly porous cellular structure of EP, a large amount of water is absorbed; thus, the total absorption rate of the concrete matrix is increased [24]. Although porous, pumice has a dense, more stable surface shape that reduces capillary absorption and enhances aggregate-binder-interaction, thus reducing total permeability [28]. Therefore, mixes with higher pumice content showed better resistance to water intrusion. The results obtained were in good agreement with those of previous investigations on lightweight concrete structures. Ma et al. [29] claimed that the inherent porosity of the aggregates and the quality of the ITZ between the aggregates and binder mostly control the water absorption behavior of GPC. In particular, in mixes with better packing (M4 and M5), the addition of $NaAlO_2$ to the activator used in this investigation contributed to greater matrix formation through a more developed N-A-S-H gel structure, which also resulted in a denser pore network. Moreover, the binder, which was finely ground with RHA, acted as a microfiller and reactive pozzolan, thereby improving the pore structure. By decreasing the open porosity and water ingress, the pozzolanic process burns calcium hydroxide and forms other binding phases [3]. Therefore, the geopolymer matrix in the pumice-rich blends exhibited a synergistic effect, resulting in a combination of lower absorption and higher strength. Even though the blends presented higher absorption than regular dense traditional concrete (usually approximately 8%), this is not a problem in the context of lightweight and nonstructural concrete, particularly if the insulation properties and self-weight are the dominant requirements. The proportion of the optimum ratio of EP to pumice should be adjusted to tailor the specific ratio according to the water absorption and thermal requirements.

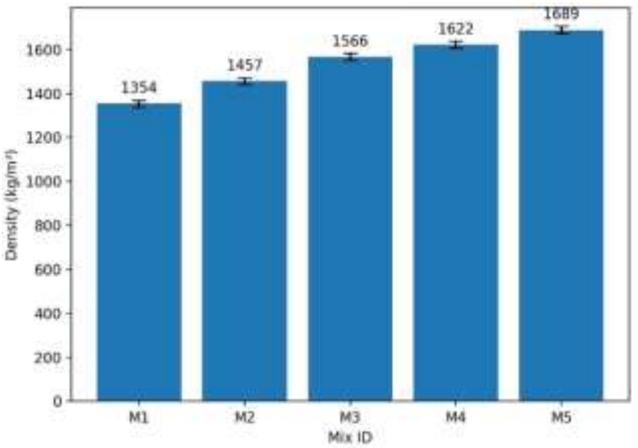

Figure 2. Dry density of rice husk ash (RHA)-based lightweight geopolymer concrete (GPC) mixes with varying ratios of pumice to expanded perlite (EP)
Note: Error bars represent ±1 standard deviation (n = 3).

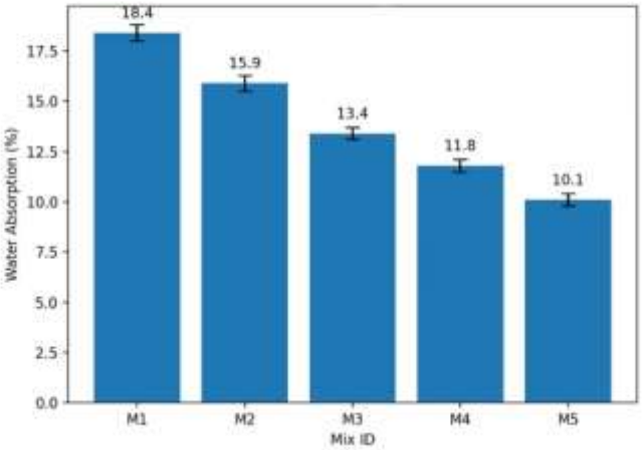

Figure 3. Water absorption of rice husk ash (RHA)-based lightweight geopolymer concrete (GPC) mixes with varying proportions of pumice and expanded perlite (EP)
Note: Error bars represent ±1 standard deviation (n = 3).

As the amount of EP decreased and the amount of pumice increased, the results presented in Table 4 and Figure 4 show that the thermal conductivity of the GPC mixes was enhanced. The lowest thermal conductivity, 0.189 W/m·K, was exhibited by Mix M1, while the highest thermal conductivity, 0.331 W/m·K, was exhibited by Mix M5 containing 100% pumice. This difference reflects the general characteristics of the thermal conductivities of both perlite and pumice and how their amount affects the thermal conductivity of the concrete mixture. As mentioned earlier, perlite has an exceptionally high insulation value because of the presence of cellular structures that trap replenished air pockets, thereby acting as superior thermal barriers [30]. Because of this characteristic of perlite, mixes M1 and M2, which contained perlite, exhibited lower thermal conductivities. Although pumice is lightweight and porous in nature, it has a higher rigidity in the form of minerals and is characterized by a low air entrapment content; thus, it has a higher thermal conductivity than perlite [31]. The marginal increment in thermal conductivity from M1 to M5 agrees with earlier observations made by Güneri [31]. This study clearly proved that concrete mixes containing higher amounts of pumice display higher heat conductivity because of increased connectivity and less internal air space entrapment [31]. It has also been clarified that Przybek et al. [32] demonstrated that the extent of thermal conductivity of GPCs largely depends on how lightweight materials behave and what form they possess. It should be between 1.4 and 1.7 W/m·K. The value of the thermal conductivity measured in this study was well within the range of thermally good-performing concrete and lower than that of normal-weight concrete [33]. These findings verify that, particularly for use in energy-efficient building envelopes, wall panels, and prefabricated insulating blocks, all the evaluated mixes provide significant thermal-insulation advantages. Mix M1 provides the best insulating properties, but its lower compressive strength and greater water absorption could restrict its use in structural projects. However, mixes M3 and M4 appear to be the optimum compromise between thermal efficiency, strength, and durability; hence, they are perfect options for non-load-bearing structural components that require both mechanical integrity and energy-saving characteristics. The addition of EP significantly increased the thermal insulating ability of RHA-based GPC, whereas pumice improved its mechanical performance. The optimal mix can be selected based on the desired balance between strength and thermal behavior, thereby enhancing the adaptability of this system for use in thermally efficient buildings (Table 5).

The compressive strength, density, and thermal conductivity performance trends were consistent with those of EP and pumice aggregates, whose porosity and surface properties have been thoroughly examined in previous studies [31]. These earlier results corroborate the interpretations made in this study, especially regarding the effects of aggregate porosity and interfacial bonding on the mechanical and thermal performance.

Correspondingly, mix M5 contains much more Al (11.05 at. %) than mix M1 does (10.62 at.%), but less Si. Thus, the Al/Si atomic ratio increased from approximately 0.367 in M1 to 0.414 in M5, which suggests greater incorporation of aluminum in the aluminosilicate network as well as increased cross-linking. This constitutes concrete compositional evidence that $NaAlO_2$ is an efficient supplier of reactive Al species that participate in geopolymerization. The mineralogical nature of the pumice accounts for the somewhat higher concentrations of minor elements (Fe, Mg, and Ca) in M5. The higher mechanical performance and reduced water absorption of M5 in the macroscopic tests are fully compatible with its higher Al/Si ratio and better polymerized gel network.

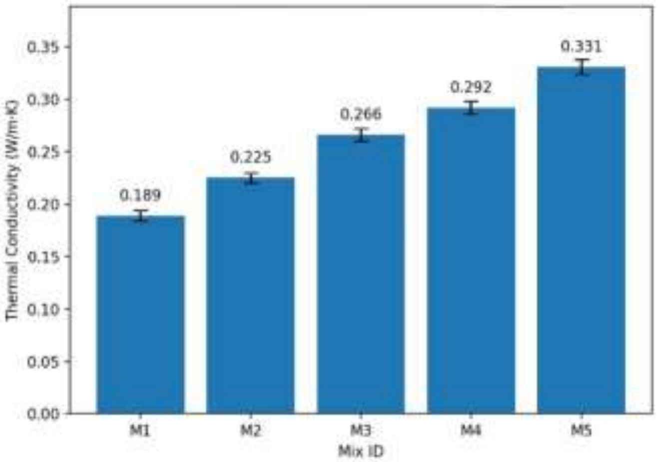

Figure 4. Thermal conductivity of rice husk ash (RHA)-based lightweight geopolymer concrete (GPC) mixes with varying proportions of pumice and expanded perlite (EP)
Note: Error bars represent ±1 standard deviation (n = 3).

Table 5. Energy-dispersive X-ray spectroscopy (EDS) atomic composition of mixes M1 and M5

Element	M1 (at.%)	M5 (at.%)
Al	10.62	11.05
Si	28.93	26.64
Na	6.08	6.16
Fe	0.31	0.98
Mg	0.26	0.67
K	1.20	1.22
Ca	0.72	0.86
O	51.88	52.42

5. COST-BENEFIT AND SCALABILITY CONSIDERATIONS

Compared with traditional OPC-based systems, the proposed RHA-based lightweight GPC offers notable cost and sustainability benefits. In many areas, RHA and volcanic aggregates, such as EP and pumice, are readily available as naturally occurring materials or inexpensive by-products, thereby reducing the cost of raw materials. Furthermore, compared with conventional cement production, the removal of high-temperature clinker lowers the energy consumption and operating expenses by approximately 40–50%. Excluding transportation savings, the laboratory-scale cost analysis showed that the material cost per cubic meter of the developed mixes was 20–30% less than that of similar lightweight OPC concretes.

The mix design and processing procedures, such as dry blending, alkaline activation, and moderate-temperature curing, are compatible with current concrete batching and curing facilities and require little modification for industrial-scale production in terms of scalability. This increases the viability of the system for extensive structural and nonstructural applications in energy-efficient buildings. This strategy offers financial and environmental incentives for the broad adoption of sustainable infrastructure projects, especially when combined with a proven reduction of up to 80% in CO_2 emissions.

6. ENVIRONMENTAL IMPACT AND CO_2 EMISSION REDUCTION

LCA studies indicated that the developed RHA-based GPC could reduce the emission of CO_2 by as much as 80%. The amount of CO_2 produced per ton of cement in a conventional production of OPC is about 0.85-0.95 tons, mostly as a result of the substances and steps of the high-temperature kiln and the calcination of limestone. Conversely, with geopolymer binders manufactured using waste products like RHA, the process of clinkerization at elevated temperatures is not necessary, and the process of alkaline activation generates much less CO_2—about 0.15 to 0.20 tons per ton of binder [7]. It was estimated that the total carbon footprint reduction relative to the case of lightweight concrete, relative to OPC, was between 75% and 82%, depending on the energy source and transportation effects, because in this research, 100% RHA was used as a binder in the mix designs. These results indicate the possibility of low-carbon GPC as a green alternative in the construction sector and are not beyond the scope of recent life-cycle assessment (LCA) studies.

7. LIMITATIONS AND FUTURE WORK

Nevertheless, it is noteworthy that the present investigation is centered on macro-level performance properties, that is, the mechanical, physical, and thermal characteristics. Energy-dispersive X-ray spectroscopy (EDS) analysis was also carried out to determine the chemical composition of the geopolymer gel and the specific role of $NaAlO_2$ in aluminum incorporation into the N-A-S-H network. From these findings, it is confirmed that the proposed activating system based on the dual alkali method, along with the combined pumice and perlite, is effective. Nevertheless, it is recommended that a thorough microscopic analysis using SEM be conducted in the near future to ensure a better understanding of the microstructural features, particularly the specific characteristics of the ITZ.

8. CONCLUSION

The findings of this study demonstrate the influence of the number of lightweight aggregates used in the mixture as well as the chemistry of the activating solution and the resulting N-A-S-H gel on the performance of RHA lightweight GPC. The use of a two-alkali activating solution of NaOH and $NaAlO_2$ was found to be highly significant for the alteration of the Al/Si ratio and the promotion of the formation of a highly cross-linked N-A-S-H gel.

The various properties of pumice and perlite were found to influence the trade-off between strength and insulation properties. Siliceous pumice, which is more reactive, enhances the strength of the geopolymer gel owing to its better reactivity, whereas perlite, which is highly porous, is mainly responsible for the enhancement of thermal efficiency. This highlights the need for the reactivity of the aggregate, not just the density, to be tailored when preparing lightweight geopolymer composites.

From an engineering and environmental perspective, the proposed method is a good approach for producing low-carbon and thermally efficient structural materials by converting agricultural and volcanic wastes to useful products while retaining good mechanical strength. These findings provide a mechanistic basis for the systematic development of lightweight GPCs, in which the chemistry of the activator, gel structure, and aggregate reactivity can be simultaneously tailored to meet specific requirements.

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