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Geopolymer as an Innovative Material for Green Roofs- A State-of-the-Art Review

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Abstract. To help minimize water temperature variations and stop excessive evaporation, effective insulation materials are frequently needed during the design and construction of ponds. In contrast to conventional materials, geopolymer mortars have great insulating qualities, making them an attractive option. An alkaline activator and aluminosilicate materials react chemically to create geopolymers, which have a three-dimensional network structure and high thermal insulation properties. Geopolymer mortars are used in ponds to promote energy efficiency and sustainability while also improving temperature stability and reducing water loss from evaporation. An alkaline activator and aluminosilicate materials react chemically to create geopolymers, which have a three-dimensional network structure and high thermal insulation properties. The use of geopolymer mortars as an insulating material in pond construction is discussed in this abstract, along with its composition, characteristics, and advantages over more conventional choices. Geopolymer mortars are used in ponds to promote energy efficiency and sustainability while also improving temperature stability and reducing water loss from evaporation. The utilization of geopolymers as cutting-edge insulating materials for structures with green roofs is thoroughly examined in this publication. As sustainable construction techniques become more prevalent, selecting the right insulating materials is essential for enhancing energy efficiency and overall building performance. Geopolymers, which can be produced from industrial waste or natural resources, offer appealing properties for green roofs, such as the ability to lessen the impact of urban heat islands, superior thermal insulation, and fire resistance. This study assesses the advantages, challenges, and potential impact of geopolymer-based insulating materials on green construction practices.

1 Introduction

The building industry has been compelled to look for cutting-edge solutions that balance the built environment with ecological balance as a result of the growing concern for environmental sustainability. Buildings with green roofs have come to symbolize this objective effectively since they effortlessly integrate architecture and nature. Numerous benefits are offered by these rooftop ecosystems, including improved stormwater management, improved air quality, and a decrease in the effects of urban heat islands. The efficacy of green roofs depends on the selection of adequate insulating materials, which are critical for controlling energy use and guaranteeing ideal indoor conditions.

The use of geopolymers in the construction of green roofs represents a paradigm change in the search for high-performance, environmentally friendly building materials. Geopolymers, which fall under the category of inorganic polymers, offer a tempting substitute for traditional insulating materials because of their special characteristics and ecologically friendly manufacturing process. A variety of feedstocks, including industrial by-products like fly ash and slag, which divert waste from landfills and reduce the need for resource-intensive materials like cement, can be used to create geopolymers. Recycling industrial waste streams, not only lowers the carbon impact of construction but also illustrates a circular economy strategy. Geopolymers and green roofs work well together because they both place a high priority on minimizing environmental effects. The use of geopolymers as insulating, waterproofing, and fire-resistant materials is in harmony with the principles of sustainable building, providing a comprehensive strategy that runs from the building's roof to its very foundation.

The superior thermal insulation, waterproofing, and fire resistance that geopolymers may offer go well in hand with the energy- and safety-conscious features of green roof buildings. While incorporating geopolymers into the design of green roofs has a lot of potential, several obstacles need to be overcome. To enable wider deployment, obstacles such as variability in material qualities, a lack of uniform testing procedures, and initial expenses must be overcome. To overcome these obstacles and change the trajectory of geopolymer-infused green roofs toward a more sustainable and resilient future,

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collaboration between academics, manufacturers, architects, and engineers, is essential [2,3]. The intricate interactions between geopolymers and green roof structures are explained in this article, along with the opportunities, difficulties, and possible solutions for using these materials for sustainable urban development. This study contributes to the body of knowledge that guides decision-making in the construction sector by a thorough review of empirical findings, simulation results, and industry insights. Stakeholders can pave the way for urban architecture that goes beyond its functional duty to act as a catalyst for environmental regeneration by embracing the synergy between green roofs and geopolymers.

2 Review

The investigation of geopolymers as insulating components for green roof structures is positioned within a larger field of study that converges on sustainable building practices, energy efficiency, and cutting-edge building materials. The following overview of the literature lists significant studies that have advanced our knowledge of the benefits, difficulties, and consequences of incorporating geopolymers into green roof systems. The conducted state-of-the-art review was a comprehensive keyword search. It was based on retrieving relevant publications based on keyword searches. These were thoroughly selected based on the major aim of the research topic.

2.1 Advantages of Geopolymer-Based Insulation for the Environment

The groundbreaking research by Yeou-Fong Li et al is regarded as one of the key contributions to the assessment of the environmental advantages associated with the use of geopolymers in construction techniques [2]. This groundbreaking study not only shed light on geopolymers' potential as insulation materials but also showed how they have the potential to transform the construction industry's commitment to sustainability. On the other hand, a study by G. Habert et al assessed the environmental potential of geopolymer-based concrete in the production of green buildings. They created geopolymers that had mechanical qualities that were on par with or even better than those of conventional cement-based materials [3]. The large reduction in the carbon footprint of buildings made possible by geopolymer-based materials was a key result of Hardjito et al [4]. Traditional cement production is known for producing high levels of carbon dioxide emissions, which adds to the environmental effect of the construction sector. In addition to keeping this trash out of landfills, the use of fly ash in geopolymers reduced the demand for cement clinker manufacture, a major source of carbon emissions. Because of the decrease in embodied carbon, geopolymers are now recognized as a powerful instrument in the construction industry's fight against climate change. The results of this study resonated outside the boundaries of material science, sparking a wider discussion regarding the restructuring of construction methods. As such, the innovative concepts offered by Rangan et al, in the context of green roof buildings provide the ideal environment for a rethinking of insulating materials [5]. Geopolymers were made more attractive as candidates for improving the environmental performance of green roof structures due to their inherent environmental advantages, which result from their capacity to utilize industrial waste streams. A persuasive argument stricken with sustainable construction concepts was the connection of geopolymer-based insulating materials with the principles of minimizing environmental effects and resource usage.

Green roofs are made up of multiple layers and materials (substrate, filter, drainage), located above the insulation and waterproofing layers of the building. Current green roof systems are still based on conventional materials and more sustainable alternative solutions are required. Geopolymers, in their many forms, can contribute to this purpose by forming part of the different layers of green roofs, from porous aggregates forming part of the substrate and drainage layers to denser continuous layers that provide thermal insulation, and resistance to fire or waterproofing.

2.2 Thermal Insulation Characteristics

The investigation of the insulating characteristics of geopolymers has shown their potential to fundamentally alter the way that energy efficiency is thought of in buildings with green roofs. In-depth investigations into this area by Jimenez and Palomo (2009) and De Silva et al. (2019) have revealed insights that highlight the crucial role of geopolymers in upholding ideal interior temperatures and maximizing energy savings[6,7]. The study by Palomo et al. (2009) is a keystone in understanding the thermal properties of geopolymers. Their research clarified a crucial characteristic: the limited thermal conductivity that geopolymers display. This characteristic highlights the material's innate ability to block the passage of heat, acting as a natural barrier to control indoor temperatures. Temperature changes on green roofs are a concern. By examining the complex link between geopolymer composition, pore structure, and thermal conductivity, De Silva et al. (2019) expanded this investigation where the research indicated that geopolymer porosity has a substantial impact on thermal performance [7]. The increased thermal insulation characteristics of geopolymers with well-optimized pores open the door to the possibility of customizing material compositions to meet particular energy efficiency goals. This finding emphasizes how adaptable geopolymers are, opening up possibilities for material engineering that meet the needs of green roof systems. These discoveries have important repercussions for the field of environmentally friendly buildings, particularly with green roofs. Geopolymer-based insulating materials are added as a dynamic thermal management layer to green roof systems, as such this material decreases the need for energy-intensive heating and cooling systems by efficiently protecting indoor rooms from changes in outdoor temperature. This helps achieve the broad objectives of lowered carbon emissions and improved building sustainability. The possibility of geopolymer-based materials to function as efficient thermal insulators inside green roof systems is highlighted by the synthesis of findings from Palomo et al. and De Silva et al. Geopolymers' low thermal conductivity not only supports green roofs' main objective to be energy-efficient but also increases their capacity to maintain stable interior temperatures and guarantee occupant comfort [6,7].

2.3 Waterproofing Properties of Geopolymers

Previous authors have studied the possibility of improving the hydrophobic behavior of geopolymers. Duan P. et al. (2016) proposed a novel waterproof, fast-setting geopolymer repair material with a hydrophobic surface and high compressive strength and bonding strength. This newly developed geopolymer repair material has a short setting time of 24 min, a high flow of 212 mm, and a high early compressive strength and bonding strength of the interfacial bonding zone as indicated by the dense microstructure. Feng B. et al. (2022) investigated the effect on the waterproof performances of different silane coupling agents (SCAs) and different SCA dosages (0 wt%–4 wt%) of metakaolin-based geopolymer. The experiments confirmed that a small amount of silicone enhanced the hydration of geopolymer and that SCAs could improve the waterproof performance of the specimens by reducing the pore structures inside them and can enhance the waterproof performance due to the reactive groups of SCA. Adding a suitable amount of SCA positively affects the self-waterproof performance of the geopolymer. In the research conducted by Ruan S. et al. (2022) a waterproof geopolymer composite fabricated by blending hydrophobic metakaolin and quartz particles, as well as PDMS agents (Polydimethylsiloxane), was developed. This work reveals the waterproof mechanisms and water absorption kinetics of geopolymer composites with hydrophobic materials and points the way to waterproof engineered geopolymer materials. Ago C. et al (2023) conducted a feasibility study of using hydrophobic geopolymer-based aggregate substitution in asphalt mixtures. The results indicate that the activators Na2SiO3/NaOH at a mix ratio of 1 have a suitable effect on the pores and the compressive strength of the new artificial aggregate most particularly sodium hydroxide. These previous recent research findings, among others, show that geopolymers can provide waterproofing properties that can be very interesting in the future construction systems for the building envelope, including green roofs.

2.4 Fire Resistance Properties of Geopolymers

Fire resistance and safety remain of the highest priority in the construction industry, and an essential characteristic that supports the structural integrity of buildings is fire resistance. The fire-resistant qualities of geopolymers have drawn a lot of interest in this context and have the potential to take buildings with green roofs to new levels of resilience and safety. A ground-breaking work by Hassan et al. opened up a new area of research into the safety of green roofs by illuminating the excellent fire-resistant qualities of geopolymer-based materials [8]. It assessed the fire performance of geopolymer-based materials exposed to high temperatures and watched to see how they responded. The results showed that geopolymers have a remarkable ability to endure high temperatures without suffering from significant structural integrity loss. This discovery was ground-breaking because it showed how geopolymers might compete effectively with other building materials for fire resistance. This important finding has a wide range of ramifications, particularly for structures with green roofs. Due to the living flora, elaborate irrigation systems, and frequently complex structural components found on green roofs, fire safety must be carefully taken into account. The use of geopolymer-based insulating materials is a promising approach to reduce fire risks without threatening the building's structural stability. This is consistent with the broad goals of sustainable construction, which include improving the building's energy efficiency and environmental performance as well as assuring the security and well-being of its occupants.

2.5 Challenges of Material Variability and Standardization

There are several difficulties associated with the use of geopolymer-based materials in construction, particularly green roof systems, which need careful thought. Material variability and the lack of uniform testing procedures have become crucial issues in the field of geopolymer technology that demand careful consideration. The groundbreaking studies by Duxson et al. (2007) highlight the intricacy of these difficulties and stress the necessity of finding solutions to successfully integrate geopolymers into construction methods [9]. The study exposed the intrinsic heterogeneity in geopolymer characteristics. The elaborated geopolymers display a range of properties impacted by varying the main raw materials, curing conditions, and time. As such comprehensive methods for maintaining repeatability are an essential component for the production of geopolymers since this variability can result in variations in mechanical strength, thermal characteristics, and durability. The results underline how crucial it is to comprehend the subtleties of raw material selection and processing to consistently produce materials with good properties. While testing processes for typical building materials are well-established, the new chemistry and characteristics of geopolymers call for specialized testing methodologies. The inability to accurately assess material performance due to standardized standards prevents architects, engineers, and construction industry professionals from adopting geopolymer-based materials with confidence [9]. Material variability can result in inconsistencies in thermal performance and structural integrity within green roof systems, jeopardizing the desired energy efficiency and longevity of the structure. The lack of standardized testing protocols not only obstructs accurate material evaluation but also hinders regulatory approval processes. This duality of challenges necessitates a concerted effort to address these issues but their seamless integration into construction methods is impeded by the absence of standardized testing procedures. Unlocking the full potential of geopolymers as insulating components in green roof systems requires addressing these issues. As such establishing industry standards, streamlining material processing, and accelerating the realization of the environmental and performance advantages of geopolymer-based construction require collaborative efforts.

2.6 Life Cycle Analysis and Economic Viability

The evaluation of environmental effects in the goal of sustainable construction goes beyond the limitations of material properties to include the whole life cycle of a building. A valuable method for thoroughly evaluating the ecological footprint of building materials is life cycle analysis (LCA). Salas al. (2018) conducted an instrumental LCA analysis on geopolymer-based insulation that not only looked at the environmental effects but also went into the financial viability of utilizing geopolymers in building insulation systems [10]. The study served as a scope for investigating the effects of geopolymer-based insulation throughout the life cycle. A comprehensive approach to the broader environmental impacts of geopolymer insulation by contrasting it with the environmental footprint of standard insulating materials was assessed.

The study showed that, even though geopolymer-based insulation materials would have greater initial prices because of the infancy of the technology, they have significant long-term environmental advantages. One of the main conclusions was that using geopolymer insulation reduced cumulative environmental effects throughout a building's lifetime. Multiple variables, including the inherent environmental advantages of geopolymers, their thermal insulation capabilities, which resulted in lower energy usage for heating and cooling, and the diminished waste formation connected with their production and use, were cited as the causes of this reduction. The LCA analysis essentially confirmed the potential of geopolymer-based insulation as a tool for advancing sustainable construction goals. This study has consequences that go beyond environmental concerns. Economic viability research is equally important in the cases of LCA studies, especially in the context of structures with green roofs. Although the initial costs of geopolymer insulation may be higher than those of traditional materials, the long-term cost savings brought about by decreased energy consumption, increased material longevity, and reduced maintenance needs highlight the geopolymer integration's all-encompassing economic appeal. This economic viewpoint fills the gap between the initial investment and the long-term advantages that develop throughout the building's life.

2.7 Results

The combined investigation of the possible interaction between geopolymers and green roof design creates a colorful scene where sustainable urban development and cutting-edge building techniques collide. The harmonious narrative that emerges from the symphony of research contributions, which span a variety of fields including environmental advantages, thermal properties, fire resistance, material variability, life cycle analysis, and collaborative efforts, highlights both the benefits and challenges inherent to geopolymer adoption in the context of green roofs.

The groundbreaking work done by previous studies has made geopolymers an example of environmental stewardship. Their work exposed a paradigm shift by demonstrating how geopolymers may transform industrial waste materials into useful building materials resulting in a decrease in carbon impact. By avoiding the production of cement and developing geopolymer-based materials, it was possible to reduce the carbon footprint, which highlights how well geopolymers align with the principles of the circular economy and the objectives of sustainable building.

Additionally, the discussion of thermal characteristics and fire resistance heralds a time when green roof systems will be safer and more energy efficient. The versatility of geopolymers discussed by the studies in this publication had a dual role in promoting energy efficiency and enhancing safety measures because of their superior thermal insulation, ability to endure high temperatures while retaining structural integrity, and ability to reduce energy consumption. However, including geopolymers in the design of green roofs is not without its challenges.

These difficulties are not challenges, but rather opportunities for interdisciplinary projects between regulatory agencies, businesses, and academics. To utilize geopolymers to their maximum potential, these issues must be resolved. The literature analysis emphasizes the dearth of thorough studies examining the numerous aspects of geopolymers used in the development of green roofs. This lack of research is a call to action for more funding, innovation, and cross-disciplinary cooperation. By closing this knowledge gap, we open the door for comprehensive solutions that take into account the demands and goals of sustainable urban development.

3 Conclusion

In conclusion, this literature analysis serves as a starting point for fresh research, paving the way for incorporating geopolymers into the development of green roofs. The combination of insights captures the dynamic interaction between new technologies and environmentally friendly urban planning, paving the way for a time when green roofs will not only flourish as environmental assets but also serve as examples of cutting-edge technology. By using the insights from this analysis to guide us as we begin our in-depth investigation, we pass the torch of knowledge forward and herald in a new era of construction that is more durable, energy-efficient, and environmentally conscientious. According to the assessed work in this study, the following conclusions can be made:

- Geopolymers have substantial potential as cutting-edge insulating components for structures with green roofs.
- Comprehensive insights are provided by extensive research across a variety of categories, including environmental effects, thermal behavior, fire resistance, material variability, life cycle evaluation, and collaborative initiatives.
- Utilizing industrial waste to reduce its carbon footprint and adhere to the principles of the circular economy, geopolymer technology displays its environmental responsibilities.
- Geopolymers' strong thermal insulation capabilities and fire resistance help green roof constructions operate more safely and efficiently.
- The difficulty of implementing geopolymers is highlighted by issues including material variability and the lack of consistent testing procedures.
- To improve material uniformity, and set testing standards, collaborative approaches are crucial.
- To fully utilize geopolymers for applications on green roofs, there is a need for increased research funding, technological advancement, and interdisciplinary collaboration.

This thorough research provides a solid foundation for increasing geopolymer integration in green roof construction, resulting in robust, sustainable, and green building practices.

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