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Geopolymer as a Viable Alternative for Moisture Control and Partial Discharge Mitigation in Buildings of Electrical Substations

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ABSTRACT

Partial discharges (PDs) accelerate insulation degradation and threaten the reliability and life-span of high-voltage substations. While PD mitigation studies largely focus on insulation materials and operating conditions, the role of substation building materials in controlling internal humidity remains underexplored. Conventional ordinary Portland cement (OPC) concrete is prone to moisture ingress, resulting in elevated humidity levels that intensify PD activity. This study review materials–environment–PD relationship by examining the properties of geopolymer concrete as an alternative to OPC. The conceptual proposal highlights the permeability, moisture resistance, and sustainability of geopolymer materials, and their potential to stabilise internal substation environments and mitigate humidity-driven PD risks are discussed. The study positions geopolymer concrete as a viable construction material for improving the long-term reliability of electrical substation infrastructure.

KEYWORDS: Electrical substations, Geopolymer concrete, Humidity control, Ordinary Portland cement, Partial discharge.

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1. INTRODUCTION

Electrical substation are vital components of power networks, serving as interface between transmission and distribution networks. Within substations, voltage transformation to threshold operational level is carried out through various electrical equipment before power delivery to end users (Ali *et al*., 2017; Bayliss and Hardy, 2007; Ezenwora *et al*., 2009). The operational reliability of such equipment is influenced by the internal environmental conditions of substation buildings, which are, in turn, governed by external ambient conditions and the materials used in their construction (Byrne, 2013). In particular, a recent study reported by Ji *et al*. (2023) and Wang *et al*. (2018) have demonstrated that unfavourable environmental conditions within substations influence the partial discharge activity. Furthermore, elevated humidity, temperature fluctuations, pressure variations, and airborne pollutants increase the frequency and severity of PD responses in indoor substations. Perhaps Ji *et al*., (2024) identified temperature, pressure, humidity, and contaminants as critical atmospheric variables influencing PD initiation and propagation. Thus, it is recommended that stringent environmental control to enhance the lifespan of electrical insulation systems must be activated.

Ordinary Portland cement (OPC) remains the most widely used construction material for electrical substation buildings. However, cement productions contribute to environmental degradation, climate change and disperses traceable level of 238U radionuclide into the environment. (Oni et al., 2017; Adnan and Anas, 2025). Beyond environmental concerns, Cement-based concrete structures are inherently susceptible to moisture ingress. The absorption, adsorption, and subsequent desorption of moisture from cementitious walls elevate internal humidity levels, creating conditions that exacerbate PD activity and accelerate insulation degradation (Byrne, 2013).

The influence of humidity on PD behaviour is well established in the literature. Ji et al. (2024) showed that strict regulation of humidity, temperature, and pressure is essential for extending the service life of electrical equipment. Tschentscher et al. (2020) demonstrated that humidity directly affects conduction processes and micro-discharge intensity at gas–solid interfaces in gas-insulated devices, highlighting moisture control as a critical strategy for reducing surface charge accumulation and PD-related failures. Li et al. (2021) further reported that high humidity accelerates insulation aging in transformers, reducing both electrical and mechanical strength, while Hassan et al. (2020) emphasized the need for comprehensive environmental monitoring to prevent insulation system failures caused by humidity, temperature, and pollution.

Despite these advances, existing PD mitigation studies predominantly focus on insulation materials, monitoring techniques, and equipment-level operating conditions, without the contribution of substation building materials to internal environmental control. Similarly, review studies on geopolymer concrete primarily emphasize mechanical performance, durability, and sustainability, without linking these properties to partial discharge mitigation in high-voltage infrastructure. This review introduces a novel perspective by integrating geopolymer material science with partial discharge mitigation through a building–environment framework. Rather than treating PD solely as an insulation or operational problem, the study positions substation building materials as an upstream control parameter capable of stabilising internal humidity and suppressing humidity-driven PD activity.

Geopolymer concrete (GPC), synthesized from industrial and agricultural by-products, offers a promising and sustainable alternative to OPC. Owing to its denser microstructure and lower permeability, GPC exhibits superior resistance to moisture ingress, improved durability, and enhanced environmental compatibility. These characteristics suggest its potential to maintain stable internal humidity conditions within substation buildings, thereby mitigating PD activity and prolonging the operational lifespan of electrical equipment.

The specific objectives of this study are to link (i) the moisture transport behaviour of geopolymer concrete, (ii) substation indoor environmental stability, and (iii) partial discharge mechanisms. Accordingly, this work positions geopolymer concrete not merely as a sustainable construction material, but as a functional humidity-regulating medium capable of enhancing the long-term reliability of electrical substation infrastructure.

2. MAIN BODY

2.1 Partial Discharge

Partial discharges (PDs) are localised electrical discharges that occur within or on the surface of electrical insulation materials when subjected to high-voltage electrical stress during equipment energisation (Byrne, 2013). They arise when the local electric field exceeds the dielectric breakdown strength but do not fully bridge the insulation gap between conductors. Instead, PDs cause progressive localised damage and accelerated ageing, which weakens insulation systems and can ultimately result in complete equipment failure and arc flashes (Awang *et al.*, 2017; Szilágyi et al., 2023). PDs are commonly classified into three types: corona, internal, and surface discharges (Hassan et al., 2020; Melo et al., 2024). Corona and internal discharges are primarily associated with factors such as mechanical wear, the presence of voids, gas ionisation around electrodes, or pre-existing deterioration within insulating materials (Wang et al., 2018; Hassan et al., 2020). In contrast, surface discharges are strongly influenced by adverse environmental conditions surrounding the insulation system, particularly humidity, temperature, and atmospheric pressure. Among these environmental factors, humidity plays a role in the initiation and exacerbation of surface partial discharge activity. Moisture adsorption on insulation and structural surfaces reduces surface resistivity, promotes contaminant deposition, and induces non-uniform electric field distributions, especially at material interfaces, pores, and surface defects (Wang et al., 2018). Consequently, sustained high-humidity environments may compromise the long-term performance and reliability of electrical insulation in high-voltage installations. Furthermore, increased moisture content enhances ionic conduction and facilitates surface charge accumulation, leading to a reduction in PD inception voltage and an increase in discharge repetition rates (Li et al., 2021). In enclosed infrastructures such as electrical substation buildings, internal humidity levels are strongly influenced by the hygroscopic behaviour and pore structure of construction materials. Conventional OPC based concrete exhibits relatively high open porosity and interconnected capillary pores, which promote water absorption, moisture retention, and cyclic adsorption–desorption processes. These moisture dynamics elevate ambient humidity and create favourable sufficient electrical conductivity for formation of conductive paths for surface PD development on electrical insulation systems. In contrast, GPC offer intrinsic properties that can mitigate humidity-driven partial discharge mechanisms. The dense aluminosilicate gel matrix of geopolymers is characterised by reduced open porosity, lower water absorption capacity, and higher bulk density compared to OPC-based concrete. These properties limit moisture ingress, diffusion, and storage within the substation building envelope, thereby stabilising internal humidity levels. Reduced moisture availability helps preserve higher surface resistivity of insulation materials and minimises electric field enhancement at interfaces and defects, ultimately suppressing the initiation and propagation of surface partial discharges. Therefore, by indirectly controlling the environme ntal conditions that govern PD behaviour (Ji et al., 2023), geopolymer materials function as preventive dielectric-support materials rather than passive structural components. This material-based approach complements conventional PD monitoring and insulation design strategies by addressing the root cause of moisture-induced surface discharge activity, thereby enhancing the reliability and service life of high-voltage equipment such as switchgear, transformers, and cables (Byrne, 2013).

2.2 Humidity

The level of humidity in the building of electrical substation plays a dual role; it either suppress or promote the activity of partial discharge. Humidity, in the context of electrical insulation, refers to the presence of water vapour in the surrounding atmosphere. It is typically quantified as relative humidity (RH) or absolute humidity, and its impact on electrical systems extends beyond ambient conditions (Ab-Ghani et al., 2019). The relative humidity expressed as a percentage is a measure of the actual amount of water in the atmosphere compared to the maximum amount of water it can hold (saturated) at the same temperature. High RH in the electrical substation is caused by water ingress through the building structure (Byrne, 2013). Moisture can infiltrate insulation through diffusion, absorption, or condensation – especially under fluctuating temperature and pressure conditions common in operational environments. Once inside, it can alter the dielectric properties, increase surface conductivity, and reduce dielectric strength, making the insulation more prone to initiating and sustaining PD activity (Ab-Ghani et al., 2019). The influence of humidity in PD research has grown as experimental studies and real-world failures have revealed that high moisture levels exacerbate insulation degradation. Water molecules interact with the insulation surface and internal structure, facilitating electron avalanche, surface tracking, and chemical breakdown of materials (Wang et al., 2018). A highly humid electrical substation building contains contaminants such as dust, salt and moisture that falls on insulation surfaces and condense that creates a conductive path to initiate discharge. This effect is strongly influenced by building material properties: OPC-based concrete, with high porosity and capillary connectivity, retains moisture creating pathway for PD activity, whereas GPC, owing to its reduced porosity, lower water absorption, higher density, and improved moisture resistance, limit moisture ingress and stabilise humidity. Consequently, geopolymer materials maintain higher insulation surface resistivity, reduce electric field enhancement, and offer a preventive, passive approach to mitigating PD in electrical substations.

2.3 Geopolymer

Geopolymer is an amorphous, eco-friendly, inorganic, and polymeric material produced by the dissolution of alumina and silica-based sources in a solution containing sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) as activator at ambient temperature (Issa et al., 2023; Ngui et al., 2022; Walkley et al., 2021). As a viable alternative to cement, geopolymers have the prospect of replacing OPC for the production of durable concrete with good structural qualities (Olarinoye et al., 2025). By considering the cementitious nature, cost-effectiveness, durability (Matsimbe et al., 2022), outstanding structural attributes and low carbon footprint status (Liu et al., 2023), geopolymer has turn out to be the most sustainable ecofriendly material for replacing conventional OPC in concrete for structural applications (Kanagaraj et al., 2024).

2.3.1 Properties of Geopolymer Concrete

Several aluminosilicate sources have been synthesised using various alkali activators in varying quantities to enhance the mechanical qualities of geopolymer concrete. The unique properties of geopolymers could be explored in mitigating partial discharge in buildings of electrical substations. Geopolymers' defining characteristics depend on the raw material sources which define their mineralogical and chemical compositions, physico-mechanical properties, structural properties as well as the manufacturing process, including the ratio of raw materials, the blending time and temperature, and any rheology modifiers, accelerators, or retarders that affect the curing and setting times (Doğan-Sağlamtimur et al., 2022). The molar ratio of silica and alumina (Si/Al), as well as the circumstances of curing, setting, and hardening of the geopolymer structures, are additional parameters that affect the properties and application areas of geopolymers (Janošević et al., 2018). Geopolymer properties are often investigated in terms of physical and mechanical properties; however, for the purpose of this work, physical properties of geopolymers such as, density, porosity durability and water absorption in relation to partial discharge mitigation in buildings will be highlighted.

Density

The density of geopolymer composites depends on their composition, the type of alkali activator (Sodium-based or potassium-based), aggregate, and the ratio of silicon to aluminium (Si/Al ratio). For instance, depending on the nature of the precursor used, the synthesis route and the curing condition, geopolymer concrete could have densities vary between 2810 – 3870 kg/m^3 as compared to 2560 – 2790 kg/m^3 for OPC concrete (Olarinoye et al., 2025). However, higher water to mix ratios increases porosity of the geopolymer thereby decreasing its bulk density. This problem can be overcome by increasing the Si/Al ratio of the geopolymer matrix to become more compact and denser with fewer pores. Thus, the high dense nature of geopolymer concrete serve as buffer for moisture accumulation to support humidity which in turn help in mitigating partial discharge in buildings of electrical substations.

Porosity

The ratios of the mixture and curing conditions influences the porosity of geopolymers. Higher porosity arises from either insufficient compaction during moulding or higher water content, which weakens the geopolymer and thereby affecting its durability. Concrete's mechanical qualities are closely related to its porosity and pore distribution, both of which can be enhanced by adding mineral admixture (Ayub et al., 2014). The chemical makeup of the raw materials, the curing conditions, and the processing technique are some of the variables that affect the porosity of geopolymer concrete. When solid aluminosilicate precursors are dissolved by alkaline hydrolysis, a supersaturated solution of aluminate and silicate varieties is

Table 1 Factors that can mitigate partial discharge in concrete

Factors	Geopolymer concrete				Portland concrete	
	2 M NaOH		12 M NaOH			
Curing days	28	90	28	90	28	90
Water absorption (%)	4.44	3.91	4.75	4.27	5.08	4.53
Volume of permissible voids (%)	10.51	9.32	10.72	9.74	11.66	10.48
Charge passed (C)	977.61	928.73	1065.14	1023.43	1887.34	1792.97

Table 2 Properties of Geopolymer, Humidity Control and PD Mitigation Mechanism

Geopolymer Properties	Humidity Control	PD Mitigation
Porosity	Lower porosity acts as humidity buffer	Decreases the risk of PD due to discontinuous pore network
Water absorption	Control internal humidity due to low water absorption capability	Prevent electrical conductivity due to lower pore leading to high surface resistivity
Density	Low permeability due to high density of GPC reduces condensation of water, controlling humidity	Denser GPC with fewer pores decreases the risk of PD
Electrical conductivity	Geopolymers with lower electrical conductivity are characterised by few pores that can prevent moisture build-up	Fewer pores hinder ion mobility thus mitigating partial discharge

produced. This results in the formation of a gel, after which the water molecules that are meant to be consumed during the precursor's dissolution are released (Aredes et al., 2015). It has been discovered that a geopolymer's porosity is significantly influenced by its early water content during formation (Castillo et al., 2021). This is due to the fact that high water content causes voids to form, increasing a material's porosity and forming a permeable geopolymer that is susceptible to shrinkage and the formation of microcracks during the curing process (Hotek et al., 2023). In the end, this will result in the concrete's shape becoming deformed (Wielgus et al., 2021). Depending on the specific application and desired characteristics, geopolymers can have a wide range of porosities. Accordingly, geopolymers have a range of pore diameters, both open and closed, and their properties are related to the raw material source and the curing method (Aredes et al., 2015). However, by increasing the rate of geopolymerisation and creating a denser matrix, a higher Si/Al ratio tends to decrease the porosity of geopolymers. From a partial discharge perspective, this reduction in porosity and pore connectivity directly limits moisture retention and ionic transport within substation building walls, thereby suppressing localised electric field distortion and space-charge accumulation that are fundamental to PD initiation and propagation under high-voltage stress. Consequently, controlling geopolymer porosity through optimised mix design and curing conditions provides a clear, material-based pathway for mitigating humidity-induced PD activity, offering a functional advantage over conventional OPC-based construction materials.

Durability

Durability has a major influence on how long concrete structures last. Prior knowledge of the durability qualities is desirable for the commercial deployment of geopolymer concrete for many applications including buildings of electrical substations. Geopolymers' chemical makeup coupled with a higher surface area and a higher concentration of amorphous silica and alumina of their precursors produce less porous gel (Ngui *et al*., 2022). This provides their exceptional durability properties that can enhance their performance to mitigate moisture ingress in buildings of electrical substations.

Water absorption

The water absorption in geopolymers is determined by porosity and curing conditions. The durability and chemical attack resistance of geopolymers are enhanced due to lower water absorption which is due to low porosity. Water absorption in fly ash and slag-based geopolymer concrete is typically lower than in Portland cement concrete. Thus, they can be utilised in severe conditions. The water absorption values of 3.91% and 4.44% for geopolymer concrete at lower NaOH concentration have been documented for 90- and 28-days curing period respectively by (Singh et al., 2024) as against 4.53% and 5.08% for Portland concrete within the same period. This reduced water absorption is associated with the dense matrix, reduced permeability, and improved microstructural integrity, all of which contribute to the long-term durability of geopolymer-based structures. From a partial discharge standpoint, lower water absorption directly limits moisture accumulation within the concrete matrix and on the internal wall surfaces of substation buildings. Reduced moisture availability suppresses ionic conduction, surface wetting, and space-charge formation-key mechanisms responsible for PD initiation and intensification under high electric field conditions. Consequently, the inherently low water absorption of geopolymer concrete provides a clear and functional pathway for mitigating humidity-induced PD activity when compared with conventional OPC-based construction materials.

Electrical Conductivity

Geopolymers are generally good insulators due to their poor electrical conductivity. The type of alkaline activator employed, porosity, and moisture level all affect conductivity. In the absence of conductive additives, geopolymers often display characteristically low electrical conductivity, typically between 10^{-4} to 10^{-3} S/cm, making them an insulating material of choice in construction. The high resistivity which is often greater than 100 kΩ·cm inhibits considerable current leakage, which limits the initiation and occurrence of partial discharges under high voltage conditions (Zhang et al., 2024). Besides, the low thermal conductivity of geopolymers and high resistivity, predisposes them to outperform the conventional Portland cement for the purpose of electrical insulation in high voltage environments. Thus, in buildings of electrical substations, geopolymer composites can minimise partial discharge by reducing surface erosion and dielectric losses from discharges (Alvarado et al., 2024). This can be attributed to their dense aluminosilicate structure which has the capacity to regulate moisture, resist void formation and ion migration (Chen et al., 2024; Dai et al., 2022; Sharmin et al., 2024). The behaviour of geopolymer composite as a sustainable insulation material for mitigating partial discharge is evidence from the work of Singh et al. (2024) as presented in Table 1, where electrical charges passing through the geopolymer concrete increased with increasing molar concentration of NaOH, while it decreased with decreasing water absorption and volume of permeable voids which are both connected to the porosity of the concrete. Besides, the quantity of charge passing through geopolymer concrete is lower as compared to the OPC concrete for the curing durations considered. This shows that geopolymer concrete can be used effectively to mitigate partial discharge in the buildings of electrical substations. Table 2 presents the causal linkage summarising the mechanism of humidity control and partial discharge mitigation of core geopolymer properties.

2.3.2 Environmental Benefit of Geopolymer

In civil engineering construction applications, there are several environmental benefits of using geopolymers rather than OPC. Such benefits include, lower carbon footprints, utilisation of industrial wastes, less energy requirements, low water consumption, less pressure on pristine natural resources, reduced air pollutant emissions, carbon sequestration potential**,** and minimal ecological damage.

Reduced Carbon Footprints

In order to produce OPC, limestone must be calcined at temperatures of about 1450 °C, which releases a significant amount of CO_2 (Al-Jiboory and Al-Hazaa, 2022). According to (Adnan and Anas, 2025; Bouchenafa et al., 2022), the CO_2 emission from the process of calcining limestone is responsible for 2 billion tonnes annual global CO_2 emission. On the other hand, calcination is not necessary for the manufacturing of some geopolymer cement particularly, those produced from industrial wastes, hence process-related CO_2 emissions are avoided. For every tonne of cement produced, OPC releases about 1 tonne of CO_2 emissions (Palod et al., 2017). This CO_2 emissions can be cut by up to 80% with geopolymers (Ruviaro et al., 2023). This directly aids in reducing global warming and achieving climate change targets such as those outlined in the Sustainable Development Goals (SDGs). This directly contributes to reducing global warming through the protection of the ecosystems, reducing natural disasters, preserving biodiversity, and ensuring sustainable human development (Pinlova et al., 2024). It also supports achieving climate change targets outlined in the Sustainable Development Goals (SDGs), which aim to improve water quality, decrease marine pollution, protect terrestrial and aquatic ecosystems, and promote sustainable agriculture and forestry.

Use of Industrial Waste

Fly ash (Aziz et al., 2023; Guan et al., 2023), blast furnace slag (Inti et al., 2016; Ashveenkumar et al., 2022), and red mud (Liu et al., 2020; Singh et al., 2018) are examples of industrial by-products that are frequently used to make geopolymers. These materials would otherwise end up in landfills or present danger of contamination of surface and underground water in the environment. By diverting trash from disposal, this lowers the dangers associated with leachate and land use. It encourages zero-waste production and the circular economy (Philip et al., 2023). This also, protects the environment through the recycling of waste that contains polymer contaminant thereby reducing the risk of toxic substances that can contaminate soil and groundwater (Jiao et al., 2025).

Decreased Energy Use

Because OPC is produced in high-temperature kilns, it requires a lot of energy. Low-temperature processing usually less than 100 °C (Ekaputri *et al*., 2017; Lopes *et al*., 2023) or ambient curing (Aziz *et al*., 2023; Nurruddin *et al*., 2018) are used in the manufacturing of geopolymers. As a result, energy consumption is lower; thereby lessening reliance on fossil fuels. The reduction of reliance on fossil fuels significantly lowers greenhouse gas emissions, a major driver of global warming and climate change. Furthermore, the decreased fossil fuel combustion enhances air quality by reducing harmful pollutants such as Sulphur dioxide and Nitrogen oxides. This ultimately leads to improved public health and fewer respiratory issues among people.

Reduced Natural Resource Mining

OPC requires extensive mining of natural mineral resources such as, gypsum, clay, and limestone, which causes ecological imbalance (Adekunle *et al*., 2017), radionuclide dispersal, biodiversity loss., pollution of the air and soil with dust. By using waste materials that already exist, geopolymers considerably reduces the requirement to extract pristine raw materials. The use of geopolymers helps protect the environment by mitigating the adverse effects of mining of natural resources. This is because the extraction of natural resources especially solid minerals often results in land excavation, soil erosion, biodiversity loss, and water pollution (Suleiman, 2024). These environmental impacts can devastate local communities that rely on natural resources for their livelihood. However, by adopting geopolymers, it significantly reduces the environmental degradation associated with mineral resources extraction.

Reduced Water Usage

Compared to OPC concrete mixes, geopolymer concrete mixes usually require less water, and can be cured in the absence of water. Also, the manufacture of cement utilises a significant amount of freshwater. This water requirement has been estimated as 0.5 kl/tons of OPC by (Selvarajan *et al*., 2017). Thus, in arid and water-limited areas, the use of geopolymer-based concrete will prevent excessive use of the available water resources. This further contributes to environmental protection by safeguarding ecosystems, minimizing pollution, saving energy, and ensuring water remains available over the long term. In addition, it supports the preservation of natural habitats, reduces carbon emissions, and helps prevent water shortages, benefiting both nature and human populations.

Lower Air Pollutant Emission

In addition to CO_2 emissions, OPC production is also linked to hazardous emissions. Such hazardous emissions. includes, emissions from the mining of lime stone, emission of nitrous oxide (N_2O), methane (CH_4) (Adekunle et al., 2017; Mohsen et al., 2022), SO_2, during production and particulate matter, which contributes to respiratory illnesses, acid rain, and smog formation. Besides, calcination of OPC raw materials and burning of fossil fuels to sustain elevated temperature in the kiln are the processes that constitute the highest environmental impact (Durastanti and Moretti, 2020). Since the manufacture of geopolymers is a lower temperature process, very little airborne pollution is released. The reduction of air pollutant emissions plays a vital role in protecting the environment. It lessens harm to ecosystems such as forests, soils, water bodies, and aquatic life by decreasing toxic substances and nutrient imbalances. This process supports biodiversity and forest vitality while also enhancing soil health and water cleanliness. In addition, cleaner air improves visibility and fosters the well-being of plants and wildlife. Moreover, lowering air pollution not only safeguards nature but also yields considerable health advantages for people, including fewer respiratory and heart diseases, reduced healthcare expenses, and longer life expectancy (Kyrchenko, 2024).

3. CONCLUSION

This article has reviewed the properties, electrical conductivity and the environmental benefits of geopolymer concrete in relation to its potential application in the construction of electrical substation buildings. The synthesis of the review indicates that geopolymer materials exhibit superior moisture resistance and lower permeability compared to ordinary Portland cement (OPC), enabling improved stabilisation of internal substation humidity. Such stabilisation plays a critical role in reducing humidity-induced partial discharge activity, thereby limiting insulation degradation, preventing premature equipment failure, and extending the operational lifespan of high-voltage electrical assets. In addition to performance benefits, the use of geopolymer concrete offers substantial environmental advantages through the valorisation of industrial by-products, reduction of landfill disposal, and mitigation of risks associated with leachate formation and groundwater contamination. These attributes collectively position geopolymer concrete as a viable and sustainable alternative to OPC for enhancing the reliability of electrical substation infrastructure. However, this study is constrained by the lack of adequate dielectric data and coupled humidity-temperature simulations tailored to geopolymer applications in substations. Future study is recommended for a controlled experimental studies and numerical modelling to establish the relationship between geopolymer material properties and partial discharge suppression, as well as to optimisation technique for geopolymer composites for long-term insulation reliability.

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