Development and Assessment of Geopolymer Concretes for Use in Road Pavements: A review

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Abstract: Concrete pavement has a major carbon footprint due to using ordinary Portland cement (OPC). In recent years, life cycle analysis and trial pavements have demonstrated that replacing OPC concrete with geopolymer concrete (GPC) for pavement installations can substantially lower the carbon footprint. Additionally, it allows for reusing industrial by-products, conserving natural resources, and reducing landfill costs. However, GPC's utilisation in large-scale road pavement applications within an Australian context is yet to be explored. Provided that the GPC meets the required prescriptive specifications of road agency requirements, it can potentially replace OPC concrete. This paper will review the suitability of using GPC in concrete pavement bases, focusing on fly ash (FA) and ground granulated blast furnace slag (GGBFS) alkali-activated systems. The behaviours of the GPC will be evaluated to provide critical insight into the suitability for utilising GPC in road pavement specifications such as Transport for New South Wales (TfNSW) QA R83 specification for concrete pavement base.

The review indicates that raw materials, mix formulation factors and curing temperature can significantly affect the properties of GPC; it exhibits different short and long-term strength, volume stability and durability properties compared to OPC concrete. Volume stability properties, such as drying shrinkage and durability properties, including carbonation-induced corrosion, are acknowledged to be crucial for road pavement applications. However, there are limited and scattered research studies on the long-term volume stability and durability behaviours of GPC, especially in pavements, and in some cases, the results are contradictory, necessitating further collation of published data.

Keywords: Geopolymer concrete, engineering properties, concrete pavement, large-scale production.

1. INTRODUCTION

OPC (ordinary Portland cement) concrete has long been the dominant choice in construction due to its reliability, but its high embodied energy significantly contributes to carbon emissions. GPC (geopolymer concrete), an alternative binder activated by alkalis, offers a potential reduction in CO_2 footprint. The strength of OPC concrete develops through the development of calcium-silicate-hydrate (C-S-H) gel, while GPC gains its strength from the polymerisation of reactive aluminosilicates in an alkaline environment. This process results in a robust polyaluminosilicate network with interconnected Si-O-Al-O-Si bonds [1, 2].

Despite the significant emissions from activators, GPC still achieves a considerably lower carbon footprint, reducing emissions by approximately 40–80% compared to traditional Portland cement concrete [3]. Additionally, GPC utilises industrial by-products such as FA (fly ash) and slag, which not only reduces greenhouse gas emissions but also conserves natural resources, contributing to sustainable construction practices [4]. By incorporating recycled industrial waste, GPC supports circular economy principles, reduces environmental pollution, and enhances long-term sustainability [5]. Economically, GPC's superior durability lowers maintenance needs and lifecycle costs, offering substantial savings for infrastructure projects [6]. With its environmental, and durability advantages, GPC positions itself as a key material for sustainable development in the construction industry. A variety of precursors, including FA, GGBFS (ground granulated iron blast furnace slag), metakaolin, rice husk ash, mine tailings, and glass waste, can be used to produce GPC, with material selection influenced by application needs, cost, and local availability [7].

The adoption of GPC as an alternative to OPC concrete is driven by its potential to reduce carbon emissions. Optimising GPC involves balancing multiple objectives, including strength, cost, and CO_2 emissions. On an average basis, GPC production cost is nearly twice of similar strength OPC-based concrete which presents a challenge in widespread adoption of it. The primarily cause of this cost is due to the high expense of alkali activators, as well as additional factors like curing energy requirements [8].

This paper reviews the potential of FA-GGBFS-based GPC for road pavements, evaluating its engineering performance per TfNSW specifications and highlighting knowledge gaps and recommendations for sustainable application.

2. KEY PROPERTIES OF GPC FOR PAVEMENTS

2.1 Raw Materials and Mix Design

GPC is composed of various raw materials, with aluminosilicate precursors and alkali activators being the key components. Table 1 summarises these materials and their influence on GPC properties. Unlike OPC concrete, GPC does not require OPC but instead relies on highly reactive aluminosilicate sources combined with an alkaline activator to form the binding matrix [9, 10]. The properties of GPC are influenced by several factors, including the type and fineness of precursors, activator type and concentration, water-to-binder ratio (W/B), curing conditions, and the addition of admixtures [11, 12].

Alkali activators play a crucial role in the geopolymerisation process, enabling the dissolution and polymerisation of precursors. In recent years, significant efforts have been made to develop more environmentally friendly and cost-effective activators with significantly lower emissions than before. Refinements in activator formulations have contributed to this improvement, making the adoption of this technology more viable. These activators can be categorised into liquid and powder forms. Liquid activators, typically a combination of sodium hydroxide and sodium silicate solution, while powder activators are commonly anhydrous sodium meta-silicate and sodium meta-silicate pentahydrate [11, 13-15]. Aggregates in GPC can be natural or recycled, though the latter may lead to lower strength, higher shrinkage, and increased chloride penetration [16]. Water in GPC primarily facilitates geopolymerisation rather than hydration, with its content significantly affecting workability, strength, and pH levels [11].

Table 1. An overview of key materials and their influence on GPC properties

Material	Type	Properties description	Reference
FA	Precursor	Forms Sodium-Aluminum-Silicate-Hydrate gel in alkali-activated systems, improving durability and mechanical properties, especially under elevated temperatures.	[17, 18]
GGBFS	Precursor	Produces Calcium-Aluminum-Silicate-Hydrate gel, enhancing strength and compactness but increasing shrinkage; accelerates GPC curing at ambient temperature.	[18-20]
Sodium hydroxide	Liquid activator	Influences geopolymerisation rate; higher concentrations enhance reaction kinetics but reduce workability and increase shrinkage.	[21]
Sodium silicate	Liquid activator	Sodium silicate pellets dissolve in water, forming an alkaline solution. This solution plays a significant role in gel formation, improving mechanical properties and compactness; optimal modulus enhances strength.	[22]
Anhydrous sodium metasilicate	Solid activator	Provides strength comparable to liquid sodium silicate at 7 days; requires longer mixing time for dissolution, improving workability. Shows an exothermic reaction, causing a temperature rise during mixing.	[13]
Sodium metasilicate pentahydrate	Solid activator	Releases crystalline water during mixing, requiring water adjustment; extended mixing time needed for proper dissolution. Shows an endothermic reaction, absorbing heat during mixing. Demonstrates lower efflorescence compared to a liquid-activated mix.	[13, 23]

2.2 Mechanical Performance of GPC

Geopolymer strength is influenced by factors such as raw material mix, activator concentration, and curing conditions. Curing plays a significant role in compressive strength development, with heat curing accelerating geopolymerisation and enabling quicker strength gain [24]. GPC has shown promising mechanical properties when compared to OPC concrete. Compressive and flexural strengths are among the most critical indicators of a material’s suitability for pavement applications. Several studies have shown that GPC, particularly when produced with FA and GGBFS systems, can achieve comparable compressive strength to OPC concrete after curing [25, 26].

GPC outperforms OPC concrete in multiple aspects. Its flexural strength is 1.4 times higher, and its splitting indirect tensile strength is 8%–12% higher than OPC concrete, regardless of whether it's cured at ambient or elevated temperatures. Blending GGBFS with FA in GPC further enhances its performance, boosting the flexural and splitting indirect tensile strengths, with the latter strength seeing up to 20% increase. The compressive strength of GPC can reach up to 80 MPa [27-29]. These properties allow GPC pavements to resist cracking and deformation under heavy vehicle loads and high traffic volumes.

3. VOLUME STABILITY AND DURABILITY

3.1 Shrinkage of GPC

Shrinkage in alkali-activated binders, including GGBFS and FA, occurs mostly in three stages: chemical, autogenous, and drying shrinkage. Chemical and autogenous shrinkage take place during the early polymerisation stage, while drying shrinkage dominates as the material cures and loses moisture. The finer pore structure in alkali-activated slag leads to higher capillary stress, while the coarser structure of FA-based binders results in slower shrinkage. Several factors influence shrinkage, such as binder proportions, W/B ratios, and curing conditions. High water content increases shrinkage by promoting porosity. Curing methods also play a role, with water and heat curing showing promise in mitigating shrinkage by stabilising the gel structure and reducing porosity. However, curing at temperatures above 100 °C can negatively affect the geopolymer structure, leading to significant shrinkage [30, 31].

GPC specimens exhibit higher early-age shrinkage, which has been attributed to autogenous and chemical shrinkages, particularly in mixes with high slag content [32]. The increased moisture loss in GPC further exacerbates shrinkage and leads to a less homogeneous microstructure, contributing to the formation of microcracks. Although restrained shrinkage in GPC has been found to be 38–57% lower than that of OPC concrete, factors like higher tensile creep and specific creep help mitigate shrinkage under restrained conditions [33]. Additionally, creep tests indicate lower strain presence in FA-dominant GPC, with slag content being a crucial factor influencing creep potential [33].

3.2 Chloride penetration resistance of GPC

The chloride diffusion coefficient is crucial for assessing GPC's resistance to chloride ingress. A study on GPCs with varying proportions of FA and GGBFS, was conducted over 120 days. The results indicated that increasing the W/B ratio from 0.32 to 0.38 led to a rise in the diffusion coefficient. However, a higher GGBFS content (40% to 100%) notably reduced the diffusion coefficient due to improved matrix densification. Microscopic analysis revealed that mixes with 100% GGBFS exhibited fewer pores and a more compact gel phase. Furthermore, higher alkali activator dosages resulted in reduced chloride diffusion. Figure 1 illustrates the inverse relationship between GGBFS content and chloride penetration depth [34].

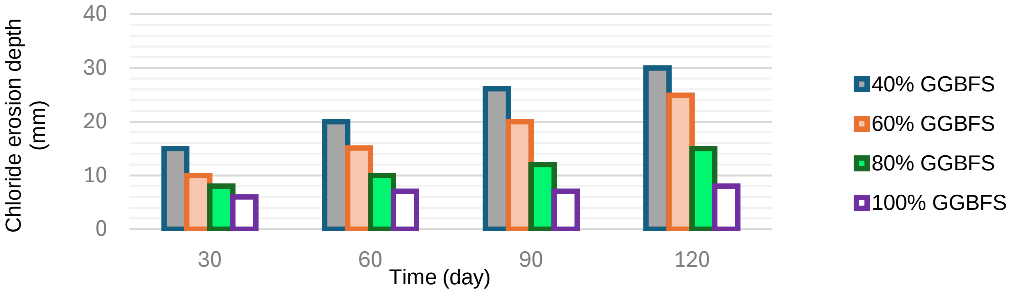

Figure 1. Impact of GGBFS content on chloride penetration in GPC [34]

3.3 Carbonation resistance of GPC

Carbonation in OPC mortar and concrete is a well-established process in which atmospheric CO_2 penetrates the concrete, dissolves in pore water, and forms carbonic acid. This acid reacts with calcium-containing phases, initially targeting calcium hydroxide (Ca $(OH)_2$) before progressively decalcifying calcium silicate hydrates (C–S–H) and calcium aluminosilicate hydrates (C–A–S–H), leading to the formation of calcium carbonate. Calcium hydroxide plays a vital role in maintaining pH stability by releasing hydroxide ions; however, once depleted, it can no longer provide this buffering effect. In alkali-activated binders, carbonation primarily results in the formation of carbonates due to interactions with alkaline pore solutions and calcium-alumino-silicate-hydrate C–A–S–H gels. While GPC generally exhibits greater susceptibility to carbonation than OPC-based systems, optimising the mix design can significantly enhance its carbonation resistance, making it more comparable to conventional cement concretes [35]. The results of a study carried out by Zhao et al. indicate that increasing slag content enhances carbonation resistance [36].

Slag improves the structure and adds calcium and alkaline substances to increase resistance. Carbonation resistance is generally lower in high-temperature cured samples compared to standard cured ones, likely due to the development of thermal shrinkage cracks during early high-temperature curing. The carbonation resistance of standard cured samples improves significantly with curing age, while high-temperature cured samples show no significant change after 28 days, as their polymerisation reactions are completed earlier [36]. Feng et al. [37] conducted a study revealing that carbonation has a significant impact on the strength of FA-slag-based GPC. An increase in FA content accelerates carbonation, resulting in greater strength loss, as illustrated in Figure 2.

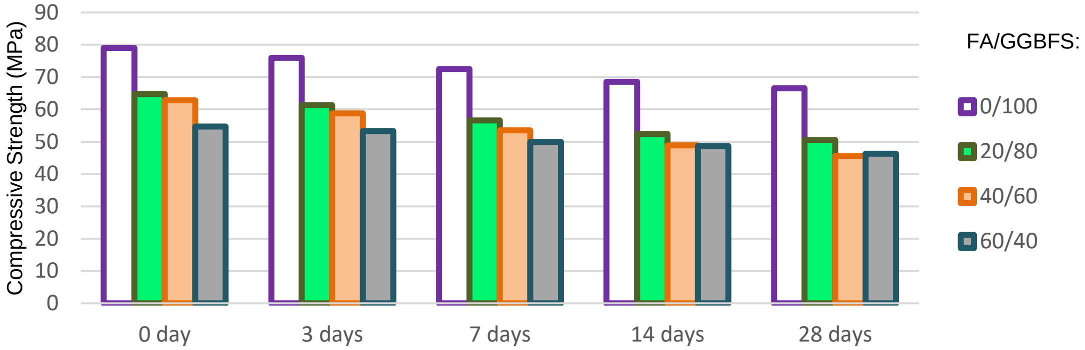

Figure 2.Effect of FA/GGBS ratio on GPC compressive strength under accelerated carbonation exposure [37]

3.5 Alkali silica reaction (ASR) in GPC

ASR in alkali-activated GPC occurs due to the high alkalinity of the activator solution, but its impact is less severe than in OPC concrete. This is because GPC has a more uniform pore structure that remains stable over time, whereas OPC concrete develops increasing pore size, leading to greater ASR-induced expansion and damage [38]. However, coarse and fine aggregates in GPC must be examined for unstable silica and tested for alkali-aggregate reactivity, with reactive aggregates it is recommended to undergo further testing before use in mix designs [39].

4. APPLICATION OF GEOPOLYMER CONCRETE IN AUSTRALIAN PAVEMENT CONSTRUCTION

GPC has seen increasing adoption in Australian infrastructure construction due to its favorable engineering properties and low carbon emissions. Figure 3 illustrates various applications of GPC across different construction fields, showcasing its versatility as a sustainable alternative to conventional concrete. Several notable projects across Australia have demonstrated its feasibility in various construction applications, particularly in pavements.

Figure 3. Examples of GPC applications in various construction fields

4.1 Brisbane West Wellcamp, Airport pavement

The 2014 Brisbane West Wellcamp Airport project saw the world's largest use of GPC, with 40,000 m³ placed for 435 mm thick pavements in turning nodes, aprons, and taxiways. The GPC mix, with a 415 kg/m³ GGBFS-FA binder and a 0.41 W/B ratio, exceeded the required 4.8 MPa flexural strength, achieving 5.8 MPa at 28 days. A 120 m³/hr twin batch plant ensured continuous supply, while an alkaline anti-evaporation spray and geotextile cover managed curing. Challenges included adapting slip form paving, optimising jointing, and the lack of standards. Despite this, the project reduced CO_2 emissions by 8,640 tonnes, proving geopolymer concrete's potential for sustainable infrastructure in Australia [40].

4.2 Wyndham Street, City of Sydney, pavement

The Wyndham Street GPC pavement project is a good example in showing what GPC can do for urban road construction. But it wasn't without its hurdles. One major challenge was the lack of established standards, which made obtaining regulatory approval challenging. The material's higher viscosity made it difficult for the crew to handle, compact, and finish, and the on-site batching was more complicated due to the careful mixing of activators with dry ingredients. There was also heavy rainfall that caused delays in the works for site preparation. Additionally, the tight deadlines for reopening traffic meant the GPC had to hit 20 MPa strength within 36 hours. Plus, there was still some uncertainty about its long-term performance, so ongoing monitoring for durability and cracking under traffic loads was needed. Despite all this, the project proved that GPC can hold its performance against OPC concrete in terms of strength and durability over 1.5 years, all while slashing CO_2 emissions. This project trial highlighted the need for better admixtures to improve workability and the importance of national standards to help push GPC adoption into the wider industry [41].

4.3 Pinkenba project in Queensland, slab

The Pinkenba project in Queensland marked a significant milestone in the application of GPC for large-scale infrastructure. The project involved the largest continuous slab pour in Australia, where Wagner's used FA-GGBFS-based GPC. However, the project encountered several challenges, such as ensuring consistent mix design over such a large-scale pour, as maintaining the material's fluidity and preventing premature setting required precise control. Environmental conditions, including high temperatures, further complicated the curing process. Additionally, regulatory approval was challenging, but GPC proved its comparable strength and durability to OPC concrete despite these obstacles [42].

5. SUITABILITY FOR ROAD PAVEMENTS AND COMPLIANCE WITH TFNSW R83

GPC has advanced significantly in construction, demonstrating its suitability for various applications, from precast elements to in-situ uses. Pavement design in New South Wales (NSW) follows guidelines ensuring a 40-year service life [43]. GPC is well-suited for rigid pavements due to its favorable mechanical properties and resistance to environmental stresses. However, careful design considerations, including proper mix design and curing, joint placement, and cover depth are necessary for optimal performance.

For road pavement applications under TfNSW specifications, a well-designed GPC mix must meet specific fresh and hardened properties criteria, as outlined in TfNSW QA R83 [44], and the test procedures in technical specification for design of geopolymer and alkali-activated binder concrete structures (SA TS 199:2023) [39]. Table 2 summarises the key properties and corresponding specification limits, providing a potential framework for GPC adoption in road pavement applications in NSW.

Table 2. Framework for GPC road Pavement based on R83, SA TS 199, and industry requirements

Category	Test	Range		Standard Reference
Fresh Properties	Slump: a) fixed-form paving b) slip-form paving	a) 50 – 70 mm b) 15 – 50 mm		R83 clause 3.6 [44]
	mass per unit volume	Typically, 2400 - 2440 kg/m3 for R83 base concrete.		R83 Clause 5.2.1.1 [44]
	Slump retention	up to 2 hours		based on industry requirement
	Setting time	a) 90 minutes (temperature < 30 °C) b) 60 minutes (temperature > 30 °C)		based on industry requirement
Strength Properties	Compressive strength	40.0 MPa at 28 days, 7-day strength ≥ 50% characteristic		R83 [44]
	Flexural strength	in the trial mix: min 4.8 MPa and not exceed 6.5 MPa at 28 days		R83 Table 7 [44]
Volume Stability Properties	Drying shrinkage	21 days: 580 με, 56 days: 680 με		R83 Table 8 [44]
Durability Properties	Acid-soluble chloride content	Less than 0.4 kg/m^3 for B2 and more severe exposure, or subject to corrosion initiation assessment.		SA TS 199:2023 [39]
	Accelerated testing for carbonation	Exposure Environment and Classification	Maximum carbonation coefficient (mm/yr0.5)	SA TS 199:2023 [39]
		B1 (Industrial, repeated wetting and drying)	6	
		A2 (Inland, non-industrial, temperate climate)	4	
		B1 (Inland, non-industrial, tropical climate)	6	
		B1 (Inland, industrial, any climatic zone)	6	
		B1 (Near coastal, 1-50 km from coastline)	6	
		B2 (Coastal, within 1 km of shoreline)	7	

6. CONCLUSIONS

GPC is a sustainable alternative to OPC for road pavements in Australia, offering lower carbon emissions and comparable or superior performance. However, its widespread adoption faces several challenges, including:

- Lack of standardised mix design methodologies. Current approaches rely heavily on empirical adjustments rather than predictive models, leading to inconsistencies in performance. Unlike OPC concrete, GPC requires evaluation based on specifications tailored to its unique chemistry, rather than relying on existing standards designed for conventional concrete. Establishing a universal mix design framework that accounts for precursor variability, activator chemistry, and curing conditions will be crucial to ensuring reliability in large-scale applications.
- Economic feasibility presents another significant challenge. The high cost of alkali activators remains a major barrier, necessitating research into alternative, cost-effective activation systems. Additionally, leveraging locally available precursor materials can reduce production and transportation costs, making GPC a more competitive alternative to OPC concrete.

To drive real-world adoption, collaboration between academia, industry, and policymakers is essential. While regulatory frameworks such as TfNSW R83 provide a starting point, further refinements are required to integrate GPC seamlessly into mainstream pavement standards. Government-supported pilot projects, incentives, and carbon pricing mechanisms could play a key role in accelerating its market penetration.

7. PROSPECTIVE DIRECTIONS FOR RESEARCH AND DEVELOPMENT

Future research on GPC for pavement construction in Australia should focus on durability, mix optimisation, and cost efficiency. Large-scale field trials are needed to evaluate performance under traffic loads and varied environmental conditions, while refining mix designs and predictive models for strength and durability.

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