

Geopolymer Concrete as a Sustainable Construction Material for Urban Heat Island Mitigation: A Comprehensive Review

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ABSTRACT

Urban heat island (UHI) intensification has become a critical issue for rapidly urbanizing cities, where the large-scale application of ordinary Portland cement (OPC) concrete leads to heat storage, high surface temperatures, and high embodied carbon. In this regard, geopolymer concrete (GPC) has emerged as a potential sustainable construction material that can be produced from industrial by-products, such as fly ash, ground granulated blast-furnace slag (GGBS), and silica-rich residues, while demonstrating enhanced resistance to heat and fire. This study critically assesses the mitigation potential of GPC in terms of UHI impact, with the focus on thermal conductivity, specific heat, solar reflectance, albedo, and thermal inertia, as well as on the effect of binder composition, precursor chemistry, curing regime, and surface finish. The available literature data indicates that GPC can be more advantageous compared to conventional OPC concrete in terms of heat reduction and high-temperature stability, which are key factors for cool pavement and climate-adapted building-envelope materials. Nevertheless, the UHI-mitigation potential of GPC is not an inherent property of binder chemistry but rather depends on the material's design and service conditions. A significant body of work has been dedicated to the potential of waste-derived geopolymer systems in reducing UHI effects and carbon emissions, thus supporting a circular construction economy. Further research is needed to develop standardized thermal performance assessment protocols, evaluate field-scale performance, monitor long-term behavior in actual conditions, and optimize GPC for combined mechanical, thermal, and environmental performance. In general, GPC seems to be a promising low-carbon alternative to conventional cementitious binders, but its UHI-mitigation potential can only be fully realized through targeted material design and field-scale evaluation.

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1. Introduction

Global urbanization has rapidly transformed natural land cover into dense aggregates of concrete, asphalt, and other impervious materials. One of the characteristic features of this process is the urban heat island (UHI) effect, i.e., the fact that cities tend to have higher air and surface temperatures than surrounding rural areas (Oke, 1982; Taha, 1997). This is primarily due to the reduction in vegetation and evapotranspiration, anthropogenic heat inputs, constrictive urban geometry that traps longwave radiation, and the low albedo and high thermal mass of conventional paving and building materials (Memon RA et. al., 2008; Vujovic et al., 2021). Ordinary Portland cement (OPC) concrete is a major contributor to this problem, as conventional concrete pavements and envelopes have relatively high thermal conductivity and heat capacity, allowing them to absorb and store significant amounts of solar energy over the diurnal cycle (Levinson & Akbari, 2002; Santamouris, 2013).

Geopolymers are inorganic aluminosilicate binders that can be activated at low temperatures and form a ceramic-like, thermally stable microstructure, offering excellent resistance to high temperatures and fire compared to

hydrated cement systems (Amran et al., 2022; Razak et al., 2022). The thermal conductivity, specific heat, and surface reflectance of geopolymers can be tailored by selecting the precursor, aggregates, and mix-design parameters (Przybek et al., 2025; Zhu, S., & Mai, X., 2019).

This review focuses on geopolymer concrete (GPC) as a material-level strategy for UHI mitigation. We first outline the processes and materials contributing to UHI formation, then examine geopolymer properties relevant to thermal performance: precursor selection, thermal conductivity, specific heat, high-temperature and fire resistance, solar reflectance and albedo, and the influence of curing regime on thermo-mechanical behavior. Subsequently, we discuss current and prospective applications of GPC in pavements and building envelopes and evaluate associated environmental and life-cycle impacts. Finally, we identify key research gaps to enable confident deployment of GPC as a climate-resilient urban material.

2. Urban Heat Island: Mechanisms and Material Drivers

The UHI effect was formally expressed by Oke (1982) who related it to the urban surface energy balance, which is the partitioning of net radiation absorbed by urban surfaces into sensible heat flux, latent heat flux, and heat storage; cities are seen as reducing latent heat flux (due to reduced vegetation and surface permeability) and increasing heat storage (due to the thermal mass of built materials). Taha (1997) also highlighted that the three key factors controlling the magnitude of urban overheating are albedo, evapotranspiration and anthropogenic heat release. Further global assessments have corroborated that UHI intensity is related to climate, city morphology and the material type, and that surfaces with low albedo and high imperviousness are among the most dominant factors (Memon RA et. al., 2008; Santamouris, 2015).

Pavements and roofs in particular have a very large portion of the exposed surface area of the urban environment, typically more than one third of the total surface cover in dense urban cores (Santamouris, 2013; Vujovic et al., 2021). The albedo of conventional dark asphalt pavements typically ranges from 0.05 to 0.15 and is often below 0.10, while the albedo of conventional grey OPC concrete pavements is in the range of approximately 0.35 to 0.40, which decreases with soiling and weathering over time (Levinson & Akbari, 2002; Pomerantz et al., 1997). Conventional paving materials have low reflectivity, high thermal mass, and under peak solar exposure, the paving materials get absorb heat and released in night hours, maintaining high surface temperatures during the night (Mohegh et al., 2017; Middel et al., 2020).

As a result, new research for UHI mitigation has focused on two complementary material-engineering strategies that minimize the solar heat gain by increasing albedo and thermal emittance, and that minimize the rate and quantity of heat conducted into and stored within the material, respectively (Santamouris, 2013; Kyriakodis & Santamouris, 2018). Field-scale demonstration projects have demonstrated that the benefit of the reflective pavement retrofit in terms of surface temperature is several degrees Celsius, while the benefit in terms of near surface air temperature is modest, but measurable, but this latter benefit is not as well established as the surface-temperature benefit (Middel et al., 2020; Ferrari et al., 2020). Geopolymer Concrete is proposed as a cool-envelope and cool-pavement material in this concept of albedo enhancement and thermal-mass reduction.

3. Geopolymer Concrete: Chemistry, Precursors, and Binder Design

Geopolymers are three-dimensional aluminosilicate networks, produced by dissolving an amorphous, silica and alumina-rich precursor in a strong alkali activator solution (usually a mixture of sodium or potassium hydroxide and sodium silicate) and then polycondensing the solution into a rigid, mostly amorphous to semi-crystalline gel (Davidovits, 2008; Duxson & Provis, 2008). Provis (2014) describes the high calcium alkali-activated slag system and the low-calcium "true" geopolymer system, the latter in which the main reaction product is a sodium aluminosilicate hydrate (N-A-S-H) gel and the former in which calcium-rich precursors also form calcium aluminosilicate hydrate (C-A-S-H) or C-(A)-S-H gel phases with hybrid characteristics. This chemical difference directly impacts behavior and strength, which in turn influences durability, and provides much of the mix-design

flexibility for which GPC is attractive for infrastructure, applications (Wang et al., 2019; Provis & van Deventer, 2009).

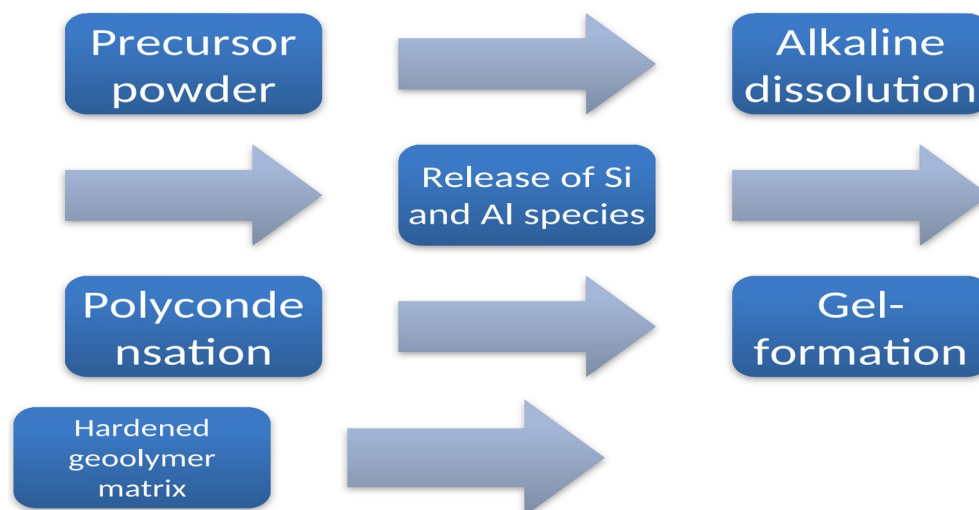


Fig. 1 Chart showing hardened geopolymer matrix formation

Geo-polymerization process is as follows: dissolution of the precursors in an alkaline activator, release of Si- and Al-species, polycondensation, gelation and formation of a hardened geopolymer network as shown in Fig. 1.

Fly ash is the most widely investigated precursor because of its ready availability, spherical particle shape and pozzolanic reactivity (Hardjito et al., 2004; Wallah& Rangan, 2006). low-calcium (Class F) fly ash geopolymers usually need high-temperature curing to gain sufficient early strength, while incorporating GGBS speeds up the reaction rate and makes it possible to acquire satisfactory strength under ambient curing(Deb et al., 2014). Blended fly ash-GGBS and fly ash-GGBS-silica fume is reported to attain compressive strength similar to or better than that of conventional structural grade OPC concrete with better resistance to sulfate and acid attack (Paruthi et al., 2024). The workability and the strength of high-calcium fly ash geopolymers have been shown to be affected by the interaction of alkaline activator content, water content, and curing regime by Chindaprasirt et al., (2007), which has been replicated in many subsequent mix design studies. This further finding was reported by Rashad (2014), who in a review on general influence of admixtures and additives in alkali-activated fly ash systems, also noted that the type and dosage of the activator and the properties of the final products are important factors that need to be taken into account besides precursor chemistry.

In addition to fly ash and GGBS, there are several other materials that are used as precursors for making cement and concrete, including metakaolin, silica fume, rice husk ash, red mud, mine tailings, and various construction and demolition wastes (Almutairi et al., 2021; Nanda & Priya, 2024). The choice of precursor combination, in addition to the $\text{SiO}_2/\text{Al}_2\text{O}_3$, $\text{Na}_2\text{O}/\text{SiO}_2$ and water-to-binder ratios of the mix, will determine the mechanical strength of the hardened geopolymer matrix as well as the pore structure, density and thermal transport properties of the matrix, which are of direct relevance to UHI-mitigation performance and which will be examined in the following sections (Ikotun et al., 2024).

Table 1: Common geopolymer precursors, their chemical character, and expected binder role

Precursor	Main oxide character	Typical calcium level	Main role in geopolymer	Common effect	References
Fly ash (Class F)	Si-rich, Al-rich	Low	Primary precursor	Often needs heat curing for early strength	(Hardjito et al., 2004; Wallah&Rangan, 2006; Davidovits, 2008)
GGBS	Ca-rich, Si-Al bearing	High	Primary or blending precursor	Accelerates setting and ambient strength	(Deb et al., 2014; Provis, 2014; Wang et al., 2019)
Metakaolin	Reactive aluminosilicate	Very low	Primary precursor	High reactivity, good strength development	(Duxson& Provis, 2008; Provis & van Deventer, 2009)
Silica fume	Amorphous silica	Negligible	Secondary silica source	Densifies microstructure, improves strength	(Rashad, 2013; Almutairi et al., 2021)
Rice husk ash	Amorphous silica	Negligible	Auxiliary silica source	Improves Si supply, sustainability benefit	(Nanda & Priya, 2024; Almutairi et al., 2021)
Red mud / mine tailings / CDW	Variable	Variable	Alternative precursor or filler	Supports waste valorization and property tuning	(Almutairi et al., 2021; Nanda & Priya, 2024)

Table 1 carries common geopolymer precursors, their main oxide composition, calcium level, role in the binder system, and typical performance effects, with source references.

4. Thermal Conductivity, Specific Heat, and Thermal Inertia of Geopolymer Concrete

4.1 Thermal conductivity

Thermal conductivity controls how quickly absorbed heat moves through and out of a material. Geopolymer concrete shows a wide conductivity range because its density varies from normal-weight OPC-like values ($\sim 1.0\text{--}1.6\text{ W/(m}\cdot\text{K)}$) down to highly insulating lightweight systems ($<0.2\text{ W/(m}\cdot\text{K)}$) (Przybek et al., 2025). Przybek et al. (2025) found foamed GPA (FP-BGA) reduced thermal conductivity by over 75% and increased thermal resistance by more than 140% versus a conventional aggregate mix. Expanded clay, perlite, and foamed lightweight geopolymer concretes show similar reductions, as entrained air and porous aggregates break solid heat paths (Zhang et al., 2024; Tayeh et al., 2021). Zhang et al. (2024) showed that dry density and pore structure, rather than binder chemistry, mainly control bulk thermal conductivity. However, lower density and conductivity typically reduce mechanical strength, so thermal improvements for insulation must be balanced against structural requirements (Tayeh et al., 2021).

4.2 Specific heat and thermal inertia

Fewer systematic studies address specific and volumetric heat capacity of geopolymer concrete, yet these properties are crucial for UHI-relevant thermal performance because they determine how much heat a material stores per degree (diurnal thermal inertia). Lower volumetric heat capacity heats and cools faster—useful for reducing nocturnal heat loss—and, with suitable daytime reflectance, helps control peak surface temperatures (Santamouris, 2013). Geopolymer concretes often have lower volumetric heat capacities than conventional concrete due to lighter binder and higher air-void content in lightweight systems, which also enhances insulating performance (Przybek et al., 2025; Sofri et al., 2022).

Table 2: Thermal behavior of geopolymer concrete

Material feature	Effect on thermal conductivity	Effect on specific heat / thermal inertia	Practical outcome	References
Higher density, fewer pores	Increases heat transfer	Increases heat storage	More heat is retained and released later	(Przybek et al., 2025; Tayeh et al., 2021)
Lower density, more air voids	Decreases heat transfer	Lowers volumetric heat capacity	Faster cooling and better insulation	(Przybek et al., 2025; Sofri et al., 2022)
Expanded perlite / porous lightweight aggregate	Strongly reduces thermal conductivity	Lowers thermal inertia	Good for insulation and envelope use	(Zhang et al., 2024; Tayeh et al., 2021;)
Foamed geopolymer aggregate	Can reduce thermal conductivity by more than 75%	Reduces heat storage capacity	Improves thermal resistance significantly	(Przybek et al., 2025)
Dense conventional geopolymer concrete	Moderate thermal conductivity	Higher thermal inertia	Better for load-bearing than insulation	(Przybek et al., 2025; Sofri et al., 2022)

Table 2 shows the effect of density, porosity, and lightweight aggregates on thermal conductivity, specific heat, and thermal inertia of geopolymer concrete (Przybek et al., 2025; Tayeh et al., 2021; Zhang et al., 2024; Sofri et al., 2022).

The thermal inertia of an envelope (or pavement) material drives both the phase lag and the amplitude attenuation of the response of surface temperature, particularly to the diurnal solar cycle. We hypothesize, based on the fact that materials with higher thermal inertia – such as dense conventional concrete – would typically accumulate heat during the daytime and release it into the evening, causing heat and consequently prolonged higher near-surface air temperatures during nighttime (commonly thought to be responsible for sustained night time UHI) will store heat at the surface longer and will delay shedding into nighttime than less massive material with less internal heat storage – to not experience as marked attenuation (Moheg et al., 2017; Middel et al., 2020).

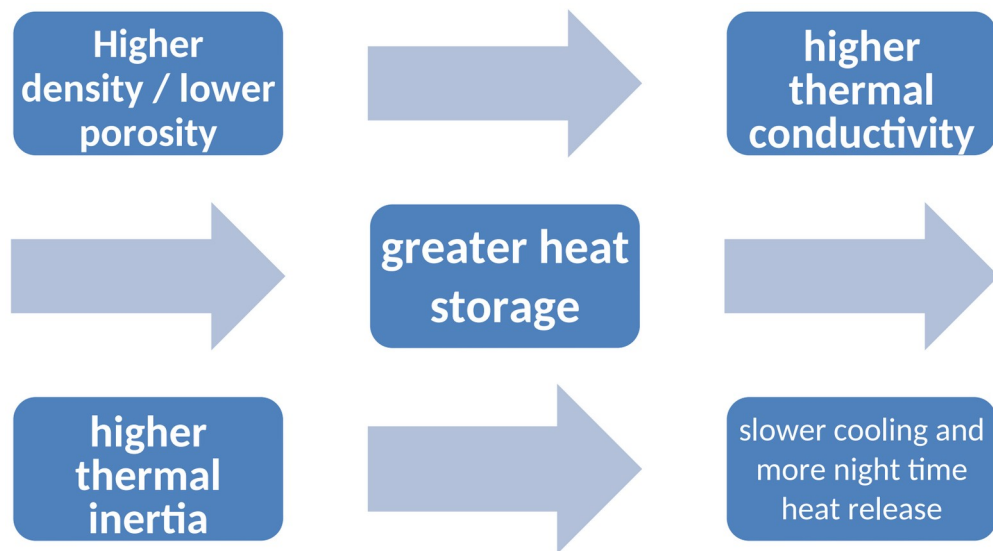


Fig. 2 Schematic showing how increasing porosity and lightweight aggregate content lowers thermal conductivity and thermal inertia in geopolymer concrete, improving insulation performance.

5. High-Temperature Behavior and Fire Resistance

Geopolymer concrete is significantly more stable under high temperatures and direct fire than OPC, giving better fire resistance and long-term durability after repeated heating. In OPC, bound water cannot escape before C–S–H dehydration and portlandite decomposition (≈ 300 – 500 °C), causing pore pressure, microcracking, and explosive spalling (Kong & Sanjayan, 2010; Amran et al., 2022). In a simulated fire test on same-grade OPC and geopolymer

specimens exposed for two hours at 500 and 1200 °C, geopolymer samples lost 7.6% and 7.77% mass while OPC lost 8.75% and 12.5%; geopolymer retained 116% and 67% of strength versus OPC's 73% and 39% at those temperatures. At 1200 °C OPC specimens cracked and spalled, whereas geopolymers showed ~7.77% mass loss, ~67% strength retention, and no cracking or spalling (Razak et al., 2022). SEM evidence suggests the geopolymer matrix consolidates rather than disintegrates, possibly via further geopolymerization and sintering at high temperature. Amran et al. (2022) concluded fire resistance depends on precursor and alkali type and dosage, aggregate makeup, and fillers/fibres, with low-CaO precursors outperforming high-CaO ones due to fewer volatile/expansive products. Developments with bamboo-ash and lightweight geopolymers show excellent strength retention after heating to 800 °C, reinforcing geopolymer advantages over OPC in high-temperature/fire conditions (Przybek et al., 2025).

Table 3: Fire and high-temperature performance of geopolymer vs OPC concrete

Temperature range	OPC concrete behavior	Geopolymer concrete behavior	Typical residual strength trend	Key observations	References
Ambient–200 °C	Minor dehydration; small strength loss	Minimal microstructural change; some systems show slight strength gain	OPC: slight decrease; GP: stable or slight increase	Water loss and early microcracking begin in OPC	(Kong & Sanjayan, 2010; Amran et al., 2022)
200–500 °C	Progressive C–S–H dehydration; portlandite decomposition above ~300–400 °C	Continued geopolymerization and sintering; matrix densification	OPC: moderate decrease; GP: often stable or improved up to ~500 °C	Fly ash-based GP can show higher residual strength than OPC at 500 °C	(Kong & Sanjayan, 2010)
500–800 °C	Severe cracking, spalling risk; significant strength loss	Retains largely intact aluminosilicate framework; reduced spalling	OPC: large decrease; GP: moderate decrease, still substantial	Geopolymer shows less cracking and no/low spalling compared to OPC	(Razak et al., 2022)
800–1200 °C	Extensive degradation, explosive spalling, very low residual strength	Matrix densifies and sinters; retains >50% compressive strength in some systems	OPC: very low; GP: considerably higher than OPC at 1200 °C	GP exhibits lower mass loss and higher structural integrity after fire	(Razak et al., 2022)

Table 3 provides Comparative high-temperature and fire behavior of geopolymer and OPC concrete-including microstructural response, residual strengths and trends, and typical mode of failure. Considering the specifically designed use in UHI applications, this thermal stability matters more for durability from continued cyclical, passive solar heating than direct fire safety: pavement and surface envelope materials that daily experience 50–70+ °C after exposure to solar irradiance have less opportunity to undergo deleterious microstructural damage than a OPC counterpart would and remain thermally and mechanically stable and resilient after many more cycles of this thermal and environmental regime (Wasim et al., 2021).

6. Solar Reflectance, Albedo, and Surface Finish

Solar reflectance (albedo) largely controls diurnal surface temperatures of pavements and roofs by determining how much shortwave radiation is absorbed versus reflected (Levinson & Akbari, 2002; Santamouris, 2013). Field and lab studies show raising pavement albedo from asphalt's ~0.05–0.10 to >0.30 (reflective coatings or light concrete) can lower peak surface temperatures by ~10 °C or more, with smaller cooling of near-surface air (Middel et al., 2020; Kyriakodis & Santamouris, 2018; Mohegh et al., 2017).

Geopolymer concretes can achieve higher surface reflectance than typical grey OPC in multiple ways, including: choice of precursor, using reflective fine aggregates, surface treatments, and reflective coatings (Zhu, S., & Mai, X., 2019). The lower density and porosity of geopolymers' binder impact nearby reflectance and emissivity, thus enabling mix designs to concurrently satisfy thermal and mechanical requirements (Przybek et al., 2025). Additionally, studies on geopolymer pavement solar reflectance and long term albedo stability are limited compared to work on thermal conductivity and fire performance (Vujovic et al., 2021; Levinson & Akbari, 2002). Much UHI

literature using measured albedos for OPC, asphalt, and coatings, extrapolates such findings to geopolymers, but direct validation is still sparse.

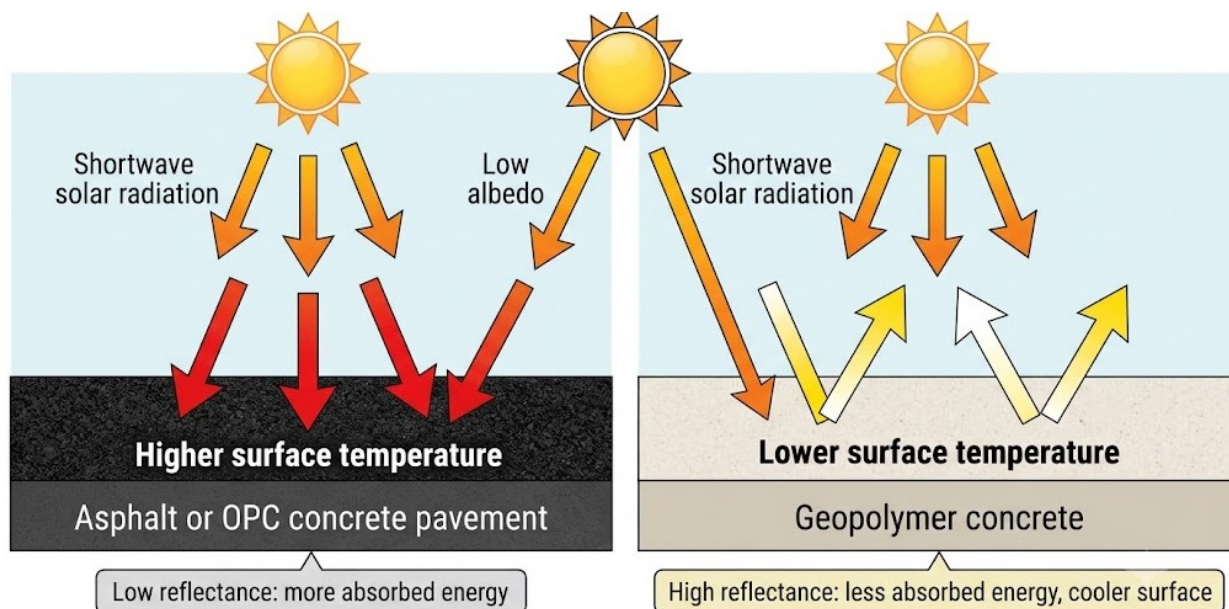


Fig 3: Impact of surface texture and solar reflectance of pavement

Dark low-albedo surfaces that absorb more energy will heat up, while light, reflective geopolymer pavement remains cool (Fig. 3). Still, little research exists on geopolymer pavement solar reflectance and the long term persistence of albedo relative to studies on geopolymer thermal conductivity and fire performance. Many UHI papers rely on measured albedos for OPC, asphalt, and coating materials and draw their own conclusions on the applicability of geopolymers, but validation in this context is inconsistent (Pomerantz et al., 1997; Kyriakodis & Santamouris, 2018).

7. Effect of Curing Strategy on the Thermo-Mechanical Behavior

Optimal curing conditions allow geopolymerization to occur to an extent that optimises density, porosity, and mechanical and thermal properties essential to UHI reduction performance. Metakaolin – based geopolymers have higher solubility under high curing temperature and shorter curing times which lead to higher strength and density up to an optimum point, while excessive time and temperature cause moisture extraction, shrinkage and microcracking and thus lower strength (Rovnaník, 2010). Fly ash and fly ash-GGBS geopolymers achieve curing strength at 60 – 90 °C for a few hours to a day while 90–120°C affects strength adversely. Curing temperature and NaOH molarity modulate strength development and durability: either excessive molarity, long cure time, or very high temperature will be harmful (Gorhan & Kurklu, 2014). For UHI, curing time/temp drive the final porosity/density, which controls the heat transfer property of thermal conductivity and volumetric heat capacity, while specific heat capacity is nearly density independent. Ambient curing and GGBS accelerated systems are being considered for high temperature oven curing not being practical for in situ pavement and building envelopes to attain sufficient strength without external heating (Deb et al., 2014; Paruthi et al., 2024). It is important to consider the compromise between curing practicality and extent of geopolymerization when relating laboratory thermal data and mix optimisation to field scale.

Table 4: Influence of curing regime on geopolymer concrete performance

Curing regime	Main microstructural effect	Strength outcome	Thermal-property implication	Practical relevance	References
Low-temperature / short curing	Incomplete geo-polymerization	Lower early strength	More porous, less predictable conductivity	Easy to apply, but may underperform	(Rovnaník, 2010; Görhan&Kürklü, 2014)
Moderate oven curing	Faster dissolution and polycondensation	Highest strength in many systems	Denser matrix, more stable thermal transport	Good for lab-optimized products	(Rovnaník, 2010; Görhan&Kürklü, 2014)
Excessive curing temperature	Moisture loss, shrinkage cracking, pore disruption	Strength decline	Unstable porosity and thermal response	Can damage performance	(Rovnaník, 2010; Görhan&Kürklü, 2014)
Ambient curing with slag/GGBS	Accelerated hardening without external heat	Moderate to high strength if mix is optimized	Practical thermal performance for field use	Best for real infrastructure use	(Deb et al., 2014; Paruthi et al., 2024)

Table 4 show the effects of different curing regimes on the microstructure, strength, the heat of the geopolymer concrete, as well as, its application in practice and the explanatory literature is specified (parentheses are literature sources in the last column).

8. Applications in Pavement and Building-Envelope Systems

8.1 Pavement applications

Pavement quality geopolymer concrete attracts interest as a pavement material with higher early strength, lower permeability, and enhanced chemical/thermal loading performance versus OPC pavements (Ikotun et al., 2024; Nanda & Priya, 2024). Published values for compressive, flexural, and split tensile strengths equal or higher than standard pavement concrete cement concrete demonstrate that they can withstand repeated loads of traffic and day/night, and annual temperature variations (Ikotun et al., 2024). Beyond load-bearing layers, fly ash- and GGBS-based geopolymers, frequently in combination with ground glass waste powder, have been employed in unbound road base and sub-base stabilization, reducing bulk use of raw materials and lowering embodied emissions while maintaining support strength (Xiao et al., 2020; Sofri et al., 2022; Migunthanna et al., 2022). To reduce UHI, pavement grade geopolymers can be engineered to balance strength, thermal properties, and light/reflective finishing to increase their reflective surface albedo (Zhu, S., & Mai, X. , 2019); however, the high focus on strength, durability, and costs and inconsistent reporting of thermal/UHI metrics signals the need for more field-centric applications studies.

8.2 Building-envelope applications

Porous or expanded aggregate-based lightweight geopolymer concretes can reach low enough thermal conductivities for use as insulation components in envelope wall, roof, and façade construction systems, in both hot-arid and hot-humid climates (Przybek et al., 2025; Zhang et al., 2024; Tayeh et al., 2021). Considering the large urban coverage of envelopes and roofs and their relationship to UHI and cooling energy demand, cool-roof and insulative-envelope design strategies developed for conventional materials can, in principle, be translated to geopolymers if similar level of reflectance, emittance and durability can be obtained (Kyriakodis & Santamouris, 2018). Its demonstrated fire resistant behavior makes geopolymer a viable solution for a not only structural but also skin exterior component where fire safety is integral (Amran et al., 2022; Razak et al., 2022).

9. Environmental and Life-Cycle Considerations

9.1 Carbon savings of geopolymers

The principal appeal of geopolymers to date has been their potential for large reductions in embodied carbon relative to OPC, achieved in part through avoiding the carbon- and energy-intensive calcination of limestone. Turner and Collins (2013) initially estimated CO₂-equivalent savings at 54–71% for geopolymer concrete, but noted these

results are sensitive to the embodied impacts of the alkali activator. Subsequent meta-analyses and LCAs show a large net savings in carbon overall, but dependent on source of precursor, transportation, amount of activator, and boundaries of assessment (Shobeiri et al., 2021). These system-wide results are supported by context-specific case studies. Kiruthika et al. (2024) demonstrated the use of geopolymer concrete to replace OPC in high-rise residential construction reduces embodied energy and CO₂ while maintaining structural performance and reducing costs, however slightly, thus Mechanical and Environmental benefits need not be mutually exclusive. In addition to embodied carbon, replacing fly ash, GGBS and other industrial by-products as precursors also contributes to circular-economy via the recycling of landfill wastes and the decreased use of virgin raw materials as demonstrated by the ongoing assessment by Almutairi et al (2021); Nanda & Priya, 2024). Nonetheless, the environmental argument for geopolymer as a UHI-reducing material is relevant to, but should not be conflated with its embodied-carbon justification. A material can have minimal embodied-carbon but insufficient operational-thermal efficacy, or the other way round. The optimal strategy is a co-optimisation of the mix design (low embodied-carbon, high operational-thermal efficacy), which has yet to be studied in detail (Wasim et al., 2021; Ikotun et al., 2024).

10. Critical Research Gaps and Future Directions

Despite progress in understanding GPC's mechanical properties, durability, fire performance and embodied-carbon advantages, three knowledge gaps hinder its use as a UHI-mitigation strategy. First, no standardized GPC-specific thermal test methods exist for pavement and envelope systems; published thermal conductivity and specific heat tests all come from small-scale steady-state laboratory studies that do not fully reflect transient, diurnal field loading (Przybek et al., 2025). Second, we lack adequate measurements of the solar reflectance, albedo and thermal emittance of GPC compared to OPC, cool pavements and reflective coatings for critical UHI-performance benchmark comparisons (Kyriakodis & Santamouris, 2018; Middel et al., 2020). Third, and most importantly, comprehensive field demonstration on a large scale, and multi-year monitoring of UHI mitigating geopolymer pavements and envelopes under real weather and traffic conditions, is essentially absent in literature. Standard cool-pavement studies already encompass a large number of field cases, but geopolymer studies continue to be largely laboratory-driven. Fourth, durability is under-examined under conditions of combined urban exposure—cyclic thermal loading, ultraviolet (UV) radiation, atmospheric weathering and (where applicable) freeze–thaw exposure. Existing GPC durability investigations are largely concerned with chemical (sulfate, acid and chloride) attack, whilst ignoring the temporal effects of environmental weathering on reflectance and thermal properties. Lastly, the optimization of GPC mix design should be multidimensional, where the impact of every mix parameter on the composite mechanical and thermal performance, embodied carbon, and costs is weighed against one another instead of multi-objective optimization of various parameters (Shobeiri et al., 2021; Ikotun et al., 2024). Filling the research gaps calls for laboratory studies, pilot-scale demonstrations, and long-term field monitoring.

11. Conclusion

Geopolymer concrete exhibits several properties that are of interest from the perspective of UHI mitigation: specific heat capacity and thermal conductivity can be tuned via control of precursors and aggregates. It exhibits improved high-temperature and fire performance relative to traditional concrete and boasts enhanced reflectance via control over mix-design and finishing. Behind these properties lies a binder chemistry which produces a significantly lower embodied carbon footprint compared to conventional concrete; therefore, it is one of few candidates in urban construction capable of delivering simultaneously with respect to the thermal operating performance and the embodied-carbon footprint. The literature demonstrates however, that the UHI mitigation performance is not an inherent property of geopolymer concrete – a characteristic inherent to any class of materials – but relies instead upon the design choices that made for, and include precursor choice, curing regimen, porosity/density management and surfacing.

In order to leverage the full potential of geopolymer for UHI mitigation, there is a need for the integration of testing standards for the assessment of concrete thermal and reflectance properties with outdoor studies reflecting realistic

urban exposure conditions including, durability assessment and combined optimisation frameworks for mixed behaviour modelling. In this way, the contribution to low-carbon, resilient pavement, housing and workplace surfaces will result in significant benefits for increasingly urbanised climates.

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