Engineering Geopolymers for Sustainable Construction: A Critical Review from Synthesis and Performance to Life-Cycle Impact

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Abstract: Background: Low-calcium geopolymers, alkali-activated aluminosilicate binders cured below 100 °C, are widely studied as substitutes for Portland cement, a major source of anthropogenic CO_2. The evidence on their performance, durability, environmental benefit and cost is scattered and often quoted without the system it came from. Objective: To follow geopolymers from synthesis to life-cycle impact and to separate robust findings from system-specific ones. Methods: Narrative critical review based on keyword searches and citation tracing. The graphics replot published values, several from the authors' own studies. No new experiments were performed. Findings: Geopolymers harden by dissolution and polycondensation into an amorphous alkali aluminosilicate network, not the calcium–silicate–hydrate gel of Portland cement. Sulfate, acid and fire resistance is generally good (in one replotted study, concrete kept 72% of its strength after 800 °C, against 33% for Portland concrete), but carbonation, efflorescence, shrinkage and workability depend strongly on precursor and activator dose, and RILEM TC 247-DTA round-robin tests show that Portland-cement test methods need validation for alkali-activated concretes. In two life-cycle assessments of 80 MPa concretes, a peer-reviewed slag-based geopolymer reached 23% of the Portland global warming potential but had higher ozone depletion, and a non-peer-reviewed sludge-based preprint reached 27%. A meta-analysis reports average greenhouse-gas savings of 12%, 30% and 50% for low-, normal- and high-strength concrete, at about twice the cost. Conclusions: Geopolymer concrete is a promising but conditional low-carbon binder. Its benefit depends on the activator, the system boundary and the strength grade, and cost, mixed results in other impact categories and missing performance-based standards limit routine use.

Keywords: Geopolymers; Alkali-activated materials; Portland cement replacement; Low-carbon construction; Durability; Carbonation; Life-cycle assessment; Sodium silicate activator.

1. INTRODUCTION

1.1. Cement, Concrete and the Carbon Problem

No other man-made material is used on the scale of concrete, and the binder that holds it together, ordinary Portland cement (OPC), carries a large share of the construction sector's environmental burden [1,2]. A binder that is expected to support a more sustainable built environment must be inexpensive to produce, strong and durable enough for its service life, compatible with its physical and chemical surroundings, and responsible for limited pollution along the way. OPC has met the first three requirements for well over a century. It is the last that now puts its dominance in question.

Cement manufacture releases CO_2 at three points (Fig. **1**). Decarbonation of limestone in the kiln liberates process CO_2 whatever fuel is used, the combustion of fuel needed to hold the kiln near 1450 °C adds more, and a smaller share arises from electricity used for grinding and handling [3,4]. The shares quoted in the literature differ because they use different system boundaries and denominators. Calcination alone was estimated to release 1.50 ± 0.12 Gt CO_2 in 2018, about 4% of fossil-fuel CO_2 emissions [5]. Add kiln fuel and electricity and the whole cement sector is covered, for which a share of roughly 7% of global anthropogenic CO_2 is often repeated [6]. The 8.6% figure is a separate estimate, based on 2012 data, of the direct emissions of concrete manufacturing as a share of all anthropogenic CO_2; its authors note that it would be higher still if supply-chain emissions were counted [2]. The three numbers describe different quantities, so they are not competing estimates of the same one.

The cement industry's response has followed four main lines: improving kiln efficiency, replacing part of the clinker with supplementary cementitious materials (SCMs), developing alternative clinkers, and capturing process CO_2 [4,7–9]. Clinker substitution is the most immediately deployable of these, but the long-term supply of the best-known SCMs, above all coal fly ash, is uncertain, and attention has therefore shifted to new SCM sources [10,11]. A more radical strategy is to dispense with Portland clinker altogether. Alkali-

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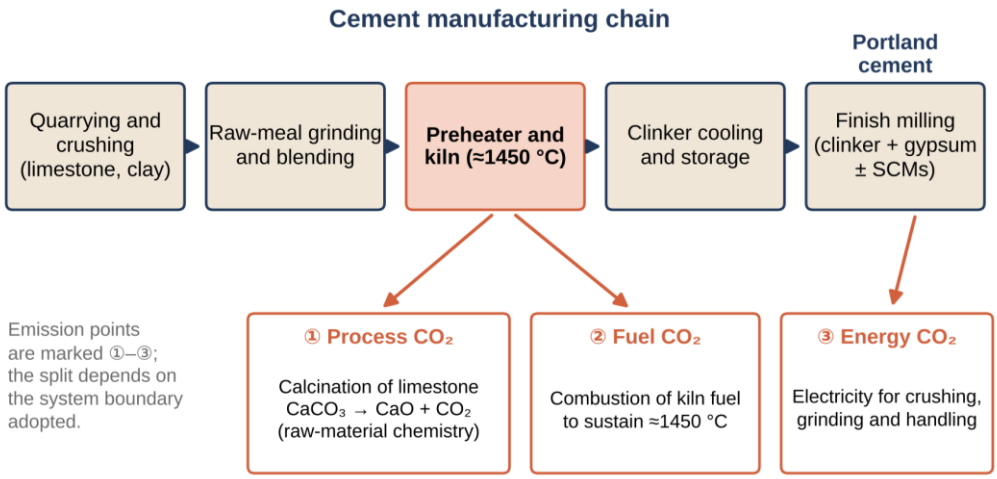


Figure 1: Simplified process chain of Portland cement manufacture and the three principal sources of CO_2: (1) calcination of limestone in the raw meal (process emissions), (2) combustion of kiln fuel and (3) energy use for grinding and handling. Original schematic prepared by the authors from the process description in the cited literature [3,5,7].

activated materials (AAMs), among them geopolymers, have been reviewed many times as candidates for that role [12–14], and the present article takes the geopolymer branch of this family as its subject.

1.2. What the Geopolymer Literature has Established

The literature is large enough that it is easiest to read by theme. The first theme is chemistry and structure. Davidovits introduced the term “geopolymer” for inorganic aluminosilicate polymers formed at low temperature [15,16]. Later work demonstrated the alkaline activation of fly ash [17], described geopolymerization as a dissolution–polycondensation sequence [18,19], and clarified how geopolymers relate to the wider family of AAMs [20–22]. The nanostructure and the influence of the alkali cation have been probed by NMR, scattering and electron microscopy [23–25], and the way aluminosilicate and calcium-silicate gels interact has been mapped in blended systems [26,27]. More recent reviews have returned to the underlying chemistry, including precursor dissolution and its monitoring in real time [28–31].

The second theme is engineering performance. Fly ash-based geopolymer concrete was demonstrated as a structural material by Hardjito *et al.* [32], and subsequent reviews have compiled mechanical properties, mix-design variables and clean-production aspects [33–37]. Work on early-age behavior and on the role of calcium in ambient-cured fly ash systems [38], and on one-part (“just add water”) formulations [39], addresses practical handling problems that limit field use of conventional two-part mixes. Recycled aggregates have been introduced as a second route to lower embodied impact [40]. The authors’ group has contributed experimental work on metakaolin-based geopolymer concrete with zeolite and nano-silica [41] and on kaolinite-based geopolymer concrete in which slag, fly ash and zeolite replaced part of the kaolinite [42].

The third theme is durability and dimensional stability. Reviews of AAM durability [43,44], carbonation [45–47] and chloride exposure [48] document benefits against sulfate, acid and elevated temperature but also reveal a sharp dependence on precursor and activator, while the RILEM TC 247-DTA round-robin program has begun to test whether durability methods developed for Portland cement concrete transfer to AAMs [49,50]. Efflorescence, shrinkage and rheology have each acquired their own review literature [51–54].

The fourth theme is environmental and economic performance. Life-cycle assessment (LCA) studies of geopolymer binders and concretes report a wide range of global warming potential (GWP) reductions, with the activator frequently identified as the hotspot [6,55–61]. A recent meta-analysis combined impact and cost data and found that greenhouse-gas savings come with higher impacts in some other categories and with a cost premium [62]. The fifth theme is deployment: commercial progress [63], the status of design codes and constructability [64], pavement-scale demonstration at an airport [65], and new manufacturing routes such as extrusion-based 3D printing [66–70]. Several 2024–2025 reviews have added to the chemical and sustainability picture [28,30,31,71].

1.3. Research Gap and Rationale

The six questions that frame this review are answered in the order in which a reader would ask them. First, what is already known? Geopolymer binders can be formed from calcined clays and industrial by-products at temperatures below 100 °C, they harden

through a mechanism that differs from Portland cement hydration, and in many systems they resist chemical and thermal attack better than OPC concrete, while a number of LCA studies report lower GWP [19,20,62].

Second, what remains unclear? The evidence is conditional. Reported strengths range from a few megapascals to values far above structural requirements, depending on precursor, activator and curing, and an inter-laboratory program (RILEM TC 247-DTA) had to be organized specifically to examine the mix design and reproducibility of compressive strength of alkali-activated concretes [49]. Carbonation, chloride transport and long-term field behavior are less consistent than the sulfate and acid results [47,50], and the environmental ranking changes with the impact category, the activator source and the system boundary [55,62].

Third, what limits earlier studies? Most reviews treat chemistry, durability, LCA or standards on their own, so the reader must reconcile, without guidance, a mechanism described at the nanometer scale, a durability result obtained on a different binder, and a GWP value computed for a third. Headline figures such as “20 MPa in 4 h” or “70–100 MPa at 28 days”, and single percentages of CO_2 saving, are also routinely repeated without noting the specific system, the test conditions or the functional unit to which they apply, and figures reproduced in secondary sources are seldom traced back to primary data.

Fourth, what specific problem does this review address? It follows a single thread from synthesis route and reaction mechanism, through nanostructure and performance, to durability, life-cycle impact and cost, and asks at each step which conclusions survive a change of precursor, activator or system boundary. It also examines the quantitative evidence behind commonly cited claims. Strength, fire-exposure and life-cycle values are replotted from named primary studies, the authors’ own among them, and two life-cycle assessments with fully reported mix designs are set side by side.

Fifth, what is new? The contribution is integrative and critical rather than experimental: (i) a mechanism-to-deployment narrative organized around the question of what is robust and what is system-specific; (ii) a structured evidence table (Section 4.1) that records, for each performance dimension, what is supported, how sensitive it is and where the evidence is thin; and (iii) an explicit treatment of how headline numbers should be read. The review also differs from an earlier overview of synthesis methods and properties by the first author [72] in its evidence grading, its treatment of the activator and cost burden, and its inclusion of work published since 2021, including shrinkage, efflorescence and rheology, which are rarely discussed in the same article as life-cycle impact.

Sixth, why does this matter? For designers, specifiers and policy makers considering geopolymer concrete, the practical question is not whether the material can work but under which conditions it does so with an environmental benefit that is not offset elsewhere in the life cycle. A synthesis that makes those conditions explicit is directly useful for green-construction practice.

1.4. Objectives and Organization

The review has four objectives: (1) to describe the structural chemistry, raw materials and reaction mechanism of geopolymers in relation to Portland cement hydration; (2) to summarize reported nanostructure, strength development, thermal behavior, chemical and dimensional durability, and to indicate how far each result depends on the binder system; (3) to compare life-cycle environmental performance and cost with Portland cement concrete, identifying the dominant contributors; and (4) to identify the technical, economic and regulatory barriers to adoption and the research needed to remove them. Section 2 describes how the evidence was gathered and treated and reviews the chemistry of precursors, activators and reaction pathways; Section 3 reports the evidence; Section 4 interprets it; and Section 5 concludes.

2. MATERIALS AND METHODS

2.1. Review Design and Literature Identification

This is a narrative critical review. No new experiments were performed. Peer-reviewed articles, book chapters, one doctoral dissertation and conference papers on geopolymers and alkali-activated materials were identified by keyword searches of Crossref and OpenAlex (combinations of “geopolymer”, “alkali-activated”, “fly ash”, “metakaolin”, “slag”, “activator”, “carbonation”, “efflorescence”, “shrinkage”, “life cycle assessment”, “cement CO_2” and “3D printing”), followed by backward and forward citation tracing from recent reviews. Publications from 2019 onward were favored, and older landmark papers were kept where they established a mechanism or a method. Papers were retained when they addressed one of the themes in Section 1.2 and the statement attributed to them could be checked against their title or abstract; the first author’s own publications, located through Crossref, were included only where they bear directly on the point made, and one preprint that has not been peer reviewed is cited and labeled as such wherever it is used. The eligibility criteria and the search protocol with its counts

are given in the next paragraph, and the proportion of self-citations is disclosed at the end of this section.

Records were eligible if they dealt with one of the themes of Section 1.2 (the chemistry, nanostructure, strength, durability, dimensional stability, life-cycle impact, cost or deployment of geopolymers and closely related alkali-activated materials), were peer-reviewed articles, book chapters, dissertations or conference papers (or, in one case, a preprint that is labeled as such wherever it is used), and made a statement that could be checked against the title or abstract or, where available, the full text. Papers from 2019 onward were favored; older ones were kept only as landmark sources for a mechanism or a method. The counts of the original searches were not recorded, so the keyword search was repeated on 14 October 2026 under a fixed protocol, and the numbers below refer to that repeat. Each of the terms “geopolymer” and “alkali-activated” was paired with each of ten topic terms (fly ash, metakaolin, slag, activator, carbonation, efflorescence, shrinkage, life cycle assessment, cement CO_2 and 3D printing), and for each pair the 200 most relevant records published from 2019 onward were taken from Crossref and from OpenAlex. The 40 queries returned 7,488 records (4,000 from Crossref and 3,488 from OpenAlex, as four OpenAlex queries returned fewer than 200), and 4,945 remained after 2,543 duplicates were removed by DOI; records without a DOI were kept. Of the 128 references, 56 date from 2019 or later, and 25 of these were among the records returned. The other 31, and the 72 older references, came in through citation tracing or earlier searches. The repeat therefore documents the search but does not reproduce the selection, and the title-and-abstract screening decisions of the original review were not recorded. Because the review is narrative, the search was neither registered nor run to a pre-specified protocol. It makes no claim to completeness and is no substitute for a systematic review.

Bibliographic details of every reference that carries a DOI were checked against its Crossref record. Numerical values are reported as published in the cited sources.

Seven of the 128 references (5.5%) were written or co-written by authors of this review [41,42,72–76]. Three of them are the sources of the data in Fig. (**4**) [41], Fig. (**8**) and Table **3** [73,74]; the other four support a few shorter statements in the Introduction and in Sections 3 and 4. To limit the influence of this overlap, each is identified as the authors’ own where it is used, and the conclusions that rest on them are set against independent studies (Sections 3.2, 3.8 and 4.1). Figs. (**5** and **6**) are based entirely on work by other groups [77,78]. The remaining risk of bias is discussed in Section 4.6.

2.2. Treatment of Numerical Data and Figures

Every quantitative graphic and the mix-design table in Section 3 reproduces numbers published in a named primary source, given in the caption. Figure (**4**) replots the authors’ experiments on metakaolin-based geopolymer concrete [41], Figure (**5**) a comparison of fly ash geopolymer and Portland cement concrete [77], and Figure (**6**) a fire-exposure study of fly ash geopolymer concrete [78]. Figure (**8**) and Table **3** draw on two life-cycle assessments by the authors, one peer reviewed [73] and one preprint [74]. Only Figs. (**5** and **6**) rest on studies by other groups [77,78]; the rest is the authors’ own work (see the disclosure in Section 2.1). The graphics were redrawn from these values, and no image from another publication is reproduced. Strengths are in megapascals as published. Percentages and ratios in the figures were calculated here from the published values. The one exception is the ozone-depletion ratio of the slag-based assessment, whose tabulated units are garbled in the source. It is marked with an asterisk in Fig. (**8**), and its derivation is given below. Because the studies differ in precursor, activator, curing and functional unit, each geopolymer is compared only with the Portland reference in its own study, and results from different studies are placed side by side but never pooled.

Derivation of the ozone-depletion ratio for Study A. The tables of the source give the ozone-depletion totals of the geopolymer and the Portland concrete in kg CFC-11 eq., but the sign of the exponent is garbled. The text states that the geopolymer system accounts for 66% and the conventional concrete for 34% of the combined impact [73]. Both shares refer to the same combined total, so their ratio is the ratio of the two impacts: 66 / 34 = 1.94, or 194% of the Portland value (the asterisked bar in Fig. **8**). The tabulated mantissas, about 4.545 and 2.339 (both $\times 10^{-13}$ if the exponents are read as equal), give the same result, 4.545 / 2.339 = 1.94. Only the ratio is used, not the absolute values, because the exponents are unreliable. For Study B the ratio comes straight from the reported totals: $9.9 \times 10^{-6} / 2.3 \times 10^{-5} = 0.43$.

2.3. Definition and Structural Chemistry

The word “geopolymer” was coined in 1978 by the French materials chemist Joseph Davidovits [15,16], who used the name poly(sialate), an abbreviation for poly(silico-oxo-aluminate), for a family of natural or synthetic inorganic polymers. A geopolymer is a three-dimensional, ceramic-like, amorphous to semi-crystalline aluminosilicate formed by chemical activation of a solid aluminosilicate with a concentrated alkaline solution at low temperature, typically below 100 °C and often at room temperature. Calcined clays, fly ash and slag are typical solids [16,20].

In the structural description, SiO_4 and AlO_4 tetrahedra share corner oxygens to form chains and rings of general formula –(–Si–O–Al–O–)$_n$–, in contrast to the oxide notation of cement chemistry (for example $Al_2O_3{\cdot}2SiO_2$). Depending on the Si:Al ratio and the linkage, the main molecular species are the poly(sialate) family (–Si–O–Al–O–), the poly(sialate-siloxo) family (–Si–O–Al–O–Si–O–) and the poly(sialate-disiloxo) family (Fig. **2**), together with organo-siloxo (polysilicone), poly(alumino-phospho) and poly(ferro-sialate) types [15,79,80]. The aluminum atoms are four-coordinated and carry a negative charge that is balanced by an alkali cation, which is why Na^+ and K^+ appear in the general formula.

The Si:Al ratio is the main compositional variable. In the Davidovits scheme it sets the degree of polymerization. At Si:Al = 1 the framework consists of short Si–O–Al sequences (poly(sialate)); each step to 2 and 3 adds Si–O–Si linkages and longer, more chain-like units (poly(sialate-siloxo) and poly(sialate-disiloxo)), which is why the applications in Table **2** range from ceramics and refractories to sealants [15,16]. Strength does not rise steadily with Si:Al. In metakaolin-based systems it passes through a maximum at an intermediate ratio near 2 that also depends on the Na/Al ratio [81,82], and in the potassium cements of Zhang *et al*. Si:Al had the largest effect on strength of the molar ratios varied [83]. The alkali content is tied to Si:Al because every four-coordinated Al carries one negative charge that needs one alkali cation to balance it, so more Al calls for more Na^+ or K^+. Alkali beyond that requirement stays mobile in the pore solution; it is the source of efflorescence and of part of the carbonation sensitivity discussed in Sections 3.4 and 3.5 [47,51,84]. Si:Al, Na/Al and water content therefore have to be read together, not as independent variables [81,82].

The term is used more narrowly than “alkali-activated material”. Geopolymers are usually taken to be the low-calcium members of the AAM family, whose principal binding phase is an alkali aluminosilicate gel (sodium or potassium aluminosilicate hydrate, N-A-S-H or K-A-S-H), as opposed to the calcium-rich calcium–aluminate–silicate–hydrate (C-A-S-H) gel formed when slag is activated [20,21,31]. This distinction matters throughout the review, because several durability results quoted for “geopolymers” were obtained on slag-based, calcium-bearing systems.

2.4. Precursors and Activators

Any material that contains sufficient reactive silica (SiO_2) and alumina (Al_2O_3) that can dissolve under alkaline conditions can serve as a precursor. Metakaolin, produced by calcining kaolin clay at about 750 °C, is the best-defined precursor and is widely used for fundamental work [85]. Fly ash, ground granulated blast-furnace slag (GGBS) and silica fume are the main industrial by-products in use [36]. Agricultural residues, including rice husk ash and sugarcane bagasse ash, have been investigated as partial replacements for cementitious and pozzolanic components [86–88]. Calcium content matters. Low-calcium (class F) fly ash

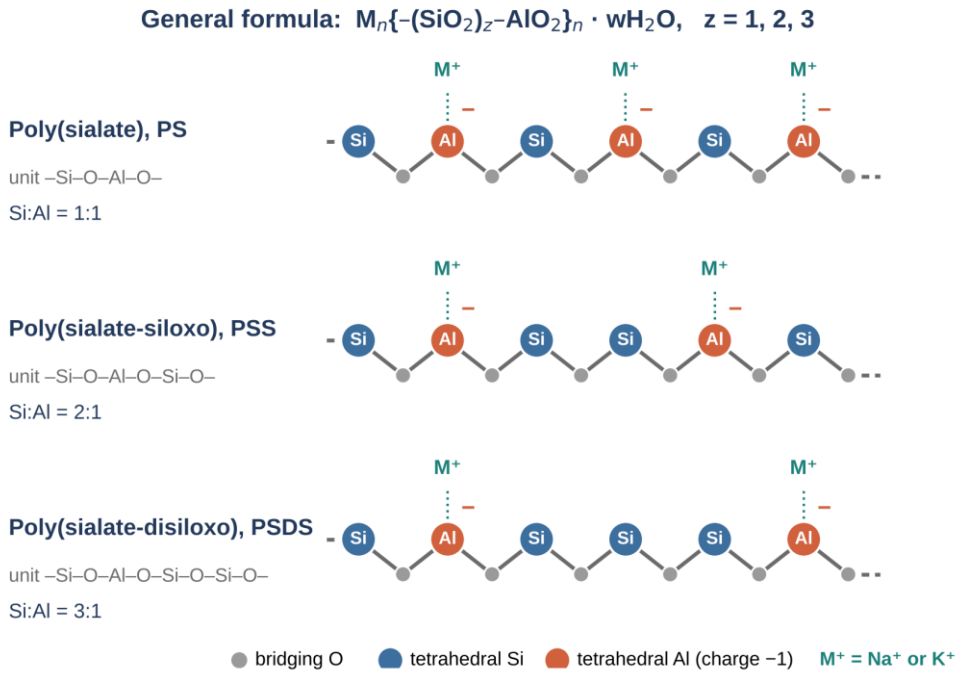


Figure 2: Poly(sialate) (PS, Si:Al = 1:1), poly(sialate-siloxo) (PSS, 2:1) and poly(sialate-disiloxo) (PSDS, 3:1) chains built from corner-sharing SiO_4 and AlO_4 tetrahedra, with the general empirical formula $M_n\{-(SiO_2)z-AlO_2\}_n{\cdot}wH_2O$ (M = Na^+ or K^+; z = 1, 2, 3). Original schematic drawn after the structural description of Davidovits [15].

and metakaolin generally require thermal curing to develop strength in a reasonable time, whereas adding slag or high-calcium ash allows setting at ambient temperature [32,38]. Table **1** summarizes these distinctions.

Two activation routes are recognized. In alkaline activation, the precursor reacts with an alkali hydroxide (NaOH or KOH) and a soluble alkali silicate to form poly(silicate), poly(siloxo), poly(silicoaluminate) and poly(sialate) structures [15,19]. In the second route, phosphoric acid acts as the activating medium and gives poly(alumino-phosphate) or silico-aluminophosphate structures [80]. Activator composition has a first-order effect on strength: the type and concentration of the alkali, the silicate modulus and the Na/K ratio change the composition and microstructure of the binder gel [81,89,90].

The activator is also the main environmental and economic weak point. Sodium silicate production is energy-intensive [91], which explains the interest in activators made from rice husk ash [92–95], from waste glass [96,97], and in one-part mixes in which a solid activator is dry-blended with the precursor [39]. These routes are revisited in Sections 3.8 and 4.3.

2.5. Reaction Mechanism and Standard Synthesis Procedure

Geopolymerization is generally described as a two-stage process: dissolution of the aluminosilicate precursor in the alkaline activating solution, followed by polycondensation of the released silicate and aluminate species into a solid, three-dimensional network [18,19,98,99]. The rate of dissolution depends on the alkalinity of the solution, the nature of the alkali cation, mixing intensity and time, and the composition and structure of the precursor [28]. Nucleation of the gel starts at particle surfaces, Si and Al species diffuse into the growing gel phase, and the sequence of dissolution, diffusion and condensation continues as the material hardens [29,100]. Temperature, pH and the size of the alkali cation influence the condensation rate; higher temperature, higher pH and larger cations are reported to accelerate hardening [23,98]. Fig. (**3**) summarizes the sequence; the stages overlap in practice and the figure is a deliberate simplification.

Table 1: Principal Aluminosilicate Precursors for Low-Calcium Geopolymers and Alkali-Activated Binders: Qualitative Characteristics Reported in the Cited Literature.

Precursor	Main Reactive Phases and Origin	Typical Behavior	Refs.
Metakaolin	Dehydroxylated kaolinite from calcination of kaolin clay (~750 °C)	Well-defined, highly reactive; used for fundamental studies; high water demand; elevated-temperature curing common	[26,85]
Class F fly ash	Aluminosilicate glass with mullite and quartz; coal-combustion by-product	Slow reaction at ambient temperature; thermal curing usually needed; variable composition	[32,38]
Slag (GGBS) and high-Ca ash	Calcium-rich glass; by-product of iron making or high-calcium coal ash	Rapid setting and ambient-temperature strength gain; C-A-S-H forms alongside or instead of N-A-S-H	[36,38]
Silica fume	Amorphous silica from silicon and ferrosilicon production	Supplies reactive silica; used to adjust the Si:Al ratio	[36,87]
Agricultural ashes	Rice husk ash, sugarcane bagasse ash and similar residues	Silica-rich; usable as partial precursor or as silica source for activators; quality depends on burning conditions	[86–88]

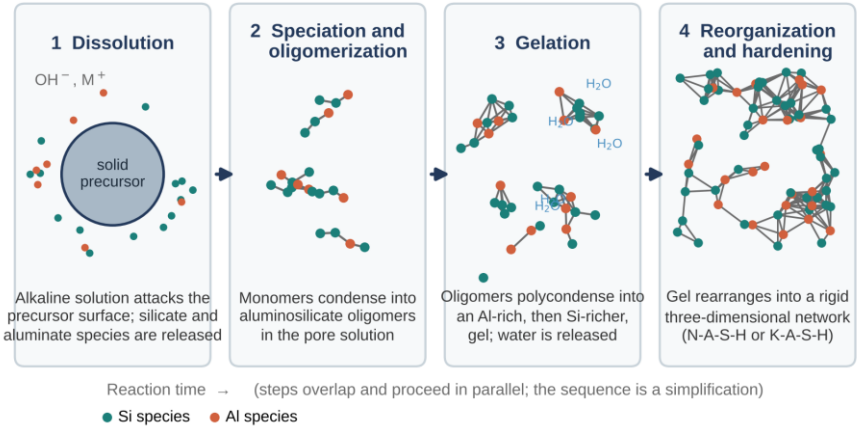


Figure 3: Four-stage conceptual pathway of geopolymerization: (1) dissolution of the aluminosilicate precursor in alkaline solution, (2) speciation and oligomerization of aluminate and silicate species, (3) gelation into an aluminosilicate network and (4) reorganization and hardening. The stages overlap in practice. Original schematic based on the mechanisms described in [12,19,20].

The role of water needs careful wording. Water acts mainly as a reaction and transport medium that is largely released as polycondensation proceeds, while the hardened gel still retains bound and pore water that changes with age and with the alkali cation [25,100]. This is consistent with the “H” in the gel names N-A-S-H and K-A-S-H, and it should not be read as meaning that the hardened gel is anhydrous.

Water takes several forms in these binders, and each affects the properties discussed in Section 3. (i) Water in the activator solution dissolves the precursor and carries the dissolved species; most of it is released again as polycondensation proceeds [19,100]. (ii) Free water that is not bound in the gel stays in the capillary pores. The more water is added for workability, the more pore volume it leaves behind on drying, and the resulting pore structure and permeability have been examined for alkali-activated fly ash [101]. (iii) Water adsorbed on pore surfaces and bound in the gel, the “H” in N-A-S-H and K-A-S-H, is held more strongly and changes with age and alkali cation [25,100]. When free and adsorbed water is lost on drying, capillary stress and self-desiccation build up and contribute to shrinkage and cracking [53,102]; water that cannot escape during heating can damage the concrete in fire [103,104]. Moving water also carries mobile alkali to the surface, where it forms efflorescence [51]. Water content is thus a first-order mix-design variable, but its effects on porosity and shrinkage are mix-specific, and the shrinkage evidence in Section 3.5 comes mainly from slag-based systems [53].

The standard laboratory procedure combines the powdered precursor with NaOH or KOH and sodium silicate solution into a homogeneous paste, casts it into molds, leaves it at ambient temperature for a few hours, cures it at about 80 °C for one to two days, and allows further development over 7–28 days [32,81]. Curing temperature and duration vary widely between studies, which is one reason why strengths from different laboratories cannot be compared directly.

3. RESULTS: REPORTED EVIDENCE ON STRUCTURE, PERFORMANCE AND ENVIRONMENTAL IMPACT

This section sets out what the reviewed sources report. Interpretation, comparison across studies and mechanistic explanation are deferred to Section 4. Where a statement holds only for a particular precursor–activator system, the system is named.

3.1. Nanostructure

The solid-state structure of geopolymers has been examined with transmission and scanning electron microscopy (TEM and SEM), light and X-ray scattering, and ^{29}Si and ^{27}Al magic-angle spinning nuclear magnetic resonance (MAS-NMR) spectroscopy [19,23,25]. Zhang *et al.* studied nine potassium poly(sialate-siloxo) cement matrices whose molar ratios were varied, and found that the Si:Al ratio had the largest effect on compressive strength, with a best value of 34.8 MPa for the optimized composition; the matrix with the highest strength also showed the most complete reaction by infrared spectroscopy, and X-ray diffraction, electron microscopy and NMR indicated a glass- or gel-like structure in which silicon chains are partly replaced by four-coordinated aluminum [83]. In the TEM study of the same fully reacted material, the network was described as particles about 5–15 nm in size with interstitial nanospaces and with ordering on a 3–10 nm scale, giving a nanoporous, sponge-like appearance, and energy-dispersive spectroscopy gave a Si:Al ratio near 2:1 [83]. The microstructure of fly ash-based geopolymers has also been examined by Škvára *et al.* [105].

Scattering and impedance measurements show that the picture depends on the alkali cation. In sodium geopolymers aged for a few months the interface between the mineral phase and the pore network was smooth and built from small elementary particles, whereas potassium and cesium geopolymers presented hierarchically organized particles that aggregated into surfaces with fractal character; aging for up to several years changed the sodium series most [25]. The incorporation of aluminum into the gel is likewise influenced by the alkali cation [23]. Whether nanocrystalline zeolite-like domains exist within the amorphous gel has been debated [24]. The question does not change the engineering conclusions below, and this review does not try to settle it.

3.2. Setting Behavior and Strength Development

Geopolymer cement is reported to develop strength rapidly at room temperature. Davidovits reported compressive strengths in excess of 20 MPa within four hours, and 70–100 MPa or more at 28 days at 20 °C, for potassium poly(sialate-siloxo) cements [16,106]. Low porosity, which compares favorably with that of Portland cement pastes and mortars, was proposed as a reason for the high strength [106]. The relationship between composition, microstructure and strength has been analyzed for metakaolin-based systems [82], and the chemical optimum is sensitive to the relative amounts of Si, Al and Na [81]. These values should be read as characteristic of those specific cements. Reviews of fly ash- and slag-based geopolymer concretes, the systems most relevant to construction, report a wide spread of compressive strengths that depends on the precursor, the activator and the curing regime [32,33,35], and a RILEM inter-laboratory

program was needed to examine the reproducibility of strength in alkali-activated concretes made to common mix designs [49]. Fly ash systems cured at ambient temperature set slowly unless a calcium source is added; replacing part of the fly ash with slag shortened setting time and raised early strength in one study [38].

The authors' experiments on metakaolin-based geopolymer concrete, cured at 80 °C for 24 h, show how strongly the activator proportions set the outcome (Fig. **4**). Raising the sodium silicate/NaOH mass ratio from 1.5 to 3 lowered the 28-day compressive strength from 25.6 to 15.0 MPa, and the best mix (MR1.5) had already reached 84% of its 28-day strength after 3 days. Replacing 10% to 50% of the metakaolin with zeolite gave 28-day strengths of 20.3 to 24.6 MPa, and the nano-silica mixes were the strongest of the series at 26.1 to 27.1 MPa [41]. These are single-laboratory results on one precursor, used here only to show how large the activator effect can be; the sensitivity of strength to the relative amounts of Si, Al and Na has also been shown independently [81].

A recent open-access comparison of a fly ash geopolymer concrete with a Portland cement concrete shows a different picture of early strength (Fig. **5**). The two concretes ended up with practically the same 28-day strength, 28.01 and 28.04 MPa, but the geopolymer was ahead at the start: 16.68 against 9.68 MPa at 3 days, which is 72% higher. The gap narrowed to 5% at 7 days (21.50 against 20.53 MPa) and 2% at 14 days (24.60 against 24.04 MPa) before disappearing. The same study reports CO_2 emissions of 117.5 kg/m³ for the geopolymer concrete and 191.3 kg/m³ for the Portland concrete, a reduction of 38.6%, and flexural strengths of 2.9, 3.7 and 4.81 MPa for the geopolymer

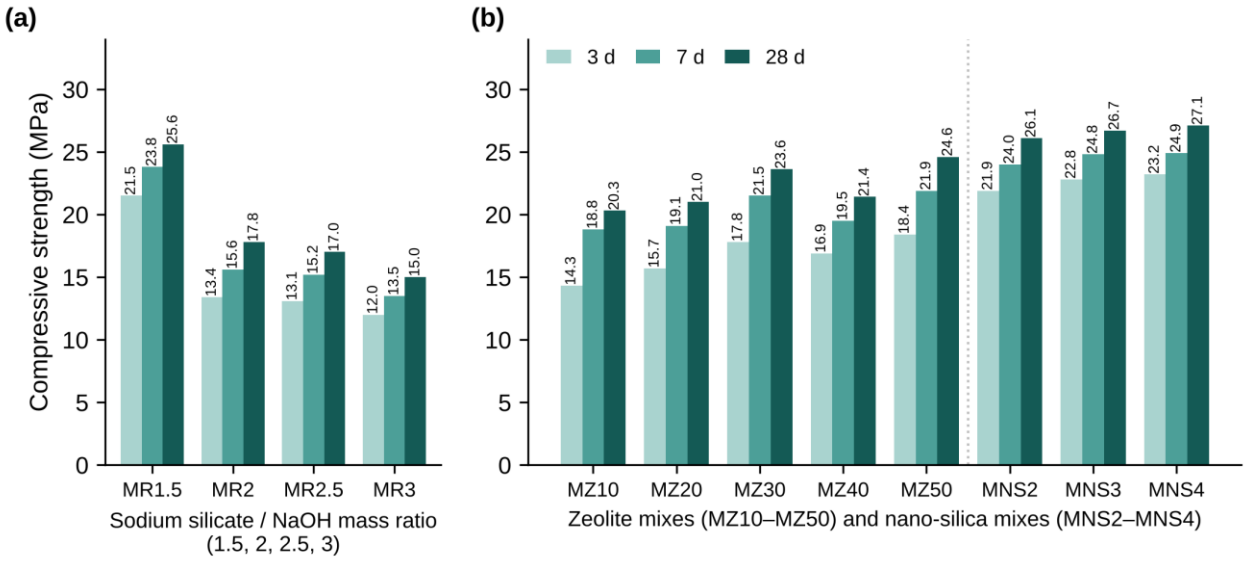


Figure 4: Compressive strength at 3, 7 and 28 days of metakaolin-based geopolymer concrete cured at 80 °C for 24 h, replotted from the authors' experimental data [41]. (a) Mixes MR1.5 to MR3, with sodium silicate/NaOH mass ratios of 1.5, 2, 2.5 and 3. (b) Mixes MZ10 to MZ50, with zeolite replacing part of the metakaolin, and mixes MNS2 to MNS4, with nano-silica; labels as in the source.

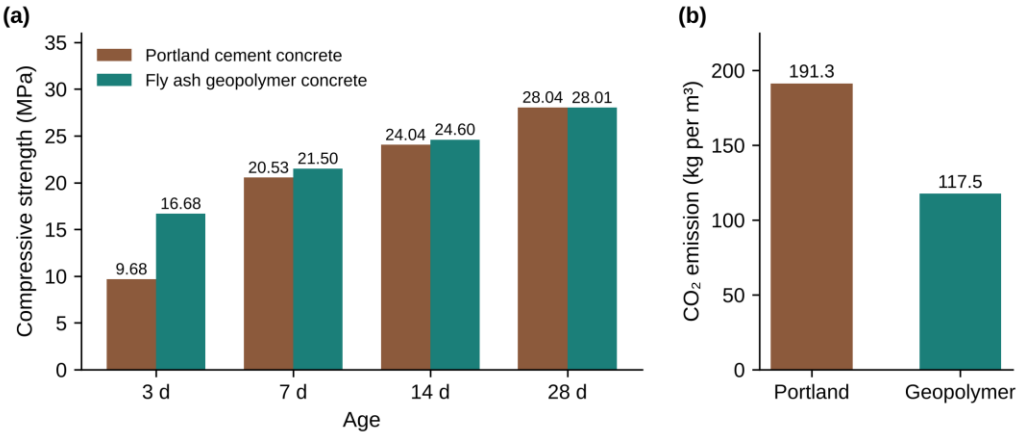


Figure 5: Fly ash geopolymer concrete compared with Portland cement concrete, replotted from the values reported by [77]. (a) Compressive strength at 3, 7, 14 and 28 days. (b) CO_2 emissions per cubic meter of concrete.

against 1.74, 3.4 and 4.3 MPa at 3, 7 and 28 days [77]. Read together with the potassium cements above, these results suggest that fast early strength is a common but not universal feature, and that its size depends on the system and the curing used.

Strength can be modified by what is added to the mix. Fibers have been reported to improve the compressive, tensile and flexural strengths of metakaolin-based geopolymer concrete while lowering density and water absorption [76]. Replacing natural aggregate with recycled aggregate has also been reviewed: geopolymer recycled aggregate concrete can be improved by raising curing temperature, using several precursors together, or adding fibers and nanoparticles, and mixes with several precursors tended to perform better than single-precursor mixes [40].

3.3. Behavior at Elevated Temperature

The quantitative fire data in this section come from a single study with one mix design and one exposure duration (1 h) per temperature, so they show the direction of the effect and not its general size. Sodium-based geopolymers are reported to retain an amorphous structure up to 500 °C, and potassium-based geopolymers to remain amorphous up to 1000 °C; both keep more strength than Portland cement pastes, which degrade continuously through dehydration of C-S-H, followed by decomposition of $Ca(OH)_2$ and $CaCO_3$ [16,107]. Fig. (**6**) replots a direct comparison of a fly ash geopolymer concrete and a Portland cement concrete, both designed for 56.4 MPa at 28 days and exposed to temperatures from 200 to 800 °C for one hour [78]. At 200 °C the geopolymer concrete kept 99.1% of its ambient strength and the Portland concrete 94.4%. At 400 °C the geopolymer concrete rose to 114.7% (64.7 MPa) while the Portland concrete fell to 86.8% (49.0 MPa). The difference then widened: residual strengths were 90.5% and 71.8% at 600 and 800 °C for the geopolymer, and 59.4% and 32.9% for the Portland concrete, which corresponds to 51.1 and 40.5 MPa against 33.5 and 18.6 MPa.

The independent literature is consistent in direction but not uniform in detail. Residual strength after heating depends on the activator and curing regime [108], on specimen size and aggregate type, because thermal incompatibility between paste and aggregate and moisture escape can cause damage even when the binder itself is stable [103,104], and on the precursor and its thermal reactions [109]. Factors governing the softening temperature and hot strength have been analyzed [110]. Fire resistance has been examined for potassium-based formulations [111], and a critical review of structural fire-resistance applications is available [107].

3.4. Chemical Durability

Two processes dominate the chemical deterioration of concrete: sulfate attack and chloride-induced corrosion of reinforcement [112]. Geopolymers contain much less calcium than Portland cement, so the calcium-based expansive products that drive sulfate attack in OPC concrete are not expected to form. Sodium and magnesium sulfate exposure of geopolymer materials has been reported to cause little damage in some systems, with behavior depending on the binder chemistry [113]. Reviews conclude that geopolymer concretes generally resist aggressive environments better than normal concrete, which has been linked to lower porosity and permeability [44,101]. Resistance to acid attack is likewise reported to be

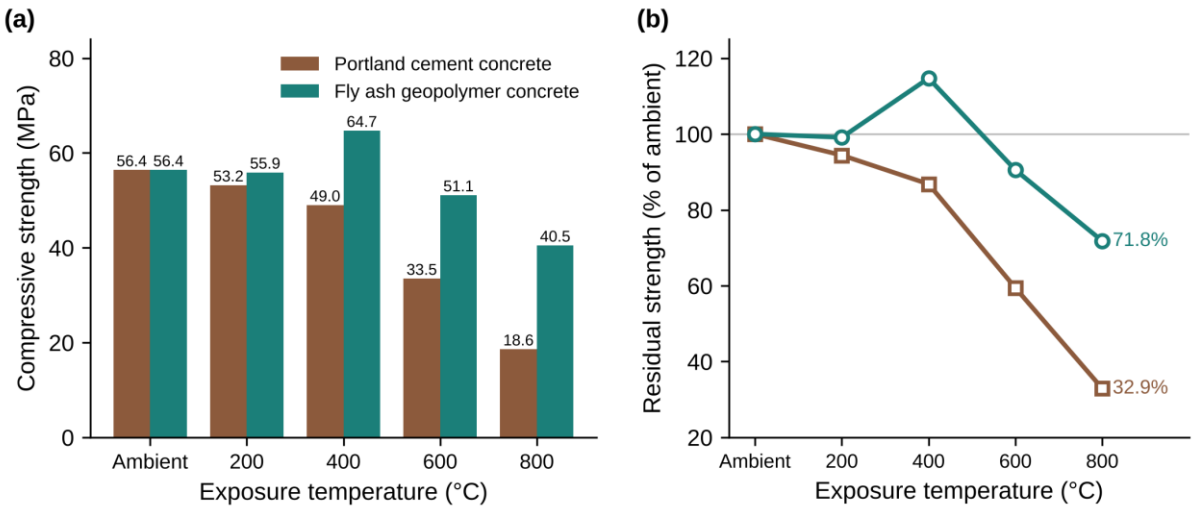


Figure 6: Compressive strength of a fly ash geopolymer concrete and a Portland cement concrete, both designed for 56.4 MPa at 28 days, after 1 h of exposure to temperatures from 200 to 800 °C, replotted from [78]. (a) Absolute strength. (b) Residual strength as a percentage of the strength at ambient temperature, as reported in the source. One mix design and one exposure duration only; the data indicate the direction of the effect, not its general size.

better than that of OPC-based materials, again with a dependence on the activator [44,114].

In chloride environments, the corrosion behavior of steel in reinforced geopolymer concrete has been compared with that in OPC concrete under cyclic wet–dry exposure [115], a low-calcium fly ash geopolymer concrete culvert has been monitored in a saline setting [116], and recent reviews of AAMs in chloride-bearing environments give a mixed but generally encouraging picture [45,48]. Geopolymers are also reported to be quite resistant to alkali–silica reaction (ASR), which can damage OPC concrete made with reactive aggregate, even though the alkali content of the binder is high [117,118], and the presence of slag or metakaolin in AAMs is reported to reduce alkali–silica reactivity [44]. The freeze–thaw evidence is thin. The only study cited here deals with alkali-activated slag concrete, a calcium-rich member of the AAM family and not a low-calcium geopolymer [119], so its good freeze–thaw durability should not be carried over to low-calcium geopolymers without confirmation.

Carbonation resistance does not uniformly favor the new binder. Atmospheric CO_2 reacts with the alkaline pore solution and lowers its pH by a mechanism different from the decalcification of $Ca(OH)_2$ and C-S-H in OPC, so the degree of protection depends strongly on precursor chemistry and activator dose [84,120]. Fly ash- and slag-based geopolymers with limited free alkalinity have shown carbonation depths comparable to those of ordinary Portland concrete of similar strength grade, whereas mixes activated with a high dose of soluble sodium silicate tend to carbonate faster and lose surface alkalinity sooner, which can threaten passivation of embedded steel earlier than in OPC systems [47]. Reviews of carbonation of AAMs confirm that outcomes depend on the binder and on the exposure regime [45,46], and a round-robin test of carbonation and chloride-penetration methods on five alkali-activated concretes was needed to establish whether Portland-cement test methods are transferable [50]. The carbonation evidence is therefore a pattern, not a single result: the degree of protection depends on the system and on the test method, which is why carbonation is rated Mixed in Table **4**.

3.5. Dimensional Stability, Efflorescence and Fresh-State Behavior

Durability in service also depends on properties that are less prominent in the headline literature. Alkali-activated slag pastes, mortars and concretes generally show larger autogenous shrinkage than their Portland cement counterparts; self-desiccation is the main driver, existing Portland-cement models give unsatisfactory estimates unless the pronounced viscoelasticity of the material is considered, and mitigation measures often carry side effects such as lower strength [53]. Because that review concerns slag-based systems, its conclusions cannot be transferred to low-calcium geopolymers without checking. For geopolymer concrete itself, restrained shrinkage and creep have been followed over a full year [102].

Efflorescence, the formation of salts on the surface and of carbonated alkali in capillary pores when mobile alkali meets humidity and CO_2, has been reviewed critically, and the factors that govern it are still not fully understood [51]. Mitigation strategies for metakaolin-based geopolymers have been compared [52]. Rheology and workability complete the picture of fresh-state behavior: a review of the rheology of AAMs is available [54], and in geopolymer 3D printing the rheological properties are decisive for printability [69]. Mix-design approaches for geopolymer concrete have been surveyed [37].

3.6. Chemistry of Geopolymer and Portland Cement Binders Compared

Portland cement hardens by hydration. C_3S and the other calcium silicates react with water to form calcium–silicate–hydrate (C-S-H) gel and $Ca(OH)_2$ [121–123]. In a geopolymer, hardening instead proceeds by polycondensation, in which Al and Si form covalent cross-linked networks. The chemical environment of Si and Al in geopolymers is closer to that of natural aluminosilicate minerals than to the hydrates of cement paste, as ^{29}Si NMR spectra of the two types of binder show [100,123]. Where calcium is present, as in slag–fly ash blends, N-A-S-H and C-A-S-H gels can coexist and interact [26,27]. Fig. (**7**) sketches how these constituents are arranged in a geopolymer concrete: aggregate surrounded by an interfacial transition zone, an alkali aluminosilicate gel binder, unreacted and partly reacted precursor particles, and pores and microcracks. The sketch is conceptual and is not drawn to scale.

3.7. Applications and Implementation

Davidovits tailored geopolymer chemistry mainly through the Si:Al ratio for uses ranging from refractory ceramics to low-carbon binders, heat-resistant composites and industrial sealants (Table **2**) [15,16].

In construction, geopolymer cement and concrete are under study for pavements, precast elements and culverts, and for structures exposed to aggressive environments [63,116]. Geopolymers have also been evaluated as adsorbents for heavy metals and dyes [124]. The principal drawbacks reported are sensitivity to curing and less practical experience than with conventional concrete [63,64].

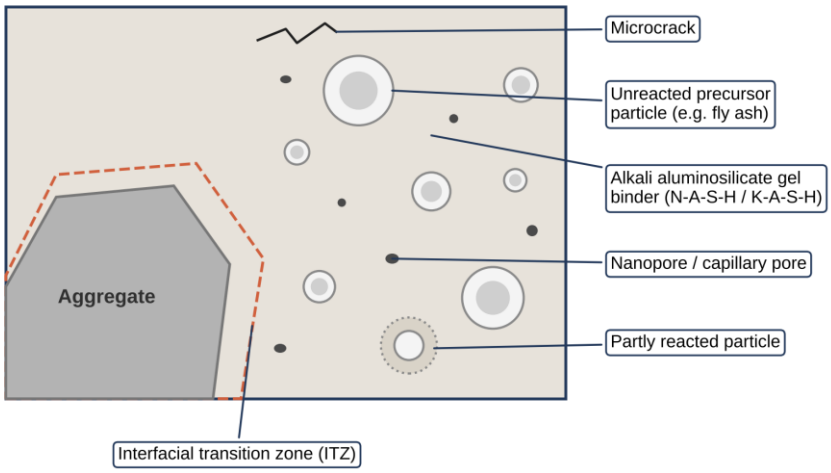


Figure 7: Conceptual sketch of the microstructure of a geopolymer concrete: aggregate with its interfacial transition zone (ITZ), an alkali aluminosilicate gel binder (N-A-S-H or K-A-S-H), unreacted and partly reacted precursor particles (for example fly ash), nanopores and capillary pores, and a microcrack. A Portland cement paste is not shown. Original schematic, not to scale; no micrograph is reproduced.

Table 2: Typical Geopolymer Applications as a Function of the Si:Al Ratio, after Davidovits [15,16]

Si:Al Ratio	Typical Application
1	Bricks, fire-resistant ceramics, refractory materials
2	Low-CO_2 cements; encapsulation and immobilization of toxic and radioactive waste
3	Heat-resistant composites, foundry tooling and equipment, fiberglass composites
> 3	Industrial sealants and binders

The clearest demonstration that geopolymer concrete can be produced and placed at infrastructure scale is the pavement at Brisbane West Wellcamp Airport in Queensland, Australia. About 40,000 m³ of fly ash- and slag-based geopolymer concrete, marketed as Earth Friendly Concrete, was used on the project, including some 25,000 m³ of pavement-grade material for the turning node, apron and taxiway; the pavement was unreinforced, 435 mm thick, specified at a flexural strength of 4.8 MPa at 28 days, and placed with a slip-form paver. The project reported avoided emissions of 8,640 metric tons of CO_2 relative to conventional Portland-cement concrete [65]. Cases of this kind remain rare, but they show that the barrier to wider adoption is no longer purely technical.

Much of the limited practical experience reflects the regulatory environment rather than the material. Dedicated design codes and standardized test methods for geopolymer concrete remain uncommon, and engineers who specify concrete through prescriptive OPC-based codes, defined by cement content and water–cement ratio, have no equivalent framework for an alkali-activated binder with a different chemistry. A systematic review concluded that the performance of geopolymer concrete is highly sensitive to mixture parameters and called for non-prescriptive testing procedures and specifications that allow alternatives to conventional concrete [64]. Until such frameworks are in wider use, specifiers and insurers are likely to remain cautious outside niche or precast applications.

An emerging application outside the cast-in-formwork model is extrusion-based 3D printing of geopolymer pastes and mortars. Because mixes can be formulated with the rapid, controllable stiffening that extrusion requires, without relying on cement hydration kinetics, they are being explored as a low-carbon alternative to the OPC-based mortars used in most construction 3D-printing trials [69,70]. The main obstacles are rheological rather than chemical: a mix must be fluid enough to pump and extrude yet stiff enough to hold its shape and bond to the previous layer throughout the open time of a print run. Studies have addressed extrusion and rheology of geopolymer nanocomposites [66], in-line activation of a geopolymer slurry so that activation occurs at the nozzle [67], and printable mixes containing brick waste [68].

3.8. Life-cycle Assessment and Environmental Benefits

Life cycle assessment (LCA) follows four steps: goal and scope definition, life-cycle inventory (LCI), impact assessment and interpretation [125,126]. It quantifies

the inputs, outputs and environmental impacts associated with the whole life cycle of a process or product. Commonly used impact indicators include abiotic resource depletion potential (ADP), global warming potential (GWP), eutrophication potential (EP), human toxicity potential (HTP) and ozone depletion potential (ODP) [58,126]. How LCA has been used to quantify the environmental impacts of OPC and PFA (fly ash) concrete products has been reviewed by Javid and Esparham [75].

In the comparative LCA by Weil *et al.* that used the CML method (developed at the Institute of Environmental Sciences, Leiden University), the sodium silicate activator solution and metakaolin were the main contributors to the GWP of geopolymer mixtures even though the mass balance is dominated by low-impact sand and aggregate; fly ash and slag contributed relatively little [58].

The authors' own assessments show how these hotspots appear in a complete inventory. Fig. (**8**) sets two of them side by side, but they do not carry equal weight. Study A is peer reviewed and is treated as the primary evidence; Study B is a preprint and serves only as a provisional second case. Each compares a geopolymer concrete with a Portland cement concrete of about 80 MPa at 28 days, for a functional unit of 1 m³, over the production stage including the upstream supply of materials, with CML characterization and cumulative energy demand calculated in SimaPro. Study A used ground granulated blast-furnace slag as the solid precursor [73]. Study B, a preprint that has not been peer reviewed, used a solid binder based on municipal wastewater sludge [74]. The mixes are listed in Table **3**: both geopolymer concretes contained 120 kg/m³ of sodium silicate solution and 80 kg/m³ of 50% NaOH solution next to 400–410 kg/m³ of solid binder, against 600 kg/m³ (A) and 410 kg/m³ (B) of Portland cement in the reference concretes.

The global warming potential of the geopolymer concrete was 172 against 743 kg CO_2 eq. in Study A, or 23% of the Portland value, and 287 against 1071 kg CO_2 eq. in Study B (preprint), or 27%. Fossil depletion (38% and 34%), cumulative energy demand (38% and 27%), eutrophication (38% and 45%) and human toxicity (80% and 72%) also favored the geopolymer. The two studies differ more in acidification (56% and 92%), and photochemical oxidation was nearly equal in Study B (99%). Ozone depletion went in different directions: in Study A the geopolymer concrete had about 1.9 times the Portland value (derivation in Section 2.2), whereas in Study B it was 43% of it (9.9×10^{-6} against 2.3×10^{-5} kg CFC-11 eq.). In Study B the sodium silicate and NaOH were the largest burdens of the geopolymer, while Portland cement and the superplasticizer dominated the reference concrete.

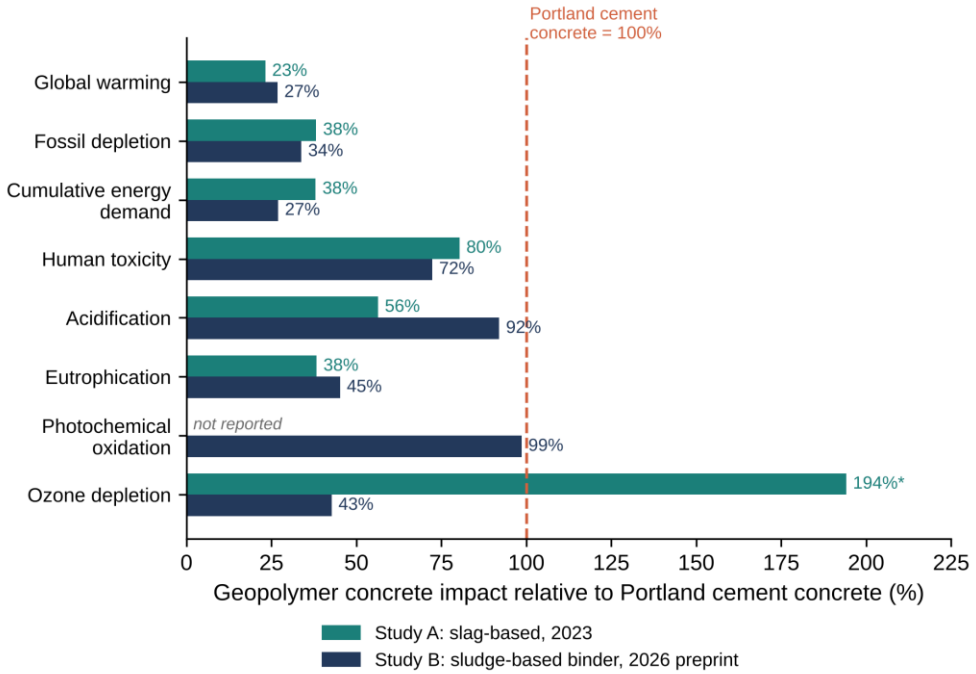


Figure 8: Impact of a geopolymer concrete relative to a Portland cement concrete of the same strength (= 100%) in two life-cycle assessments by the authors, each for 1 m³ of concrete of about 80 MPa at 28 days (production stage with upstream supply; CML characterization and cumulative energy demand). Study A (peer reviewed): slag-based geopolymer [73]. Study B (provisional): geopolymer with a wastewater-sludge-based binder, a preprint that has not been peer reviewed [74]. Ratios were calculated from the totals reported in each study. *Derived from the shares of 66% and 34% stated in the text of Study A (66/34 = 1.94; Section 2.2), because the tabulated units are illegible. Photochemical oxidation is omitted for Study A because the reported values are rounded too coarsely to give a ratio.

The Study A ozone result is the clearest case of burden shifting in Fig. (**8**), so it is worth a closer look. In the source, sodium hydroxide accounts for about 80% of the geopolymer's ozone-depletion impact, sodium silicate for about 10% and the slag for about 4% [73]. The penalty thus comes from the activator, not from the precursor. Why Study B shows the opposite sign cannot be settled from the published data. The two geopolymers use different solid binders, the Portland references contain different amounts of cement (600 and 410 kg/m³, Table **3**), and the contributions to this category in Study B are not examined here. The absolute values also differ by many orders of magnitude for the same functional unit, about 10^{-13} kg CFC-11 eq. in Study A and about 10^{-5} kg CFC-11 eq. in Study B, which is another reason to rely on the ratio and not on the absolute figure. The result is best read as a warning that activator supply chains can shift burdens to categories other than climate change, not as a quantified ozone penalty for geopolymer concrete in general.

Other LCAs agree on the importance of the activator. A cradle-to-gate assessment of geopolymer concretes made from industrial side streams found that mixes with less sodium silicate and metakaolin performed better, and that a 10% reduction in metakaolin content reduced the global warming impact by 16% relative to traditional concrete [61]. An assessment of one-part geopolymer concrete compared structural grades against OPC concrete of the same grade and noted lower embodied energy when sodium carbonate replaced liquid sodium hydroxide [6]. Studies using rice husk ash-derived sodium silicate report that substituting commercial waterglass lowers CO_2 emissions without a large loss of strength in mortars [92]; silicate derived from rice husk ash has also served as the activator for fly ash geopolymer cement [94] and, with 10 M NaOH, for GGBS-based geopolymer concrete [95]. Sodium silicate powder has been produced from waste glass cullet for alkali activation [96], and the environmental impacts of alkali-activated concrete made with a waste glass-derived silicate activator have been analyzed [97]. Earlier assessments of geopolymer binders and concretes [55–57,59,60,127] differ in their reported reductions because of differences in activator, transport distances, curing and system boundaries.

Environmental performance is only part of the adoption calculus, and cost remains an obstacle. A meta-analysis by Martínez and Miller compiled geopolymer and Portland-cement concrete mix designs from peer-reviewed review and machine-learning articles that had themselves extracted data from many studies; the source studies and mixes are listed in Table S1 of that paper [62]. It covered only mixes with fly ash, blast-furnace slag, metakaolin or rice husk ash as solid precursor or supplementary cementitious material, and only geopolymers activated with commercial sodium hydroxide and sodium silicate. Compressive strengths were converted to the standard 150 × 300 mm cylinder equivalent, duplicates and outliers (beyond 1.5 times the interquartile range) were removed, and the mixes were grouped into low-strength ($5 \le f_c < 25$ MPa), normal-strength ($25 \le f_c < 50$ MPa) and high-strength ($f_c > 50$ MPa) classes. The comparison was cradle to gate, that is, production and transport of the constituents plus curing, and covered GHG, NOx, SOx, PM10, PM2.5, VOC and CO emissions as well as manufacturing cost [62]. It reported GHG emissions on average 12% lower for low-strength, 30% lower for normal-strength and 50% lower for high-strength geopolymer concrete (Fig. **9**), higher emissions in several other categories, and a production cost of roughly twice that of conventional concrete, with the alkaline activator identified as the main driver of both

Table 3: Mix Proportions (kg/m³) of the Geopolymer and Portland Cement Concretes in the Two Life-cycle Assessments of Fig. (8), as Reported for Study A [73] and Study B [74]. Both are Designed for About 80 MPa at 28 Days. The NaOH Solution is 50% in Both Studies and the Sodium Silicate Solution is 37% in Study B. A Dash Means the Material was not Used. Column Totals Equal the Sum of the Listed Constituents (For Example, Study A Geopolymer: 410 + 120 + 80 + 8 + 31 + 850 + 850 = 2349 kg/m³).

Material	A: Geopolymer	A: Portland	B: Geopolymer	B: Portland
Portland cement	—	600	—	410
Solid binder (A: slag; B: wastewater-sludge-based)	410	—	400	—
Sodium silicate solution	120	—	120	—
NaOH solution (50%)	80	—	80	—
Superplasticizer	8	25	8	8
Water	31	180	10	103
Coarse aggregate	850	1020	850	1026
Fine aggregate	850	524	850	810
Total	2349	2349	2318	2357

impact and cost [62]. A separate analysis has examined the cost of avoiding CO_2 with fly ash geopolymer concrete [128]. Taken together with the results above, the environmental advantage of geopolymer concrete is real but narrower, and its economic case weaker, than a GWP-only comparison would suggest.

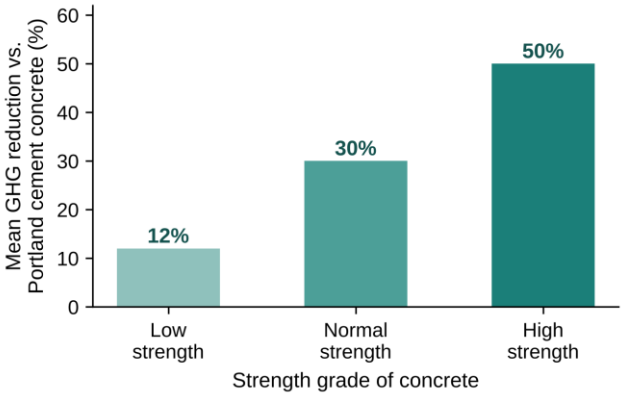


Figure 9: Average reduction in greenhouse-gas emissions of geopolymer concrete relative to Portland-cement concrete, by strength class, as reported in the meta-analysis of [62]. Strength classes are those defined in [62].

4. DISCUSSION

4.1. What the Evidence Supports and Where it is System-Specific

The results above show that geopolymer binders differ from Portland cement in kind, not only in degree, and that differences in kind explain both their strengths and their inconsistencies. The reported advantages in sulfate, acid and thermal exposure agree with independent studies of fly ash and slag systems [44,103,108,113,114]. The agreement is qualitative, however. When the same properties are tracked quantitatively, outcomes diverge with the activator, the curing regime and the aggregate [64,103,108], and the same is true of carbonation and chloride transport [47,48,50]. The headline strength values (20 MPa at 4 h and 70–100 MPa at 28 days) should therefore be read as properties of particular potassium poly(sialate-siloxo) cements [16,106], not as design values for geopolymer concrete in general; even within that family, the nine formulations examined by Zhang *et al.* spanned a wide strength range with a best value of 34.8 MPa [83]. For fly ash and slag concretes of the kind used in practice, strengths documented in reviews are lower and more variable [33,35,49]. Table **4** summarizes how far each performance dimension is supported, how sensitive it is, and where the evidence is thin; the evidence-status terms it uses are defined in the note below the table.

Evidence-status terms in Table **4**. Supported: consistent in direction across several independent studies or reviews, although the size of the effect may vary. Mixed: direction or size differs between systems, test methods or studies, but an identifiable pattern (given in the sensitivities column) explains much of the variation. Limited: evidence from a single study or meta-analysis, or from a related binder only, such as alkali-activated slag instead of low-calcium geopolymer. Gap: no dedicated evidence or standard was found in the reviewed sources. A qualifier in brackets states the main restriction on a classification.

Two points stand out when the table is read as a whole. First, the dimensions in which geopolymers are best supported (sulfate and acid resistance, behavior at temperature) are those governed mainly by the absence of calcium-bearing hydrates, whereas the dimensions that remain open (carbonation, chloride transport, shrinkage, efflorescence, long-term behavior, standardization) depend on pore-solution chemistry, alkali mobility and mix design, for which no single predictive model yet exists. Second, several of the strongest quantitative claims in the secondary literature trace back to single sources, which is why the graphics in this article replot only values that could be traced to a named primary study, and why each geopolymer is compared only with the reference concrete of its own study.

4.2. Mechanistic Interpretation

The gel chemistry offers a coherent, though partly inferential, explanation of the pattern in Table **4**. A geopolymer binder contains little calcium, so neither portlandite nor monosulfate-type phases are available to form the expansive products of sulfate attack, and the aluminosilicate network is not decalcified by acid in the way C-S-H is [20,113,114]. This interpretation is consistent with the literature, but it should not be treated as proven for every system. The dependence of acid and sulfate behavior on the activator [113,114] indicates that gel composition, and not calcium content alone, matters. Where slag or high-calcium ash is added to allow ambient curing [38], C-A-S-H forms alongside N-A-S-H [26,27], and the resulting binder inherits some of the vulnerabilities of calcium-bearing gels. This is also why durability evidence gathered on alkali-activated slag, such as the freeze–thaw result [119] or the autogenous-shrinkage review [53], cannot be carried over to low-calcium geopolymers without confirmation.

The behavior at elevated temperature is plausibly related to the same structural difference. Portland cement pastes lose strength as C-S-H dehydrates and $Ca(OH)_2$ and $CaCO_3$ decompose [16], whereas the aluminosilicate network of a geopolymer contains no equivalent hydrates. The residual strengths in Fig. (**6**) follow this pattern: at 800 °C the geopolymer concrete keeps 72% of its ambient strength and the Portland

Table 4: Evidence Summary for the Main Performance Dimensions of Geopolymer Binders and Concretes Compared with Portland Cement: What the Reviewed Sources Report, Main Sensitivities, and the Status of the Evidence (Qualitative Synthesis of the Cited Literature; no New Data). Evidence-Status Terms are Defined in the Note Below the Table.

Dimension	Reported Evidence	Main Sensitivities and Caveats	Evidence Status	Refs.
Early strength	Geopolymer cement reported to exceed 20 MPa within 4 h at room temperature; a fly ash geopolymer concrete was 72% stronger than Portland concrete at 3 days but equal at 28 days (Fig. 5)	Specific to the system and curing; ambient-cured fly ash systems need an added calcium source	Mixed (system-specific)	[38,77,106]
28-day strength	70–100 MPa or more reported for geopolymer cement; wide range for fly ash and slag concretes	Precursor, activator, curing regime; reproducibility must be demonstrated	Mixed (system-specific)	[16,33,35,49]
Elevated temperature	Higher residual strength than Portland cement: 72% against 33% at 800 °C in Fig. 6; potassium systems reported amorphous to 1000 °C	Activator, aggregate, specimen size, moisture escape; one mix and one exposure duration in the replotted study	Supported (qualitative; size from one mix)	[78,103,107, 108,110]
Sulfate and acid	Low-calcium binder resists sulfate and acid attack better than OPC	Depends on activator and binder chemistry	Supported	[44,113,114]
Chloride and corrosion	Mixed but generally encouraging results under wet–dry and saline exposure	Mix design; test method	Mixed	[48,115,116]
Alkali–silica reaction	Quite resistant despite high binder alkalinity	Slag or metakaolin reduces reactivity	Supported	[44,117,118]
Freeze–thaw	Good durability reported	Cited evidence concerns alkali-activated slag concrete, not low-calcium geopolymer	Limited (slag evidence only)	[119]
Carbonation	Depths comparable to OPC for fly ash or slag mixes with limited free alkalinity; faster with high silicate dose	Precursor, activator dose, test conditions; accelerated tests may mislead	Mixed (coherent pattern, system-specific size)	[46,47,50,84,120]
Shrinkage and efflorescence	Autogenous shrinkage of slag-based systems exceeds that of Portland cement; efflorescence controlled by pore structure and soluble alkali	Activator dose, silicate content, curing, pore structure	Limited (mainly slag-based evidence)	[51–53,102]
Global warming potential	73% lower in the peer-reviewed Study A and 77% lower in the preprint Study B (Fig. 8); on average 12%, 30% and 50% lower for low-, normal- and high-strength concrete in a meta-analysis	Activator, binder source, transport, system boundary; one assessment is an unreviewed preprint	Supported (magnitude varies)	[58,61,62,73,74]
Other impact categories	Lower in most categories in Fig. 8, but acidification near parity in one study and ozone depletion higher in the other; several categories worse in pooled data	Impact category; by-product allocation; activator	Mixed	[62,73,74,97]
Cost	Roughly twice that of conventional concrete	Price of sodium silicate activator	Limited (one meta-analysis)	[62,128]
Codes and test methods	Few dedicated design codes; non-prescriptive procedures needed	Region; test-method validation	Gap	[50,64]

concrete 33%. The superior behavior of potassium systems over sodium systems agrees with the alkali-cation effects on pore structure and gel organization reported by Melar *et al.* [25] and Duxson *et al.* [23], although a direct causal link between those differences and high-temperature stability has not been shown in the sources reviewed here. Studies on the thermal reactions of fly ash geopolymer pastes show that the precursor itself changes the thermal response [109], and the mismatch between paste and aggregate can dominate the response of concrete [103], so the temperature curve of a geopolymer concrete is a property of the whole composite.

Carbonation illustrates the limits of mechanistic transfer from Portland cement. In OPC, carbonation

consumes portlandite and then decalcifies C-S-H, and the pH is buffered until portlandite is exhausted. In low-calcium geopolymers there is no such buffer, so the alkalinity that protects steel is the alkalinity of the pore solution, which depends on the type and dose of activator [47,84,120]. This explains, at least qualitatively, why mixes with high sodium silicate doses carbonate faster. It also implies that accelerated carbonation tests at elevated CO_2 concentration may not rank materials as natural exposure does, a concern raised specifically for alkali-activated binders [84] and the reason for the RILEM comparison of test methods [50].

The early-age advantage in Fig. (**5**) points to a related difference in kinetics. A geopolymer that is in solution as soon as it is mixed can begin polycondensation immediately, whereas Portland cement must first dissolve calcium silicates and nucleate hydrates, a sequence that leaves an induction period during which little strength develops [19,121]. That would be consistent with a geopolymer 72% stronger at 3 days, but the available data do not establish which step controls the rate in the geopolymer. That the gap had closed by 28 days also shows that early strength was not accompanied by higher final strength in this system, and the curing history of the two concretes [77] matters for any such comparison.

Additives affect the microstructure and therefore the mechanical results, although the evidence is again system-specific. Fibers have likewise been reported to improve compressive, tensile and flexural strengths of metakaolin-based geopolymer concrete while reducing density and water absorption [76]. In the authors' metakaolin series, the activator ratio changed 28-day strength far more than the mineral additions did: going from a sodium silicate/NaOH ratio of 1.5 to 3 cost about 10 MPa, whereas 50% zeolite cost about 1 MPa and nano-silica added 0.5 to 1.5 MPa (Fig. **4**) [41]. That ranking suggests that activator proportions are a first-order variable, although the mechanism was not tested here. Such results show what can be tuned but not that the effects will transfer to other precursors.

4.3. Environmental Implications and the Burden-Shifting Problem

The LCA evidence agrees on the direction of the effect on GWP but not on its size. Published reductions vary with the activator, with transport and curing assumptions and with the strength grade [55–57,62,127]. In the authors' two assessments (Fig. **8**; Study A peer reviewed, Study B a preprint and therefore provisional), the global warming potential of the geopolymer concrete was 23% and 27% of the Portland value and the cumulative energy demand 38% and 27%. Acidification reached 92% in the sludge-based preprint, however, and ozone depletion in the slag-based study was higher than for Portland concrete (Section 3.8), which fits the general finding that the benefit is concentrated in climate impact and energy. The meta-analysis (Fig. **9**) reaches a more cautious general figure, with GHG savings that rise with strength grade from 12% to 50% and with higher emissions in several other categories [62]. Both of the authors' reference concretes were high-strength mixes with 410 to 600 kg/m³ of cement, and their GWP savings of 77% and 73% exceed the pooled 50% for high-strength concrete. Differences in system boundary, transport distances and allocation of by-products are plausible reasons, but they were not tested here. Single-study figures are case-specific and should not be read as typical.

The mechanism of burden shifting is the activator. Sodium silicate and, in metakaolin mixes, the calcined clay dominate the geopolymer GWP [58,61], and in the sludge-based assessment of Section 3.8 sodium silicate and NaOH were the largest burdens [74]; sodium silicate production itself is energy-intensive [91]; and it is the main driver of the cost premium [62]. These findings support three strategies. First, binders should be promoted where chemical resistance, rather than cost alone, governs the choice. Second, blending precursors (metakaolin with fly ash, for example) can reduce the demand for sodium silicate by adjusting the Si/Al balance of the mix, in line with the finding that mixes with less sodium silicate and metakaolin performed better [61]. Third, silicate derived from rice husk ash or waste glass is a promising way to reduce energy use and emissions from the activator [92,94–97], and one-part formulations offer another route to safer handling and lower embodied energy [6,39]. Each strategy has been shown at laboratory or mortar scale; none has been demonstrated across the supply chain at the scale of the Wellcamp pavements.

Resource availability is the third element of the environmental argument. Fly ash and slag are by-products of other industries, and their long-term supply is uncertain as coal combustion and blast-furnace ironmaking change [11]. A comparison between geopolymer and OPC that treats by-products as burden-free may therefore overstate the benefit if the same by-products would otherwise be used as SCMs in Portland cement concrete [10,62]. This allocation question is not resolved in the sources reviewed and should be explicit in future LCAs. Recycled aggregate adds a further, partly independent, lever on embodied impact, although its effect on the mechanical and durability performance of geopolymer concrete must be demonstrated mix by mix [40].

4.4. Volume Stability, Efflorescence and Workability

Shrinkage, efflorescence and workability rarely appear in the headline claims for geopolymers, yet they decide whether a mix that passes laboratory strength tests can be built. The finding that alkali-activated slag shows more autogenous shrinkage than Portland cement, with self-desiccation as the main driver [53], suggests that fine-pored, highly alkaline binders may be prone to early cracking, and cracking in turn undermines the chloride and carbonation resistance discussed above. The same pore-solution alkalinity that supports passivation of steel is the source of efflorescence when alkali is mobile and meets humid, CO_2-bearing air [51], which is why mitigation depends on the formulation [52]. These links are inferential and mix-specific. The authors are not aware of a study that follows shrinkage, efflorescence and carbonation on the same low-calcium geopolymer concrete, which would be a useful experiment.

Workability links chemistry to practice in a more direct way. Highly viscous alkaline activator solutions and rapid gelation limit the time available to mix, place and finish, and the review of AAM rheology [54] and the 3D-printing literature [67,69] both treat control of rheology as central. In-line activation at the nozzle [67] is an example of an engineering solution to a chemical constraint, and mix-design methods [37] are the more general response.

4.5. Practical and Regulatory Implications

The Wellcamp pavements show that geopolymer concrete can be batched, delivered and slip-formed with conventional equipment [65]. They are, however, a single reported project, and the avoided emissions quoted for it have not been independently audited in the material reviewed. The main practical barrier remains regulatory. Prescriptive codes based on cement content cannot accommodate a binder whose performance is controlled by activator chemistry; performance-based specifications, supported by durability test methods validated for alkali-activated materials, are the logical response [49,50,64]. For 3D printing, the open-time and rheology challenge is specific to geopolymers, and in-line activation is an engineering solution to it [67]. Where the application is precast, cured in controlled conditions, and where the exposure is chemically aggressive, the combination of controlled curing and resistance to attack suggests the best near-term fit.

4.6. Limitations

Several limitations qualify the conclusions. The review is narrative, its selection followed the criteria of Section 2.1 but not a registered protocol, and the literature search was not exhaustive, so selection bias cannot be excluded. The quantitative graphics replot values from a small number of primary studies, three of them from the authors' group (Fig. **4**, Fig. **8** and Table **3**), which is a potential source of bias, and each study uses its own materials, curing and test conditions; the fire-exposure study used a single mix design and exposure duration, one of the two life-cycle assessments is a preprint that has not been peer reviewed, and the ozone-depletion ratio for the slag-based assessment had to be derived from shares stated in the text (Section 2.2). Most of the durability and LCA evidence comes from laboratory-scale studies of a limited number of binder systems, with few long-term field data, and the two LCAs cover the production stage only, so use and end-of-life are not addressed. For some of the 128 references the authors had access only to the title or abstract, so claim-level support could be checked only at that level. Statements that rest on these references are less firmly supported than those checked against the full text. Finally, 7 of the 128 references (5.5%) are papers by the authors' group [41,42,72–76]. They were cited only where they bear on the point made and are identified as the authors' own where they are used, but they have not all been independently replicated. Their weight in Figs. (**4** and **8**) and Table **3** is a limitation that readers should keep in mind.

4.7. Future Research Directions

Five needs emerge. (1) Primary, traceable datasets of early-age and long-term strength for fly ash-, slag- and metakaolin-based concretes, produced under standardized curing and reported with uncertainty. (2) Carbonation and chloride-transport studies that link pore-solution chemistry to natural-exposure performance, using the methods being validated by RILEM TC 247-DTA [50]. (3) Joint measurements of shrinkage, efflorescence and carbonation on the same low-calcium mixes. (4) LCAs with consistent functional units, transparent allocation of by-products, and sensitivity to the activator source. (5) Demonstration projects with monitored durability and independently audited emissions, so that performance-based specifications can be written on field evidence.

5. CONCLUSIONS

This review set out to relate the chemistry of geopolymers to their performance, environmental impact and prospects for use in construction. Concerning the first objective, geopolymers harden by dissolution of aluminosilicate precursors and polycondensation into an alkali aluminosilicate network (N-A-S-H or K-A-S-H), unlike the C-S-H of Portland cement, and the nanoscale structure reported for such networks consists of particles roughly 5–15 nm in size

separated by nanopores. On the second, potassium poly(sialate-siloxo) cements are reported to gain strength very quickly at room temperature, and the literature describes good resistance to sulfate, acid and high temperature; carbonation resistance, efflorescence, shrinkage and workability depend strongly on precursor chemistry and activator dose. On the third, in the LCA comparison examined, two assessments of about 80 MPa concretes gave a GWP of 23% (slag-based, peer reviewed) and 27% (sludge-based, a non-peer-reviewed preprint and therefore provisional) of the Portland value, with ozone depletion higher in the slag-based case, and the activator, above all sodium silicate, is the main environmental hotspot and cost driver, and a meta-analysis reports an average GHG saving of 12–50% depending on strength grade, a cost roughly twice that of conventional concrete and higher impacts in some other categories.

On the fourth objective, adoption is limited less by chemistry than by activator sourcing and cost, by sensitivity to curing and mix design, and by the absence of widely adopted design codes and standardized test methods. The Wellcamp airport pavements show that the barriers are not insurmountable, but they are not yet routine. The practical implications are to prioritize chemically aggressive and precast applications, to develop lower-impact activators and blended precursors, and to pursue performance-based specifications. Future work should supply traceable primary data, natural-exposure carbonation and chloride results, LCAs with transparent boundaries, and monitored field projects. On the evidence reviewed, geopolymer concrete is a promising but conditional low-carbon binder, not yet a routine one. Its climate benefit is real but depends on the activator, the system boundary and the strength grade, and it comes with a production cost about twice that of conventional concrete, mixed results in other impact categories and unresolved regulatory gaps.

ABBREVIATIONS

AAM, alkali-activated material; ADP, abiotic resource depletion potential; ASR, alkali–silica reaction; CED, cumulative energy demand; C-A-S-H, calcium–aluminate–silicate–hydrate; C-S-H, calcium–silicate–hydrate; CML, Institute of Environmental Sciences, Leiden University, impact-assessment method; EP, eutrophication potential; GGBS, ground granulated blast-furnace slag; GHG, greenhouse gas; GWP, global warming potential; GWP100, global warming potential over a 100-year horizon; HTP, human toxicity potential; ITZ, interfacial transition zone; K-A-S-H, potassium–aluminate–silicate–hydrate; LCA, life cycle assessment; LCI, life-cycle inventory; MAS-NMR, magic-angle spinning nuclear magnetic resonance; N-A-S-H, sodium–aluminate–silicate–hydrate; ODP, ozone depletion potential; OPC, ordinary Portland cement; SCM, supplementary cementitious material; SEM, scanning electron microscopy; TEM, transmission electron microscopy.

AUTHOR CONTRIBUTIONS

A.E. conceived the review and defined its scope. R.N. and A.N. jointly conducted the literature analysis, with R.N. making the major contribution to the literature search, analysis, and synthesis. R.N. drafted substantial parts of the initial manuscript, while A.N. contributed to the manuscript drafting and organization. A.H. contributed to the literature analysis and interpretation of the reviewed studies. A.E. critically revised the manuscript for important intellectual content and supervised the overall work. All authors read and approved the final manuscript.

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CONFLICT OF INTEREST

The authors declare no conflict of interest related to this manuscript. Seven of the 128 references were written or co-written by the authors; this self-citation is disclosed in Sections 2.1 and 4.6.

ETHICS, CONSENT FOR PUBLICATION AND DATA AVAILABILITY

Not applicable. This review is based on published literature on geopolymer materials science and involved no human participants, human data or animal subjects. Consent for publication: not applicable.

No new data were generated or analyzed in the preparation of this review. All information discussed is available within the cited sources listed in the References section. The graphics were redrawn by the authors from numerical values reported in the cited sources (Section 2.2); the sludge-based life-cycle assessment cited in Section 3.8 is available as a preprint.

USE OF AI-ASSISTED TOOLS

A generative AI assistant was used to support language editing. The authors reviewed and edited all content and take full responsibility for the manuscript.

APPENDICES

None.

REFERENCES

[1] Monteiro PJM, Miller SA, Horvath A. Towards sustainable concrete. *Nat Mater*. 2017;16(7):698-9. doi:10.1038/nmat4930

[2] Miller SA, Horvath A, Monteiro PJM. Readily implementable techniques can cut annual CO_2 emissions from the production of concrete by over 20%. *Environ Res Lett*. 2016;11(7):074029. doi:10.1088/1748-9326/11/7/074029

[3] Gartner E. Industrially interesting approaches to “low-CO2” cements. *Cem Concr Res*. 2004;34(9):1489-98. doi:10.1016/j.cemconres.2004.01.021

[4] Antunes M, Santos RL, Pereira J, *et al.* Alternative Clinker Technologies for Reducing Carbon Emissions in Cement Industry: A Critical Review. *Materials*. 2021;15(1):209. doi:10.3390/ma15010209

[5] Andrew RM. Global CO_2 emissions from cement production, 1928–2018. *Earth Syst Sci Data*. 2019;11(4):1675-710. doi:10.5194/essd-11-1675-2019

[6] Neupane K. Evaluation of environmental sustainability of one-part geopolymer binder concrete. *Cleaner Materials*. 2022;6:100138. doi:10.1016/j.clema.2022.100138

[7] Scrivener KL, John VM, Gartner EM. Eco-efficient cements: Potential economically viable solutions for a low-CO2 cement-based materials industry. *Cem Concr Res*. 2018;114:2-26. doi:10.1016/j.cemconres.2018.03.015

[8] Habert G, Miller SA, John VM, *et al.* Environmental impacts and decarbonization strategies in the cement and concrete industries. *Nat Rev Earth Environ*. 2020;1(11):559-73. doi:10.1038/s43017-020-0093-3

[9] Marandi N, Shirzad S. Sustainable cement and concrete technologies: a review of materials and processes for carbon reduction. *Innov Infrastruct Solut*. 2025;10(9):408. doi:10.1007/s41062-025-02213-5

[10] Juenger MC, Snellings R, Bernal SA. Supplementary cementitious materials: New sources, characterization, and performance insights. *Cem Concr Res*. 2019;122:257-73. doi:10.1016/j.cemconres.2019.05.008

[11] Snellings R, Suraneni P, Skibsted J. Future and emerging supplementary cementitious materials. *Cem Concr Res*. 2023;171:107199. doi:10.1016/j.cemconres.2023.107199

[12] Shi C, Jiménez AF, Palomo A. New cements for the 21st century: The pursuit of an alternative to Portland cement. *Cem Concr Res*. 2011;41(7):750-63. doi:10.1016/j.cemconres.2011.03.016

[13] Shi C, Qu B, Provis JL. Recent progress in low-carbon binders. *Cem Concr Res*. 2019;122:227-50. doi:10.1016/j.cemconres.2019.05.009

[14] Duxson P, Provis JL, Lukey GC, *et al.* The role of inorganic polymer technology in the development of ‘green concrete’. *Cem Concr Res*. 2007;37(12):1590-7. doi:10.1016/j.cemconres.2007.08.018

[15] Davidovits J. Geopolymers. *J Therm Anal*. 1991;37(8):1633-56. doi:10.1007/bf01912193

[16] Davidovits J. 30 years of successes and failures in geopolymer applications. Market trends and potential breakthroughs. In: Proceedings of the Geopolymer 2002 International Conference; 2002 Oct 28-29; Melbourne, Australia.

[17] Palomo A, Grutzeck M, Blanco M. Alkali-activated fly ashes. *Cem Concr Res*. 1999;29(8):1323-9. doi:10.1016/s0008-8846(98)00243-9

[18] Xu H, Van Deventer J. The geopolymerisation of alumino-silicate minerals. *Int J Miner Process*. 2000;59(3):247-66. doi:10.1016/s0301-7516(99)00074-5

[19] Duxson P, Fernández-Jiménez A, Provis JL, *et al.* Geopolymer technology: the current state of the art. *J Mater Sci*. 2006;42(9):2917-33. doi:10.1007/s10853-006-0637-z

[20] Provis JL, Bernal SA. Geopolymers and Related Alkali-Activated Materials. *Annu Rev Mater Res*. 2014;44(1):299-327. doi:10.1146/annurev-matsci-070813-113515

[21] Provis JL. Alkali-activated materials. *Cem Concr Res*. 2018;114:40-8. doi:10.1016/j.cemconres.2017.02.009

[22] Provis JL, van Deventer JSJ, editors. Alkali activated materials: state-of-the-art report, RILEM TC 224-AAM. Dordrecht: Springer; 2014. doi:10.1007/978-94-007-7672-2

[23] Duxson P, Lukey GC, Separovic F, *et al.* Effect of Alkali Cations on Aluminum Incorporation in Geopolymeric Gels. *Ind Eng Chem Res*. 2005;44(4):832-9. doi:10.1021/ie0494216

[24] Provis JL, Lukey GC, van Deventer JSJ. Do Geopolymers Actually Contain Nanocrystalline Zeolites? A Reexamination of Existing Results. *Chem Mater*. 2005;17(12):3075-85. doi:10.1021/cm050230i

[25] Melar J, Renaudin G, Leroux F, *et al.* The Porous Network and its Interface inside Geopolymers as a Function of Alkali Cation and Aging. *J Phys Chem C*. 2015;119(31):17619-32. doi:10.1021/acs.jpcc.5b02340

[26] Garcia-Lodeiro I, Palomo A, Fernández-Jiménez A, *et al.* Compatibility studies between N-A-S-H and C-A-S-H gels. Study in the ternary diagram Na2O–CaO–Al2O3–SiO2–H2O. *Cem Concr Res*. 2011;41(9):923-31. doi:10.1016/j.cemconres.2011.05.006

[27] Walkley B, San Nicolas R, Sani MA, *et al.* Phase evolution of C-(N)-A-S-H/N-A-S-H gel blends investigated via alkali-activation of synthetic calcium aluminosilicate precursors. *Cem Concr Res*. 2016;89:120-35. doi:10.1016/j.cemconres.2016.08.010

[28] El Fadili H, Ait-Khouia Y, Ouffa N, *et al.* Comprehensive review on alkaline dissolution of aluminosilicates and its role in the mechanisms and properties of geopolymers and alkali-activated materials. *Case Stud Constr Mater*. 2025;23:e05330. doi:10.1016/j.cscm.2025.e05330

[29] Chuewangkam N, Kidkhunthod P, Pinitsoontorn S. Direct evidence for the mechanism of early-stage geopolymerization process. *Case Stud Constr Mater*. 2024;21:e03539. doi:10.1016/j.cscm.2024.e03539

[30] Madirisha MM, Dada OR, Ikotun BD. Chemical fundamentals of geopolymers in sustainable construction. *Mater Today Sustain*. 2024;27:100842. doi:10.1016/j.mtsust.2024.100842

[31] Mohan Kumar SGK, Kinuthia JM, Oti J, *et al.* Geopolymer Chemistry and Composition: A Comprehensive Review of Synthesis, Reaction Mechanisms, and Material Properties—Oriented with Sustainable Construction. *Materials*. 2025;18(16):3823. doi:10.3390/ma18163823

[32] Hardjito D, Wallah SE, Sumajouw DMJ, *et al.* On the Development of Fly Ash-Based Geopolymer Concrete. *ACI Mater J*. 2004;101(6):467-72. doi:10.14359/13485

[33] Ding Y, Dai JG, Shi CJ. Mechanical properties of alkali-activated concrete: A state-of-the-art review. *Constr Build Mater*. 2016;127:68-79. doi:10.1016/j.conbuildmat.2016.09.121

[34] Amran YM, Alyousef R, Alabduljabbar H, *et al.* Clean production and properties of geopolymer concrete; A review. *J Clean Prod*. 2020;251:119679. doi:10.1016/j.jclepro.2019.119679

[35] Ahmed HU, Mohammed AA, Rafiq S, *et al.* Compressive Strength of Sustainable Geopolymer Concrete Composites: A State-of-the-Art Review. *Sustainability*. 2021;13(24):13502. doi:10.3390/su132413502

[36] Azad NM, Samarakoon SSM. Utilization of Industrial By-Products/Waste to Manufacture Geopolymer Cement/Concrete. *Sustainability*. 2021;13(2):873. doi:10.3390/su13020873

[37] Ansari MA, Shariq M, Mahdi F. Geopolymer concrete for clean and sustainable construction – A state-of-the-art review on the mix design approaches. *Structures*. 2023;55:1045-70. doi:10.1016/j.istruc.2023.06.089

[38] Nath P, Sarker PK. Effect of GGBFS on setting, workability and early strength properties of fly ash geopolymer concrete cured in ambient condition. *Constr Build Mater*. 2014;66:163-71. doi:10.1016/j.conbuildmat.2014.05.080

[39] Luukkonen T, Abdollahnejad Z, Yliniemi J, *et al.* One-part alkali-activated materials: A review. *Cem Concr Res*. 2018;103:21-34. doi:10.1016/j.cemconres.2017.10.001

[40] Zhang P, Sun X, Wang F, *et al.* Mechanical Properties and Durability of Geopolymer Recycled Aggregate Concrete: A Review. *Polymers*. 2023;15(3):615. doi:10.3390/polym15030615

[41] Esparham A. Investigation of the Effects of Nano Silica Particles and Zeolite on the Mechanical Strengths of Metakaolin-Based Geopolymer Concrete. *Int J Innov Eng*. 2021;1(4):82-95. doi:10.59615/ijie.1.4.82

[42] Esparham A, Hosseni MH, Mousavi Kashi A, Emami F, Moradikhou AB. Impact of replacing kaolinite with slag, fly ash and zeolite on the mechanical strengths of geopolymer concrete based on kaolinite. Build Eng Hous Sci. 2020;13(3):9-15.

[43] Bernal SA, Provis JL. Durability of Alkali-Activated Materials: Progress and Perspectives. *J Am Ceram Soc*. 2014;97(4):997-1008. doi:10.1111/jace.12831

[44] Amran M, Al-Fakih A, Chu S, *et al.* Long-term durability properties of geopolymer concrete: An in-depth review. *Case Stud Constr Mater*. 2021;15:e00661. doi:10.1016/j.cscm.2021.e00661

[45] Zhang X, Long K, Liu W, *et al.* Carbonation and Chloride Ions' Penetration of Alkali-Activated Materials: A Review. *Molecules*. 2020;25(21):5074. doi:10.3390/molecules25215074

[46] Lamaa G, Duarte APC, Silva RV, *et al.* Carbonation of Alkali-Activated Materials: A Review. *Materials*. 2023;16(8):3086. doi:10.3390/ma16083086

[47] Zhao C, Li Z, Peng S, *et al.* State-of-the-art review of geopolymer concrete carbonation: From impact analysis to model establishment. *Case Stud Constr Mater*. 2024;20:e03124. doi:10.1016/j.cscm.2024.e03124

[48] Salami BA, Ibrahim M, Algaifi HA, *et al.* A review on the durability performance of alkali-activated binders subjected to chloride-bearing environment. *Constr Build Mater*. 2022;317:125947. doi:10.1016/j.conbuildmat.2021.125947

[49] Provis JL, Arbi K, Bernal SA, *et al.* RILEM TC 247-DTA round robin test: mix design and reproducibility of compressive strength of alkali-activated concretes. *Mater Struct*. 2019;52(5):99. doi:10.1617/s11527-019-1396-z

[50] Gluth GJG, Arbi K, Bernal SA, *et al.* RILEM TC 247-DTA round robin test: carbonation and chloride penetration testing of alkali-activated concretes. *Mater Struct*. 2020;53(1):21. doi:10.1617/s11527-020-1449-3

[51] Longhi MA, Zhang Z, Rodríguez ED, *et al.* Efflorescence of Alkali-Activated Cements (Geopolymers) and the Impacts on Material Structures: A Critical Analysis. *Front Mater*. 2019;6:89. doi:10.3389/fmats.2019.00089

[52] Longhi MA, Zhang Z, Walkley B, *et al.* Strategies for control and mitigation of efflorescence in metakaolin-based geopolymers. *Cem Concr Res*. 2021;144:106431. doi:10.1016/j.cemconres.2021.106431

Li Z, Chen Y, Provis JL, *et al.* Autogenous shrinkage of alkali-activated slag: A critical review. *Cem Concr Res*. 2023;172:107244. doi:10.1016/j.cemconres.2023.107244

Lu C, Zhang Z, Shi C, *et al.* Rheology of alkali-activated materials: A review. *Cem Concr Compos*. 2021;121:104061. doi:10.1016/j.cemconcomp.2021.104061

[53] Habert G, d'Espinose de Lacaillerie J, Roussel N. An environmental evaluation of geopolymer based concrete production: reviewing current research trends. *J Clean Prod*. 2011;19(11):1229-38. doi:10.1016/j.jclepro.2011.03.012

[54] McLellan BC, Williams RP, Lay J, *et al.* Costs and carbon emissions for geopolymer pastes in comparison to ordinary portland cement. *J Clean Prod*. 2011;19(9-10):1080-90. doi:10.1016/j.jclepro.2011.02.010

[55] Turner LK, Collins FG. Carbon dioxide equivalent (CO2-e) emissions: A comparison between geopolymer and OPC cement concrete. *Constr Build Mater*. 2013;43:125-30. doi:10.1016/j.conbuildmat.2013.01.023

[56] Weil M, Dombrowski K, Buchwald A. Life-cycle analysis of geopolymers. In: Provis JL, van Deventer JSJ, editors. Geopolymers: structure, processing, properties and industrial applications. Cambridge: Woodhead Publishing; 2009. p. 194-210. doi:10.1533/9781845696382.2.194

[57] Salas DA, Ramirez AD, Ulloa N, *et al.* Life cycle assessment of geopolymer concrete. *Constr Build Mater*. 2018;190:170-7. doi:10.1016/j.conbuildmat.2018.09.123

[58] Passuello A, Rodríguez ED, Hirt E, *et al.* Evaluation of the potential improvement in the environmental footprint of geopolymers using waste-derived activators. *J Clean Prod*. 2017;166:680-9. doi:10.1016/j.jclepro.2017.08.007

[59] Munir Q, Abdulkareem M, Horttanainen M, *et al.* A comparative cradle-to-gate life cycle assessment of geopolymer concrete produced from industrial side streams in comparison with traditional concrete. *Sci Total Environ*. 2023;865:161230. doi:10.1016/j.scitotenv.2022.161230

[60] Martínez A, Miller SA. Life cycle assessment and production cost of geopolymer concrete: A meta-analysis. *Resour Conserv Recycl*. 2025;215:108018. doi:10.1016/j.resconrec.2024.108018

[61] Van Deventer JS, Provis JL, Duxson P. Technical and commercial progress in the adoption of geopolymer cement. *Miner Eng*. 2012;29:89-104. doi:10.1016/j.mineng.2011.09.009

[62] Martínez A, Miller SA. A review of drivers for implementing geopolymers in construction: Codes and constructability. *Resour Conserv Recycl*. 2023;199:107238. doi:10.1016/j.resconrec.2023.107238

[63] Glasby T, Day J, Genrich R, *et al.* EFC geopolymer concrete aircraft pavements at Brisbane West Wellcamp Airport. In: Concrete 2015: Proceedings of the 27th Biennial National Conference of the Concrete Institute of Australia; 2015; Melbourne, Australia. Concrete Institute of Australia; 2015. p. 1051-9.

[64] Panda B, Unluer C, Tan MJ. Extrusion and rheology characterization of geopolymer nanocomposites used in 3D printing. *Compos Part B Eng*. 2019;176:107290. doi:10.1016/j.compositesb.2019.107290

[65] Muthukrishnan S, Ramakrishnan S, Sanjayan J. In-line activation of geopolymer slurry for concrete 3D printing. *Cem Concr Res*. 2022;162:107008. doi:10.1016/j.cemconres.2022.107008

[66] Pasupathy K, Ramakrishnan S, Sanjayan J. 3D concrete printing of eco-friendly geopolymer containing brick waste. *Cem Concr Compos*. 2023;138:104943. doi:10.1016/j.cemconcomp.2023.104943

[67] Barve P, Bahrami A, Shah S. Geopolymer 3D printing: a comprehensive review on rheological and structural performance assessment, printing process parameters, and microstructure. *Front Mater*. 2023;10:1241869. doi:10.3389/fmats.2023.1241869

[68] Ricciotti L, Apicella A, Perrotta V, *et al.* Geopolymer Materials for Extrusion-Based 3D-Printing: A Review. *Polymers*. 2023;15(24):4688. doi:10.3390/polym15244688

[69] Ricciotti L, Lucariello D, Perrotta V, *et al.* Sustainable Alkali-Activated and Geopolymer Materials: What Is the Future for Italy? *Recycling*. 2025;10(4):140. doi:10.3390/recycling10040140

[70] Esparham A, Moradikhou AB, Mehrdadi N. Introduction to synthesise method of geopolymer concrete and corresponding properties. J Iran Ceram Soc. 2021;16(4):13-24.

[71] Esparham A, Vatin NI, Kharun M, *et al.* A Study of Modern Eco-Friendly Composite (Geopolymer) Based on Blast Furnace Slag Compared to Conventional Concrete Using the Life Cycle Assessment Approach. *Infrastructures*. 2023;8(3):58. doi:10.3390/infrastructures8030058

[72] Esparham, Alireza. "Investigation the Properties of Geopolymers for Use as Sustainable Materials." *Basparesh* 13.1 (2023): 65-77.

[73] Javid MN, Esparham A. A review of life cycle assessment (LCA) in quantifying environmental impacts of OPC and PFA concrete products. Civ Proj J. 2021;3(2):22-31.

[74] Esparham, Alireza. "A review of the features of geopolymer cementitious composites for use in green construction and

sustainable urban development." *Central Asian Journal of Environmental Science and Technology Innovation* 3.3 (2022): 64-74.

[75] Adnan, Anas M. Geopolymer concrete as a sustainable alternative to OPC. *J Umm Al-Qura Univ Eng Archit*. 2025;16(4):1223-45. doi:10.1007/s43995-025-00155-8

[76] Rahmadina A, Ekaputri JJ. Mechanical Properties of Geopolymer Concrete Exposed to Combustion. *MATEC Web Conf*. 2017;138:01022. doi:10.1051/matecconf/201713801022

[77] Koleżyński A, Król M, Żychowicz M. The structure of geopolymers – Theoretical studies. *J Mol Struct*. 2018;1163:465-71. doi:10.1016/j.molstruc.2018.03.033

[78] Wang YS, Alrefaei Y, Dai JG. Silico-Aluminophosphate and Alkali-Aluminosilicate Geopolymers: A Comparative Review. *Front Mater*. 2019;6:106. doi:10.3389/fmats.2019.00106

[79] Rowles M, O'Connor B. Chemical optimisation of the compressive strength of aluminosilicate geopolymers synthesised by sodium silicate activation of metakaolinite. *J Mater Chem*. 2003;13(5):1161-5. doi:10.1039/b212629j

[80] Duxson P, Provis JL, Lukey GC, *et al.* Understanding the relationship between geopolymer composition, microstructure and mechanical properties. *Colloids Surf A Physicochem Eng Asp*. 2005;269(1-3):47-58. doi:10.1016/j.colsurfa.2005.06.060

[81] Zhang Y, Sun W, Li Z. Synthesis and Microstructural Characterization of Fully-Reacted Potassium-Poly(sialate-Siloxo) Geopolymeric Cement Matrix. *ACI Mater J*. 2008;105(2):156-64. doi:10.14359/19756

[82] Bernal SA, Provis JL, Brice DG, *et al*. Accelerated carbonation testing of alkali-activated binders significantly underestimates service life: The role of pore solution chemistry. *Cem Concr Res*. 2012;42(10):1317-26. doi:10.1016/j.cemconres.2012.07.002

[83] Rashad AM. Metakaolin as cementitious material: History, scours, production and composition – A comprehensive overview. *Constr Build Mater*. 2013;41:303-18. doi:10.1016/j.conbuildmat.2012.12.001

[84] Castaldelli V, Moraes J, Akasaki J, *et al.* Study of the binary system fly ash/sugarcane bagasse ash (FA/SCBA) in SiO2/K2O alkali-activated binders. *Fuel*. 2016;174:307-16. doi:10.1016/j.fuel.2016.02.020

[85] He J, Jie Y, Zhang J, *et al.* Synthesis and characterization of red mud and rice husk ash-based geopolymer composites. *Cem Concr Compos*. 2013;37:108-18. doi:10.1016/j.cemconcomp.2012.11.010

[86] Esparham, A., and N. Mehrdadi. "Effect of combined different sources of alumina silicate on mechanical properties and carbonation depth of environmentally friendly geopolymeric composite based on metakaolin." *International Journal of Engineering, Transactions A: Basics* 36.7 (2023): 1383-97.

[87] Fernández-Jiménez A, Palomo A. Composition and microstructure of alkali activated fly ash binder: Effect of the activator. *Cem Concr Res*. 2005;35(10):1984-92. doi:10.1016/j.cemconres.2005.03.003

[88] van Jaarsveld J, van Deventer J, Lukey G. The effect of composition and temperature on the properties of fly ash- and kaolinite-based geopolymers. *Chem Eng J*. 2002;89(1-3):63-73. doi:10.1016/s1385-8947(02)00025-6

[89] Fawer M, Concannon M, Rieber W. Life cycle inventories for the production of sodium silicates. *Int J Life Cycle Assess*. 1999;4(4):207. doi:10.1007/bf02979498

[90] Mellado A, Catalán C, Bouzón N, *et al.* Carbon footprint of geopolymeric mortar: study of the contribution of the alkaline activating solution and assessment of an alternative route. *RSC Adv*. 2014;4(45):23846-52. doi:10.1039/c4ra03375b

[91] Bernal SA, Rodríguez ED, Mejia de Gutiérrez R, *et al.* Activation of Metakaolin/Slag Blends Using Alkaline Solutions Based on Chemically Modified Silica Fume and Rice Husk Ash. *Waste Biomass Valor*. 2011;3(1):99-108. doi:10.1007/s12649-011-9093-3

[92] Handayani L, Aprilia S, Abdullah, *et al.* Sodium Silicate from Rice Husk Ash and Their Effects as Geopolymer Cement. *Polymers*. 2022;14(14):2920. doi:10.3390/polym14142920

[93] Oti J, Adeleke BO, Mudiyanselage PR, *et al.* A Comprehensive Performance Evaluation of GGBS-Based Geopolymer Concrete Activated by a Rice Husk Ash-Synthesised Sodium Silicate Solution and Sodium Hydroxide. *Recycling*. 2024;9(2):23. doi:10.3390/recycling9020023

[94] Vinai R, Soutsos M. Production of sodium silicate powder from waste glass cullet for alkali activation of alternative binders. *Cem Concr Res*. 2019;116:45-56. doi:10.1016/j.cemconres.2018.11.008

[95] Bianco I, Ap Dafydd Tomos B, Vinai R. Analysis of the environmental impacts of alkali-activated concrete produced with waste glass-derived silicate activator – A LCA study. *J Clean Prod*. 2021;316:128383. doi:10.1016/j.jclepro.2021.128383

[96] Khale D, Chaudhary R. Mechanism of geopolymerization and factors influencing its development: a review. *J Mater Sci*. 2007;42(3):729-46. doi:10.1007/s10853-006-0401-4

[97] Sun Z. Reaction mechanisms of fly ash and metakaolin geopolymers and environmental compatibility [dissertation]. Aachen: RWTH Aachen University; 2020. doi:10.18154/RWTH-2020-07378

[98] Provis JL, Palomo A, Shi C. Advances in understanding alkali-activated materials. *Cem Concr Res*. 2015;78:110-25. doi:10.1016/j.cemconres.2015.04.013

[99] Ma Y, Hu J, Ye G. The pore structure and permeability of alkali activated fly ash. *Fuel*. 2013;104:771-80. doi:10.1016/j.fuel.2012.05.034

[100] Negahban E, Bagheri A, Sanjayan J. One-Year study of restrained shrinkage and creep behaviours of geopolymer concrete. *Constr Build Mater*. 2023;376:131057. doi:10.1016/j.conbuildmat.2023.131057

[101] Kong DL, Sanjayan JG. Effect of elevated temperatures on geopolymer paste, mortar and concrete. *Cem Concr Res*. 2010;40(2):334-9. doi:10.1016/j.cemconres.2009.10.017

[102] Sarker PK, Kelly S, Yao Z. Effect of fire exposure on cracking, spalling and residual strength of fly ash geopolymer concrete. *Mater Des*. 2014;63:584-92. doi:10.1016/j.matdes.2014.06.059

[103] Škvára F, Kopecký L, Němeček J, *et al.* Microstructure of geopolymer materials based on fly ash. *Ceram-Silik*. 2006;50(4):208-15.

[104] Davidovits J. Properties of geopolymer cements. In: Proceedings of the First International Conference on Alkaline Cements and Concretes; 1994; Kiev, Ukraine. Kiev: VIPOL Stock Company; 1994. p. 131-49.

[105] Lahoti M, Tan KH, Yang EH. A critical review of geopolymer properties for structural fire-resistance applications. *Constr Build Mater*. 2019;221:514-26. doi:10.1016/j.conbuildmat.2019.06.076

[106] Bakharev T. Thermal behaviour of geopolymers prepared using class F fly ash and elevated temperature curing. *Cem Concr Res*. 2006;36(6):1134-47. doi:10.1016/j.cemconres.2006.03.022

[107] Rickard WD, Temuujin J, van Riessen A. Thermal analysis of geopolymer pastes synthesised from five fly ashes of variable composition. *J Non-Cryst Solids*. 2012;358(15):1830-9. doi:10.1016/j.jnoncrysol.2012.05.032

[108] Pan Z, Sanjayan JG. Factors influencing softening temperature and hot-strength of geopolymers. *Cem Concr Compos*. 2012;34(2):261-4. doi:10.1016/j.cemconcomp.2011.09.019

[109] Sakkas K, Panias D, Nomikos P, *et al.* Potassium based geopolymer for passive fire protection of concrete tunnels linings. *Tunn Undergr Space Technol*. 2014;43:148-56. doi:10.1016/j.tust.2014.05.003

[110] Tian Y, Liu Y, Xie YM, *et al.* Coupled effects of chlorides and sulfates on steel reinforcement corrosion in concrete structures: A comprehensive review. *Case Stud Constr Mater*. 2025;22:e04263. doi:10.1016/j.cscm.2025.e04263

[111] Bakharev T. Durability of geopolymer materials in sodium and magnesium sulfate solutions. *Cem Concr Res*. 2005;35(6):1233-46. doi:10.1016/j.cemconres.2004.09.002

[112] Bakharev T. Resistance of geopolymer materials to acid attack. *Cem Concr Res*. 2005;35(4):658-70. doi:10.1016/j.cemconres.2004.06.005

[113] Kupwade-Patil K, Allouche EN. Examination of Chloride-Induced Corrosion in Reinforced Geopolymer Concretes. *J Mater Civ Eng*. 2013;25(10):1465-76. doi:10.1061/(asce)mt.1943-5533.0000672

[114] Pasupathy K, Berndt M, Sanjayan J, *et al.* Durability of low-calcium fly ash based geopolymer concrete culvert in a saline environment. *Cem Concr Res*. 2017;100:297-310. doi:10.1016/j.cemconres.2017.07.010

[115] García-Lodeiro I, Palomo A, Fernández-Jiménez A. Alkali–aggregate reaction in activated fly ash systems. *Cem Concr Res*. 2007;37(2):175-83. doi:10.1016/j.cemconres.2006.11.002

[116] Fernandez-Jimenez A, García-Lodeiro I, Palomo A. Durability of alkali-activated fly ash cementitious materials. *J Mater Sci*. 2006;42(9):3055-65. doi:10.1007/s10853-006-0584-8

[117] Fu Y, Cai L, Yonggen W. Freeze–thaw cycle test and damage mechanics models of alkali-activated slag concrete. *Constr Build Mater*. 2011;25(7):3144-8. doi:10.1016/j.conbuildmat.2010.12.006

[118] Bernal SA, Provis JL, Walkley B, *et al.* Gel nanostructure in alkali-activated binders based on slag and fly ash, and effects of accelerated carbonation. *Cem Concr Res*. 2013;53:127-44. doi:10.1016/j.cemconres.2013.06.007

[119] Scrivener KL, Juilland P, Monteiro PJ. Advances in understanding hydration of Portland cement. *Cem Concr Res*. 2015;78:38-56. doi:10.1016/j.cemconres.2015.05.025

[120] Richardson I. The calcium silicate hydrates. *Cem Concr Res*. 2008;38(2):137-58. doi:10.1016/j.cemconres.2007.11.005

[121] Beaudoin J, Odler I. Hydration, setting and hardening of Portland cement. In: Hewlett PC, Liska M, editors. Lea's chemistry of cement and concrete. 5th ed. Oxford: Butterworth-Heinemann; 2019. p. 157-250. doi:10.1016/b978-0-08-100773-0.00005-8

[122] Siyal AA, Shamsuddin MR, Khan MI, *et al.* A review on geopolymers as emerging materials for the adsorption of heavy metals and dyes. *J Environ Manage*. 2018;224:327-39. doi:10.1016/j.jenvman.2018.07.046

[123] International Organization for Standardization. ISO 14040:2006. Environmental management — Life cycle assessment — Principles and framework. Geneva: ISO; 2006.

[124] International Organization for Standardization. ISO 14044:2006. Environmental management — Life cycle assessment — Requirements and guidelines. Geneva: ISO; 2006.

[125] Yang KH, Song JK, Song KI. Assessment of CO2 reduction of alkali-activated concrete. *J Clean Prod*. 2013;39:265-72. doi:10.1016/j.jclepro.2012.08.001

[126] Luan C, Zhou A, Li Y, *et al.* CO2 avoidance cost of fly ash geopolymer concrete. *Constr Build Mater*. 2024;416:135193. doi:10.1016/j.conbuildmat.2024.135193

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