



Alkali-Activated Materials For Low-Carbon Construction: A Review

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Abstract: The construction industry accounts for nearly 8 % of global anthropogenic CO₂ emissions, primarily due to the production of Ordinary Portland Cement (OPC). To achieve carbon-neutral construction, alternative binders with low embodied energy and carbon footprints are being widely studied. Alkali-activated materials (AAMs)—including alkali-activated slag (AAS), fly ash geopolymers, and hybrid binders—are among the most promising candidates. This review provides a comprehensive synthesis of recent research on AAMs for low-carbon construction, addressing material chemistry, processing, performance, life-cycle assessment, and industrial implementation. Key findings indicate that AAMs can reduce embodied CO₂ by 40–80 % relative to OPC, while achieving comparable mechanical and durability performance under optimized curing. However, challenges remain regarding activator sustainability, precursor variability, and standardization. Future research priorities include development of one-part systems, ambient-curing formulations, and harmonized life-cycle assessment methodologies.

Keywords - Alkali-activated materials, geopolymer, low-carbon construction, sustainability, life-cycle assessment, circular economy.

1. INTRODUCTION

The built environment is central to sustainable development, yet it contributes substantially to environmental degradation. Cement manufacturing alone emits approximately **0.9 tonnes of CO₂ per tonne of clinker**, accounting for 6–8 % of global CO₂ emissions [1]. These emissions arise from both the calcination of limestone and fossil-fuel energy demand. Therefore, achieving net-zero construction requires both **process decarbonization** and **material substitution**.

Alkali-activated materials (AAMs), often referred to as geopolymers or alkali-activated binders, offer an alternative route. Instead of relying on calcium silicate hydration as in OPC, AAMs are produced by activating aluminosilicate precursors with alkaline solutions (e.g., NaOH, Na₂SiO₃), forming **N-A-S-H** (sodium aluminosilicate hydrate) or **C-A-S-H** (calcium aluminosilicate hydrate) gels. The precursors—industrial by-products such as **fly ash**, **ground granulated blast-furnace slag (GGBFS)**, or **calcined clays**—allow valorization of waste while reducing dependence on high-energy clinker [2], [3].

Research on AAMs has grown rapidly, with thousands of publications over the past decade. This review consolidates global knowledge to evaluate their viability as **low-carbon binders**, addressing five key questions:

1. What are the main types and chemistries of AAMs?
2. How do their mechanical and durability properties compare to OPC?
3. What are their environmental advantages and trade-offs?
4. What is the industrial readiness of AAMs?
5. What future research is required to scale these materials sustainably?

2. ALKALI-ACTIVATED MATERIALS: FUNDAMENTALS

2.1 Definition and Classification

AAMs are inorganic binders produced through **alkaline activation** of aluminosilicate sources. Depending on calcium content, they can be broadly classified as [4]:

- **Low-calcium AAMs (geopolymers)** – typically derived from fly ash, metakaolin; form N-A-S-H gels.
- **High-calcium AAMs (alkali-activated slags)** – derived from GGBFS; form C-A-S-H and hybrid gels.
- **Hybrid systems** – blends of slag and fly ash, balancing reactivity and workability.

The fundamental reaction mechanism involves **dissolution**, **gelation**, and **polycondensation**, producing a dense microstructure with limited capillary porosity. Figure 1 (schematic description below) outlines the main reaction pathway.

2.2 Reaction Chemistry

Activation occurs when hydroxide ions depolymerize aluminosilicate species, releasing $[\text{SiO}_4]^{4-}$ and $[\text{AlO}_4]^{5-}$ units that re-polymerize into amorphous gels. The ratio of $\text{Si}/\text{Al} > 2$ yields a more polymerized, durable network. For high-Ca systems, Ca^{2+} participates to form C-A-S-H phases analogous to C-S-H in OPC but with higher cross-linking [5].

2.3 Advantages Over OPC

- No requirement for limestone calcination → lower CO_2 .
- Use of industrial by-products → waste valorization.
- Enhanced durability (acid, sulfate, and thermal resistance).
- Rapid strength development (for slag-rich systems).
- However, challenges include activator cost, safety, and curing energy.

3. PRECURSORS, ACTIVATORS, AND MIX DESIGN PARAMETERS

3.1 Precursor Materials

Common precursors include:

Precursor	Origin	Chemical (approx.)	Composition	Remarks
Fly Ash (Class F/C)	Coal combustion residue	SiO_2 40–60 %, Al_2O_3 20–35 %, $\text{CaO} < 10$ %		Requires heat curing; widely used in geopolymer concrete.
GGBFS	Steel industry by-product	CaO 30–45 %, SiO_2 35–40 %, Al_2O_3 10–15 %		High reactivity; suitable for ambient curing.
Metakaolin	Calcined kaolinite clay	$\text{SiO}_2 \approx 55$ %, $\text{Al}_2\text{O}_3 \approx 40$ %		Consistent quality; costly precursor.
Mine tailings industrial residues	/ Mining waste	Variable; often Fe- and Si-rich		Emerging sustainable source [6].

Hybrid mixtures of fly ash + slag balance workability and early strength [7].

3.2 Alkaline Activators

Alkali activators dissolve the precursor and promote polymerization. Typical activators [8]:

- Sodium or potassium hydroxide (NaOH, KOH)
- Sodium silicate (Na_2SiO_3)
- One-part activators (dry powders containing alkali salts)

The **silicate modulus** ($M_s = \text{SiO}_2/\text{Na}_2\text{O}$) significantly influences setting and strength. Typical $M_s = 1.0\text{--}1.5$ yields optimum properties [9]. High molarity ($> 12\text{ M}$) improves dissolution but increases cost and risk.

3.3 Mix Design Variables

Important parameters include [10]:

- **Alkali dosage** (4–10 % Na_2O by binder mass)
- **Water-to-binder ratio (w/b)** $\approx 0.3\text{--}0.4$
- **Curing regime:** ambient (20–30 °C) or heat (60–80 °C)
- **Addition of fillers/recycled aggregates** to improve sustainability.

Table 2 summarizes optimal conditions reported across representative studies.

Study	Precursor	Activator	Curing	28-day Strength (MPa)
Hardjito & Rangan (2005) [11]	Fly ash	$\text{NaOH} + \text{Na}_2\text{SiO}_3$	60 °C $\times$ 24 h	55–65
Provis (2018) [4]	GGBFS	NaOH	Ambient	60–80
Nath & Adesina (2020) [12]	FA + GGBFS	$\text{Na}_2\text{SiO}_3 / \text{NaOH} = 2$	30 °C	65

3.4 Curing Effects

Heat curing accelerates geopolymerization but consumes energy. Recent research emphasizes **ambient-cure AAMs**, especially for field concretes. Inclusion of Ca-rich slag or alkali-carbonates enhances ambient strength [13].

4. MECHANICAL AND DURABILITY PERFORMANCE

4.1 Compressive and Flexural Strength

AAMs can equal or exceed OPC in strength. Typical compressive strengths range 40–80 MPa for slag-rich systems [14]. Strength development depends on precursor reactivity, curing, and activator type. Fly-ash geopolymers often require heat curing to achieve comparable performance.

Flexural strength typically reaches 4–7 MPa, and modulus of elasticity ranges 25–35 GPa [15]. Hybrid systems offer balanced workability and strength gain.

4.2 Workability and Setting

Workability is affected by activator viscosity and silicate modulus. Incorporation of superplasticizers compatible with alkaline media is under active study [16]. Setting time can vary from minutes (highly alkaline slag systems) to hours (low-Ca fly ash).

4.3 Durability Characteristics

AAMs exhibit **enhanced chemical resistance** to acid and sulfate environments due to low $\text{Ca}(\text{OH})_2$ content [17]. Chloride-penetration resistance is often superior to OPC [18].

However, **carbonation** is a concern: AAMs decalcify faster than OPC, though carbonation curing can sequester CO_2 while improving strength [19]. Shrinkage and efflorescence remain issues for high-alkali systems [20].

4.4 Microstructure and Porosity

Microstructural studies using SEM, XRD, and NMR reveal dense gel networks with refined pores (10–50 nm). Incorporation of nano-silica or fibers can further densify microstructure [21].

5. ENVIRONMENTAL AND LIFE-CYCLE ASSESSMENT

5.1 Carbon Footprint Comparison

Multiple studies have reported that the embodied CO_2 of alkali-activated materials (AAMs) is **40 %–80 % lower** than that of Ordinary Portland Cement (OPC) [22], [23]. The reduction arises primarily from the absence of limestone calcination and the utilization of industrial by-products as precursors. Table 3 presents representative life-cycle assessment (LCA) results.

Binder Type	CO_2 -eq. (kg CO_2 /t binder)	Reduction vs OPC	Notes / Source
OPC	850–900	—	Typical global average [1]
Fly-ash geopolymer	250–450	50–70 %	Requires heat curing [22]
Alkali-activated slag	300–500	40–60 %	Ambient-cure feasible [23]
Hybrid FA+GGBFS	200–400	60–80 %	Optimised logistics [24]

However, **activator production** (especially sodium silicate) can contribute up to 50 % of total embodied CO_2 if produced from virgin sources [25]. Therefore, future improvement requires decarbonized or waste-derived activators (e.g., from rice-husk ash or recycled glass).

5.2 Energy Demand and Resource Efficiency

AAM production avoids the 1450 °C clinkering step of OPC, reducing thermal energy consumption by 50–80 %. Electrical energy use, mainly for grinding and mixing, is comparable. When combined with **low-temperature curing** (< 60 °C) or **ambient curing**, total embodied energy can fall below 2 GJ/t binder, compared with ~5 GJ/t for OPC [26].

5.3 Other Environmental Indicators

Recent meta-analyses [27] show that while global warming potential (GWP) decreases strongly, certain impact categories may rise:

- **Human toxicity / ecotoxicity:** due to caustic activators.
- **Ozone depletion potential:** linked to upstream sodium silicate manufacture.
- **Water use:** modestly higher for wet-mix activator systems.

Hence, *net environmental benefit* depends on supply-chain configuration, transport distance (< 200 km preferred), and curing regime.

5.4 Circular-Economy Integration

AAM technology enables valorization of **fly ash, slag, red-mud, and mine tailings**, supporting circular-economy goals. Hybrid systems using recycled aggregates further reduce waste disposal and natural-aggregate extraction [28].

6. INDUSTRIAL IMPLEMENTATION AND CASE STUDIES

6.1 Technology Readiness

Industrial adoption has progressed from laboratory to **pilot-scale production** in several regions. According to Provis et al. [4], the technology readiness level (TRL) of AAMs is 6–8 for precast elements, and 4–6 for in-situ concreting.

Precast and block manufacturing

Companies in Australia, the UK, and China have commercialized **geopolymer precast blocks, pavers, and pipes**, benefiting from controlled curing and uniform quality [29]. Strengths of 60–70 MPa and shrinkage below 500 $\mu\epsilon$ have been achieved.

In-situ concreting

Field placement of AAM concrete remains limited because of activator handling and rapid setting. “One-part” dry-mix binders (powder activators) that require only water addition are under active development [30].

6.2 Regional Applications

- **Australia:** Large-scale fly-ash geopolymer bridge decks (e.g., Toowoomba Bridge, 2010) demonstrate long-term durability.
- **Europe:** Alkali-activated slag cements used in sewer linings and marine environments due to sulfate resistance.
- **China & India:** Pilot production lines integrating steel-slag and red-mud precursors are emerging [31].
- **Middle East:** Geopolymer tiles for high-temperature and acid-resistant environments.

6.3 Economic Viability

Cost analyses [32] reveal that AAMs can be cost-competitive with OPC ($\pm 10\%$) when precursors are locally available and activator production is optimized. However, sodium silicate cost and transport distance remain critical variables.

7. CHALLENGES, OPPORTUNITIES, AND FUTURE DIRECTIONS

7.1 Key Challenges

1. Activator Sustainability and Cost

- Sodium silicate contributes 40–60 % of total embodied energy [25].
- Research is shifting toward alternative activators: sodium carbonate, waste-glass-derived silicates, and bio-alkalis.

2. Precursor Availability and Variability

- Fly-ash supply is declining as coal power phases out.
- Chemical variability of industrial residues complicates mix standardization [33].

3. Durability Uncertainties

- Carbonation and efflorescence can reduce alkalinity.
- Long-term chloride and freeze–thaw performance data remain limited [19].

4. Standardization and Codes

- Few international standards exist (e.g., ASTM C1709-21 only provides guidelines).
- Structural design codes for AAM concretes are under development (RILEM TC 247-DTA).

5. Curing and Workability

- Some AAMs require elevated-temperature curing; practical ambient-cure systems are essential.
- Compatibility of chemical admixtures under high-pH conditions remains problematic [16].

7.2 Opportunities

- **Carbon-Neutral Construction Pathway:** Integrating AAMs with carbon-capture curing can potentially achieve net-negative CO₂ [19].
- **Digital and 3-D Printing:** AAMs' fast-setting behavior suits additive manufacturing of construction components [34].
- **Hybrid Cement Systems:** Partial replacement (30–50 %) of OPC with AAM binder enhances sustainability while retaining familiarity [35].
- **Regional Waste Utilization:** Mine tailings, rice-husk ash, and phosphogypsum present vast untapped precursor resources [6].

7.3 Future Research Directions

1. **Green Activator Development** – e.g., low-energy silicate synthesis from agricultural or glass waste.
2. **Ambient-Cure Formulations** – balancing early strength with workability.
3. **Long-Term Durability Testing** – 10- to 20-year field data to validate models.
4. **Unified Life-Cycle Methodology** – standard functional units and boundaries for fair comparison with OPC.
5. **Scale-Up Demonstration Projects** – real-world structural applications (bridges, pavements).
6. **Socio-Economic and Policy Research** – understanding market acceptance, supply-chain logistics, and code integration.

8. CONCLUSION

This review consolidates global research on **alkali-activated materials (AAMs)** as sustainable binders for low-carbon construction. The following conclusions can be drawn:

1. **Environmental Benefit:** AAMs offer 40–80 % lower embodied CO₂ than OPC, mainly by avoiding clinker calcination and utilizing industrial by-products.
2. **Performance:** Compressive strengths exceeding 60 MPa and superior chemical resistance are achievable with optimized activator systems.
3. **Durability:** Resistance to acid and sulfate attack is high, but carbonation and efflorescence require control.
4. **Implementation:** Precast applications are commercially viable; in-situ concreting needs simplification (e.g., one-part systems).
5. **Remaining Barriers:** High activator footprint, precursor variability, lack of codes, and limited long-term data constrain widespread adoption.
6. **Outlook:** Integration with circular-economy principles, renewable activators, and standardized LCA protocols will accelerate mainstream deployment of AAMs in the global transition to low-carbon construction.

9.ACKNOWLEDGMENT

We acknowledge the contributions of researchers worldwide in developing sustainable binder technologies and the datasets used for this synthesis.

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