

Green Building Materials Technology Research

Summary of Solid-Waste Geopolymer Silicon-Based Nano- Cementitious Material Technology

Composition & Structure · Performance Characteristics · Core
Advantages · Application Scenarios · Industry Bottlenecks

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Executive Summary

Emission Reduction vs. Traditional Cement	28-day compressive strength	High-temperature resistance limit	Heavy metal immobilization rate
60%–80%	55–136 MPa	1000–1200 °C	≥ 90%

CO ₂ emission reduction	Depends on raw material system	No oxidation or decomposition	Partial systems > 98%
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Geopolymer is a class of three-dimensional network inorganic polymeric cementitious materials formed by alkali-activated polycondensation using silico-aluminous solid waste as precursors. Since its proposal by French scientist Joseph Davidovits in the late 1970s, it has been regarded as one of the most promising alternative routes to Portland cement.

Huzhu Green Building has independently developed silicon-based nano-cementitious materials modified with lanthanide rare-earth salts based on geopolymer theory, which have broad application prospects in the field of solid waste resource utilization in terms of composition, reaction mechanism and performance characteristics. This report quantitatively analyzes its core advantages from five dimensions: low-carbon environmental protection, resource utilization, performance, construction efficiency, and recycling. It also systematically compares with ordinary Portland cement, and proposes development recommendations based on engineering cases, standards and policies, and industry bottlenecks.

Analysis shows that geopolymer significantly outperforms traditional cement in high-temperature resistance, acid corrosion resistance, early strength rapid hardening, and heavy metal immobilization. Production-stage carbon emissions can be reduced by 60%–80%, making it an important technological carrier for high-value utilization of industrial solid waste and low-carbon transformation of the construction industry. Meanwhile, its shrinkage control, activator cost, long-term durability data, and standard system remain key bottlenecks restricting large-scale promotion.

I. Introduction

The emergence of geopolymer is both a product of emission reduction pressure on the cement industry and a result of industrial solid waste resource utilization demand. The following first explains its industrial background and technical origin.

(I) Research Background

Concrete is the most widely used construction material globally, and its performance mainly relies on Portland cement. More than 95% of cement on the market is Portland cement system. Its production requires calcining limestone at approximately 1450 °C, which not only consumes large amounts of limestone resources and energy, but also emits pollutants such as carbon dioxide, sulfur trioxide, and dust.

From a carbon emission perspective, the cement industry is a typical sector with difficult emission reduction: global cement production accounts for approximately 5%–8% of total anthropogenic CO₂ emissions. Global cement output in 2020 was estimated at 5.9 billion tons, corresponding to over 4.8 billion tons of CO₂ emissions. Under the dual-carbon goals, the cement industry's gradual inclusion in the carbon trading system will significantly raise carbon emission costs.

From a resource perspective, China has a huge stockpile of industrial solid waste. Taking coal gangue as an example, its annual output has exceeded 700 million tons, with cumulative stockpiling exceeding 6 billion tons. Silico-aluminous solid wastes such as fly ash, ground granulated blast-furnace slag, steel slag, red mud, and tailings are also massive in volume. Traditional disposal mainly involves filling pits and roads, backfilling, and low-performance brick and tile building materials, which neither fully utilizes the silico-aluminous components nor avoids secondary pollution risks.

Driven by both "emission reduction pressure" and "solid waste consumption demand", geopolymers have entered the industrialization field of vision: they are not only a candidate route for low-carbon cementitious materials, but also a key technological path to achieve "treating waste with waste" and high-value utilization of solid waste.

(II) Definition and Origin of Geopolymer

Geopolymer is an inorganic material with cementitious properties formed by a series of chemical reactions of solid materials containing active silico-aluminate components under the

action of chemical activators. In the 1970s, Joseph Davidovits first discovered and named geopolymer, initially prepared from kaolin via alkali activation reaction. With further research, the raw material range gradually expanded from kaolin to natural minerals such as volcanic pumice and fly ash, as well as industrial waste residues.

Geopolymer can be defined from three perspectives:

1. **Preparation perspective: A chemical reaction product obtained from silico-aluminous materials such as metakaolin or fly ash combined with alkali activator through specific process treatment. Its properties are similar to ceramics, and its chemical composition is close to certain natural pozzolans.**
2. **Spatial structure perspective: A new type of high-performance inorganic polymeric material characterized by a unique three-dimensional oxide network structure.**
3. **Chemical bond perspective: An inorganic polymer skeleton formed by covalent bonding of elements such as Si and Al.**

From a material positioning perspective, geopolymer is a new type of alkali-activated cementitious material distinct from traditional Portland cement. With abundant raw material resources, low energy consumption, low pollution characteristics, and the advantage of not consuming limestone resources, it is known as "green environmental-friendly cement". The academic community generally believes that geopolymer is expected to become a key material for ecological architecture in the 21st century.

II. Material Composition and Structural Characteristics

To understand the performance advantages of geopolymer, one must first understand what it is composed of and how its bonds are formed. The following expands from three levels: raw material system, structural model, and reaction mechanism.

(I) Raw Material System

The geopolymer raw material system consists of three parts: "silico-aluminous precursor + alkali activator + functional admixture", with industrial solid waste occupying a core position.

Component Category	Typical Raw Materials	Function
Alumino-silicate precursor (natural minerals)	Kaolin, metakaolin, diatomite, K-feldspar tailings, pozzolan	Provides active SiO_2 , Al_2O_3
Alumino-silicate precursor (industrial solid waste)	Fly ash, GGBS, steel slag, coal gangue, red mud, phosphorus slag, vanadium tailings, waste glass, tailings	Provides active alumino-silicate components while consuming solid waste
Alkali activator	NaOH, KOH, water glass (sodium/potassium silicate), sodium carbonate	Provides alkaline environment, breaks Si-O and Al-O bonds and participates in skeleton construction
Hardening accelerator and corrective material	Amorphous calcium silicate, low Ca/Si ratio calcium silicate, silica fume, metakaolin	Accelerates hardening, corrects Si/Al ratio
Admixtures and reinforcements	Retarder, shrinkage-reducing agent, superplasticizer, carbon fiber, glass fiber	Adjusts setting time, inhibits shrinkage, improves workability, enhances strength and toughness

It is worth emphasizing that fly ash, coal gangue, slag, steel slag, manganese slag, construction waste powder, etc., have become main raw materials for geopolymer preparation due to their rich silicon and aluminum elements and reactive activity, achieving resource utilization of "treating waste with waste".

(II) Three-Dimensional Network Structure

The main component of geopolymer is amorphous to semi-crystalline three-dimensional aluminosilicate polymer. Its structure is similar to the linking mode of organic polymers while maintaining the basic framework of inorganic silicon-oxygen tetrahedra and aluminum-oxygen tetrahedra.

Davidovits expressed the geopolymer polymerization formula as $Mn\{-(SiO_2)_z-AlO_2\}_n \cdot wH_2O$, where M represents alkali metal elements, z represents the Si/Al ratio, and n is the degree of polymerization. According to different Si/Al ratios in the structural unit, geopolymers can be divided into three types.

Type	Structural Unit	Si/Al Ratio
Polysialate (PS)	-Si-O-Al-O-	1
Polysialate-siloxo (PSS)	-Si-O-Al-O-Si-O-	2
Polysialate-disiloxo (PSDS)	-Si-O-Al-O-Si-O-Si-O-	3

In the three-dimensional network, any two aluminum-oxygen tetrahedra cannot share the same bridging oxygen. They must individually bond with four silicon-oxygen tetrahedra via bridging oxygen (internally) or with one to three silicon-oxygen tetrahedra (on the surface). Silicon is tetravalent, making silicon-oxygen tetrahedra electrically neutral; aluminum is trivalent yet bonds with four oxygen atoms, making aluminum-oxygen tetrahedra negatively charged. It requires absorption of cations such as Na^+ , K^+ , Li^+ , Ca^{2+} , and Ba^{2+} to balance charge, ultimately making the system electrically neutral.

This structural feature has two profound implications: first, the network skeleton is mainly bonded by covalent and ionic bonds with high bond energy and strong directionality, endowing the material with high strength and high stability; second, the network voids can accommodate and bind cations and heavy metal ions, giving the material ion exchange and immobilization functions. It is widely believed in the industry that the Si-O bond energy in the geopolymer skeleton is as high as 535 kJ/mol and has directionality and resistance to rotation, which is the fundamental source of its oxidation resistance.

(III) Geopolymerization Reaction Mechanism

The formation process of geopolymer can be summarized into three core stages: dissolution, monomer reconstruction, and polycondensation:

1. **Dissolution stage:** Under the action of strong alkali activator (such as NaOH, water glass), the silico-aluminate glass phase in solid waste undergoes Si-O and Al-O bond cleavage, dissociating active silicon and aluminum ions.
2. **Monomer reconstruction stage:** The dissociated silicon and aluminum ions recombine to form oligomeric silicon-oxygen tetrahedra and aluminum-oxygen tetrahedra monomers.
3. **Polycondensation stage:** Oligomeric monomers condense by sharing oxygen atoms to form a three-dimensional network inorganic polymer structure, with alkali metal ions participating in charge balance and skeleton construction.

A more detailed mechanism model refines it into four steps: dissolution of aluminosilicate mineral powder in alkaline solution; diffusion of dissolved alumino-silicate complexes from solid particle surfaces into inter-particle spaces; gel phase formation leading to polymerization between alkali silicate solution and alumino-silicate complexes; the gel phase gradually expels remaining water and solidifies into geopolymer bulk.

According to whether the activation system contains calcium, it can be divided into calcium-containing alkali-activated system and calcium-free alkali-activated system. In the calcium-containing system, NaOH acts as a catalyst to dissolve alumino-silicate compounds, further reacts with Ca(OH)_2 to form calcium silicate and calcium aluminate minerals, and regenerates NaOH to participate in the next reaction cycle. In the calcium-free system, N-A-S-H gel is mainly formed.

Compared with the hydration reaction of Portland cement, geopolymerization has a notable feature: no other substances are lost during the reaction except dehydration, and this dehydration reaction is reversible under strong alkaline conditions — this means that geopolymer waste can be directly crushed and reused as raw material to prepare geopolymer materials again.

III. Performance Characteristics of Geopolymer Cementitious Materials

The performance advantages of geopolymer are concentrated in six aspects: mechanics, heat resistance, durability, corrosion resistance, volume stability, and immobilization capacity.

Quantitative indicators are given item by item below.

(I) Early Strength Rapid Hardening and High Strength

During geopolymerization, sol formation and dehydration reactions proceed rapidly, and the network skeleton forms easily, allowing rapid production of high-strength products. Test data show that mortar mixed with water and standard sand requires only 4 hours at 20 °C to reach approximately 70% of its final strength (about 15–20 MPa), and the 28-day compressive strength can reach 70–100 MPa.

Material System	Strength Performance
Metakaolin-based mortar	At 20 °C, reaches ~70% of final strength in 4 h; 28-day compressive strength 70–100 MPa
Fly ash-based geopolymer	28-day compressive strength 55.6–136 MPa
Smelting reduction slag-based geopolymer	28-day compressive strength 93.4 MPa
Full geopolymer concrete	14-day and 28-day compressive strengths are 30.71% and 47.59% higher than conventional concrete
Carbon fiber reinforced geopolymer	Flexural 245 MPa, tensile 327 MPa, shear 14 MPa

From a mechanistic perspective, the strength advantage of geopolymer stems from its chemical structure: geopolymer does not involve calcium silicate hydration reactions. The final product is mainly composed of ionic and covalent bonds, with van der Waals bonds as auxiliary, and its properties are similar to natural zeolite minerals. Traditional cement, by contrast, is dominated by van der Waals bonds and hydrogen bonds. Portland cement contains low-strength chemical bonds and is prone to damage and cracking under high pressure. The geopolymer structure does not rely on these low-strength bonds, thus having a higher strength ceiling.

(II) Excellent High-Temperature Resistance and Fireproof Performance

Geopolymer itself is an oxide network structure system that does not oxidize or decompose between 1000–1200 °C. Meanwhile, the dense oxide network can isolate air and protect internal substances from oxidation.

More notably, after firing at 480 °C, 580 °C and 680 °C, the strength of geopolymer cementitious materials not only did not decrease but actually increased, which may be due to high temperature promoting the formation of new mineral crystals. Related studies also show that the residual strength retention rate of three-component geopolymer paste remains above 70% at temperatures up to 900 °C.

Carbon fiber reinforced geopolymer materials also perform outstandingly at high temperatures: even in an 800 °C high-temperature environment, the material can still retain 63% of its original flexural strength.

This characteristic gives geopolymer advantages unparalleled by Portland cement in high-temperature scenarios such as non-ferrous metal casting, metallurgy, refractory materials, and fireproof components.

(III) Outstanding Durability

The excellent durability of geopolymer stems on the one hand from its stable network structure, and on the other hand from its ability to completely avoid alkali-aggregate reaction (AAR) caused by metal ion migration and aggregate reaction in ordinary cement.

Ordinary Portland cement concrete may expand by approximately 1.5 mm/m after 200 days due to alkali-aggregate reaction, which is a major safety hazard. Geopolymer, however, eliminates metal ion migration and aggregate reaction and does not expand, thus having strong resistance to natural degradation. Davidovits, after examining ancient buildings such as the Roman Colosseum, ancient Greek concrete walls, and Egyptian pyramids, found that these ancient building materials have "zeolite-like" structures, which he believed was an important reason for their ability to stand for thousands of years.

In addition, the three-dimensional network structure of geopolymer allows it to maintain structural integrity at both high and low temperatures, exhibiting good frost resistance and oxidation resistance, while also having low permeability. The corrosion rate of steel reinforcement in geopolymer concrete is also lower than in ordinary Portland cement concrete.

(IV) Excellent Chemical Corrosion Resistance

Si-O and Al-O in the geopolymer network structure are relatively difficult to react with acids (except HF) at room temperature, making them suitable for manufacturing acid-resistant materials. Multiple comparative tests have provided clear quantitative conclusions.

Test Condition	Geopolymer Performance	Ordinary Portland Cement Performance
H ₂ SO ₄ (pH=0) immersion 60 d	Mass loss ~3%	Mass loss ~63%
3% H ₂ SO ₄ solution immersion 28 d	Compressive strength loss 13%–21%	Compressive strength loss 51%
5% H ₂ SO ₄ solution	Decomposition rate only 1/12 of Portland cement	—
Seawater immersion 28 d	Strength decrease 15%	Strength decrease 44%

Under the same acidic conditions, the strength retention rate of geopolymer cementitious materials is significantly higher than that of ordinary Portland cement, and the stronger the acidity, the more obvious the advantage. Meanwhile, geopolymer cementitious materials also exhibit excellent sulfate resistance.

This performance gives it outstanding value in strong corrosion scenarios such as wastewater treatment systems, industrial flooring, coastal structures and marine engineering, tunnel segments, and salt spray environments.

(V) Volume Stability and Adjustable Thermal Expansion Coefficient

Geopolymer exhibits low high-temperature shrinkage and low expansion rate, and its expansion coefficient is adjustable. The main indicators are shown in the table below.

Indicator	Value
Linear shrinkage during hardening	Only 1/5–1/8 of ordinary cement
Shrinkage at 400 °C (potassium aluminosilicate polymer)	0.2%–1.0%
Shrinkage at 800 °C	0.2%–2.0%
Linear expansion coefficient (0–1000 °C)	$(2.1\text{--}4.5) \times 10^{-6} / ^\circ\text{C}$
Expansion coefficient adjustment range (Si/Al = 2–20)	$(4\text{--}25) \times 10^{-6} / ^\circ\text{C}$

The adjustability of the expansion coefficient has important engineering significance: when preparing composite materials, the thermal expansion coefficient of geopolymer can be adjusted to match fillers such as ceramics, steel, and copper, thereby reducing internal stress caused by different thermal expansion coefficients and improving the service life of composite materials.

(VI) Immobilization Capacity for Heavy Metals and Radionuclides

The structure of geopolymer is a "crystal-like" structure composed of cyclic molecular chains. Cyclic molecules combine to form closed cavities (cage-like), which can compartmentalize and enclose metal ions and other toxic substances within the cavities. Aluminum ions in the skeleton can also adsorb metal ions. Some studies suggest that metal ions also participate in the formation of the geopolymer structure, thus more effectively immobilizing metal ions in the system.

Immobilization Target	Immobilization Rate
Hg, As, Fe, Mn, Pb and other heavy metal ions	$\geq 90\%$
High-calcium fly ash geopolymer for Pb, Cr, Hg (dosage 0.025%/0.025%/0.01%)	$> 98\%$
Cs ⁺ , Sr ²⁺ in nuclear facility foundation solidification	$> 99\%$, structurally stable under γ -ray irradiation

Since the network skeleton remains relatively stable even under nuclear radiation and the material has excellent hydrothermal resistance, geopolymer is widely used in the solidification

and treatment of heavy metals and nuclear waste, ensuring long-term safe immobilization with no leakage risk.

(VII) Summary of Main Physical Performance Parameters

For engineering comparison and selection, the main performance parameters of geopolymer cementitious materials are summarized as follows.

Performance Dimension	Typical Indicators
28-day compressive strength	55.6–136 MPa (depending on raw material system)
Tensile strength	2–8 MPa
Flexural strength	5–10 MPa
4-hour early strength	Up to ~70% of final strength
High-temperature resistance limit	1000–1200 °C, no oxidation or decomposition
Linear shrinkage	1/5–1/8 of ordinary cement
Linear expansion coefficient	$(2.1\text{--}4.5) \times 10^{-6} / ^\circ\text{C}$ (0–1000 °C)
Heavy metal immobilization rate	$\geq 90\%$ (partial systems >98%)
CO ₂ emission	Approx. 1/10–1/5 of equal-weight cement

IV. Analysis of Core Advantages of Geopolymer Cementitious Materials

Based on the performance characteristics, this section extracts five core advantages of geopolymer from the value dimension and systematically compares them with ordinary Portland cement.

(I) Low-Carbon Environmental Protection Advantage

The low-carbon attribute of geopolymer comes from fundamental differences in production pathways. Traditional cement relies on high-temperature calcination of limestone at 1450 °C, with carbon emissions coming both from fuel combustion and from limestone decomposition

itself. Geopolymer, by contrast, uses existing solid waste materials as precursors and replaces high-temperature calcination with chemical activation, avoiding this process.

Comparison Item	Ordinary Portland Cement	Geopolymer Cementitious Material
Production energy consumption	Baseline	Approx. 1/6–1/4 of cement
CO ₂ emission (equal weight)	Baseline	Approx. 1/10–1/5
CO ₂ emission (authoritative review caliber)	Baseline	Only 20%–60%
Emission reduction by solid waste-based geopolymer	Baseline	Approx. 80%
Carbon reduction per unit volume of geopolymer concrete	Baseline	Approx. 43% (embodied carbon reduction up to 45%)
Field-measured carbon reduction	Baseline	60%–80%

减排效益的工程验证

英国 A10 公路采用地聚物注浆技术进行软弱地基快速加固，相较传统全深度重建方案减少碳排放 62.43%（约 326.7 吨二氧化碳当量）。这说明地聚物的减排效益不仅在实验室可验证，在真实工程中同样可观。

Academician Wu Zhongwei once pointed out that the energy consumption of geopolymer materials is only 1/20 of ceramics, 1/70 of steel, and 1/150 of plastics. In addition, its preparation process has no NO_x, SO₂ or CO emissions, and does not consume limestone resources.

(II) Resource and Cost Advantages

Wide range of raw material sources. The main raw materials used to prepare geopolymer are alumino-silicate compounds (natural alumino-silicate minerals, kaolin, etc.), as well as industrial slag such as blast furnace slag, steel slag, fly ash, coal gangue, waste glass, and various furnace slags. Oxygen, silicon and aluminum are the three most abundant elements in the Earth's crust, with reserves far exceeding those of metal materials.

Low cost and capable of consuming solid waste. Industrial solid waste as raw material has dual value: it not only reduces raw material costs but also finds a high-value outlet for solid waste. Taking coal gangue as an example, using the alkali activation process to prepare geopolymer materials can achieve strength 1.5 times that of traditional cement, significantly outperforming extensive utilization methods such as brick making and backfilling.

成本结构的现实约束

碱激发剂（尤其是水玻璃）价格较高，约占材料总成本的 30%—50%，这是目前地聚物经济性的主要短板；固废的收集、预处理和运输也增加了间接成本。但随着碳市场扩容、水泥行业纳入碳交易体系，碳排放成本上升将通过“碳资产”积累抵消部分生产成本。

(III) Performance and Service Life Advantages

The performance advantages of geopolymer can be summarized as "four highs, one stability, one immobilization":

1. **High strength:** The final product is mainly composed of ionic and covalent bonds, with strength significantly higher than cement. Carbon fiber reinforced systems can reach flexural strength up to 245 MPa.
2. **High temperature resistance:** Maintains structural stability at 1000–1200 °C; strength does not decrease but increases after calcination at 680 °C.
3. **Corrosion resistance:** Acid resistance, sulfate resistance, and seawater erosion resistance are significantly superior to ordinary Portland cement.
4. **High durability:** No alkali-aggregate reaction expansion risk; frost resistance, impermeability, and oxidation resistance; strong resistance to natural degradation.
5. **Volume stability:** Shrinkage is only 1/5–1/8 of ordinary cement; thermal expansion coefficient is adjustable.
6. **Strong immobilization capacity:** Heavy metal immobilization rate $\geq 90\%$; can stably immobilize radionuclides.

In terms of structural service life, the lower permeability of geopolymer means lower chloride ion intrusion rate and longer service life. Existing studies show that geopolymer concrete generally outperforms corresponding ordinary Portland cement concrete in aggressive environments, and is especially suitable for scenarios such as tunnel segments, sewage pipes, bridge piers, coastal bridges, and underwater structures.

(IV) Construction Efficiency Advantages

The rapid hardening and early strength characteristics of geopolymer directly translate into construction efficiency. At 20 °C, the material can reach 15–20 MPa strength in 4 hours, enabling rapid repair of infrastructure such as roads and airports — pedestrian access after 1 hour, vehicular traffic after 4 hours, and aircraft takeoff/landing after 6 hours.

During the 1991 Gulf War, the temporary airfield built by the US on the battlefield used geopolymer cement (Pyrament) for rapid completion and deployment, becoming a classic case of the material's military engineering value.

Field measurements also confirm this advantage: The Hangzhou Tonglu National Highway 320 maintenance project used trenchless geopolymer grouting technology. The material reached 10 MPa compressive strength in 3 h, over 20 MPa in 1 day, and traffic could be opened after 6 h. Construction efficiency was 5 times higher than traditional cement grout. Reinforcement of 1.6 km of damaged road section was completed within 48 h, with deflection values reduced by 40%.

In terms of low-temperature construction, the low-temperature special geopolymer solidifying agent developed for the Jinan deep foundation pit backfill project can still reach the 0.8 MPa strength standard at -15 °C, shortening the 7-day strength achievement time from 3 days to 1 day and saving 40% of the construction period compared with traditional lime-soil backfilling.

(V) Recycling Advantage

From the geopolymer reaction mechanism, geopolymerization is essentially a dehydration reaction between aluminosilicic acids and is reversible under alkaline conditions. Therefore, geopolymer products can be crushed and reused as raw materials for geopolymer preparation,

whereas cement cannot be reused as raw material after use. This characteristic gives geopolymer the "cradle-to-cradle" closed-loop material attribute, which can greatly save raw materials and energy and reduce environmental pollution.

(VI) Systematic Comparison with Ordinary Portland Cement

Based on the foregoing analysis, a systematic comparison between geopolymer and ordinary Portland cement is shown in the table below.

Comparison Dimension	Ordinary Portland Cement	Geopolymer Cementitious Material
Main raw materials	Limestone, clay (non-renewable)	Alumino-silicate minerals and industrial solid waste
Preparation temperature	Calcination at ~1450 °C	Chemical activation from room temp to 90 °C
Cementing mechanism	Hydration reaction (C-S-H gel)	Polycondensation (N-A-S-H 3D network)
Dominant chemical bonds	Van der Waals bonds, hydrogen bonds	Ionic bonds, covalent bonds
28-day compressive strength	Generally 30–60 MPa	55.6–136 MPa
Early strength	Slow	~70% of final strength in 4 h
High temperature resistance	Calcium compounds decompose, crack and spall at high temperature	Structurally stable at 1000–1200 °C
Acid resistance	H ₂ SO ₄ (pH=0) immersion 60 d, mass loss 63%	Mass loss only 3% under same conditions
Seawater resistance	28 d strength decrease 44%	28 d strength decrease 15%
Alkali-aggregate reaction	Expansion risk (can expand 1.5 mm/m in 200 d)	Basically eliminated
Drying shrinkage	Baseline	1/5–1/8 of baseline
Heavy metal immobilization	Limited capacity	Immobilization rate ≥90%
Recyclability	Cannot be reused as raw material after use	Can be crushed and recycled

CO ₂ emission	Accounts for ~5%–8% of anthropogenic emissions	60%–80% lower than cement
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V. Typical Application Fields

With its performance and construction advantages, geopolymers have formed practical cases in construction engineering, road emergency repair, solid waste solidification, high-temperature and corrosion-resistant engineering, precast components, and other fields.

(I) Construction Engineering and Infrastructure

In the infrastructure and construction fields, geopolymer cementitious materials are used for structural components, foundation treatment, and reinforcement and repair. An innovative repair method uses fiber composite-made externally bonded flexible panels to significantly improve the failure load and deflection of structures. Continuous fiber composite materials have been widely used in Japan, the US and other places, mainly for reinforcing buildings and damaged bridges in earthquake and hurricane-prone areas.

In terms of foundation and subgrade treatment, China Construction Eighth Engineering Division used industrial solid wastes such as casting residue powder and slag powder to prepare geopolymer cementitious materials in projects including Shenzhen Fuwai Hospital Phase III and Yanro Intelligent Connected Vehicle Industrial Park. They performed in-situ modification and solidification of engineering muck such as cohesive soil and silty clay, achieving 0.5 MPa compressive strength in 3 days and exceeding 1.0 MPa in 7 days, meeting the requirements of temporary construction platforms and artificial hard crust layers.

(II) Roads and Rapid Emergency Repair

Geopolymer plays an important role in transportation and emergency repair engineering due to its rapid hardening and early strength properties. In addition to the aforementioned National Highway 320 maintenance case, the UK A10 highway addressed pavement settlement caused by foundation voids using geopolymer grouting technology: liquid geopolymer was injected

through 1-meter grid boreholes to fill voids 1.5 meters deep below the base course, raising the pavement bearing capacity to 180% of the original design value. Construction took only 6 weeks, shortening the construction period by 80% compared with the traditional full-depth reconstruction scheme.

In geopolymer grouting applications, the material's high strength, rapid curing, and trenchless, low-interference construction method make it especially suitable for emergency repair of heavy-duty roads with high daily traffic volume where traffic cannot be long-term blocked.

(III) Solid Waste, Hazardous Waste and Nuclear Waste Solidification

After polymerization, geopolymer forms a "cage-type" structure that can efficiently immobilize most heavy metal ions. It also has excellent hydrothermal resistance and can maintain excellent structural stability for a long time in the hydrothermal environment of nuclear waste, therefore being widely used in the treatment of heavy metals and nuclear waste.

A typical case is the German BPS project, which used geopolymer cementitious materials to solidify the foundation of a nuclear waste treatment facility. Through the "cage-type" three-dimensional network structure, radioactive elements are immobilized, with heavy metal ion (e.g., Cs^+ , Sr^{2+}) immobilization rates exceeding 99%. The material remains structurally stable under γ -ray irradiation, with 28-day compressive strength reaching 80 MPa, meeting the long-term safety requirements of nuclear facilities.

In the direction of solid waste resource utilization, difficult-to-treat waste residues such as vanadium tailings, stone coal vanadium extraction tailings, and red mud are used to prepare geopolymers through combined mechanical activation and alkali activation, which not only reduces the occupation of agricultural and forestry land and the risk of water and soil pollution caused by tailings stockpiling, but also produces usable cementitious materials.

(IV) High-Temperature and Corrosion-Resistant Special Engineering

With its ability to maintain excellent structural stability in 1000–1200 °C high-temperature environments, geopolymer has found wide application in non-ferrous metal casting and

metallurgy industries, and can be used as fireproof components, industrial furnace linings, high-temperature flues and other refractory materials. In corrosion-resistant engineering, geopolymer is suitable for strong corrosion environments such as tunnel segments, sewage pipes, industrial flooring, coastal structures and underwater structures.

(V) Precast Components and Prefabricated Buildings

Geopolymer can be steam-cured or cured at room temperature, with fast mold turnover, making it very suitable for large-scale production in factory environments. Against the backdrop of the construction industry's transformation toward intelligent construction, demand for geopolymer precast components (such as pipe galleries, cable trench cover plates, and modular building units) is expected to grow rapidly. Its rapid hardening characteristic can significantly shorten demolding time, accelerate formwork turnover, and thus increase factory production capacity.

(VI) Aviation, Automotive and Art Decoration

In the aviation field, geopolymer-based composites are used in cargo aircraft cabins, ceilings, floor panels and sidewalls, as well as wire insulation, with 2,500–3,000 kg of composite material produced to date. In the automotive field, the Benetton F1 racing team used geopolymer composites to make thermal barriers in 1994–1995, winning championships for two consecutive years under conditions of severe vibration and temperatures above 700 °C. It remains favored by many F1 racing teams to this day.

In the art and decoration field, geopolymer products look similar to natural stone and are easy to shape, being widely used in art and decorative products. In addition, grain silos built with geopolymer have low maintenance costs, self-regulating temperature and humidity functions, no dampness reversion, and can inhibit mold growth. Their high-strength properties can also prevent rodent infestation.

VI. Standards and Policy Environment

The lack of standards was long a major obstacle to geopolymer promotion, but this situation is changing rapidly in recent years.

(I) Domestic Standard System

China's standard system for solid waste-based cementitious materials and geopolymers is rapidly improving, forming a parallel pattern of national standards, industry standards, group standards and local standards.

Standard No.	Standard Name	Status and Implementation Date
GB/T 28294-2024	Steel Slag Composite Material	Current, effective 2025-01-01
T/CECS 10400-2024	Solid Waste-Based Cementitious Material	Current, effective 2024-12-01
T/CECS 1943-2025	Technical Specification for Application of Solid Waste-Based Cementitious Material Concrete	Current, effective 2025-11-01
T/CECS 689-2020	Technical Specification for Application of Solid Waste-Based Cementitious Material	Current
JC/T 2956-2026	Solid Waste-Based Cementitious Material for Road	To be implemented, 2026-09-01
Industry Standard (for comments)	Technical Specification for Application of Solid Waste-Based Cementitious Material	Open for comments 2025-10
T/SXHZ 003-2025	Coal-Based Solid Waste Cementitious Material	Current
T/XJCETS 016-2025	Standard Technical Guideline for Preparation of Geopolymer from Industrial Solid Waste	Current

Among them, T/XJCETS 016-2025 established the first full-process standard for industrial solid waste geopolymers, covering the entire chain of raw materials, preparation, testing and application. It specifies thresholds such as total alumino-silicate content $\geq 70\%$, amorphous

phase $\geq 50\%$, and loss on ignition $\leq 8\%$ for raw materials. It stipulates that the compound activator has a modulus of 1.2–1.8 and alkali equivalent of 4%–8%, and mandates heavy metal leaching limits and carbon emission $\leq 200 \text{ kgCO}_2/\text{m}^3$ requirements. It is an important standard progress under the "dual-carbon" policy orientation.

(II) International Standard Progress

At the international level, ASTM C1948/C1948M-24 Standard Specification for Alkali-Activated Cementitious Materials has been released and implemented, and ASTM C1697-25a Standard Specification for Blended Supplementary Cementitious Materials has also been updated, providing an international reference for the standardized application of alkali-activated cementitious materials.

(III) Policy and Market Drivers

On the policy side, the inclusion of the cement industry in the carbon trading system under the dual-carbon goals will significantly raise carbon emission costs. Geopolymer technology can offset its production costs by accumulating "carbon assets", helping enterprises gain competitive advantages in the future carbon pricing system. The promotion of the construction industry's transformation toward intelligent construction and green low-carbon during the "15th Five-Year Plan" period has also created clear market space for geopolymer precast components and green building materials.

VII. Main Problems and Challenges

Although geopolymer has significant advantages, there is still a clear distance from large-scale replacement of Portland cement. Objectively sorting out its bottlenecks helps to formulate more targeted technical routes.

(I) Technical and Performance Bottlenecks

From the material itself, the following eight problems are most prominent:

1. **Large raw material composition fluctuation:** The chemical composition of industrial waste slag is greatly affected by upstream processes, leading to geopolymer performance fluctuations. More advanced online detection and dynamic proportioning technology is needed.
2. **Shrinkage and cracking risk:** Some geopolymer materials have large drying shrinkage, which may cause cracking, especially in mass structures. Shrinkage-reducing agents or fiber toughening measures are needed.
3. **Alkali-aggregate reaction risk:** High-concentration alkaline environment may trigger alkali-aggregate reaction, posing challenges to long-term durability.
4. **High brittleness:** Needs improvement through fiber reinforcement and toughening. Currently, flexural strength can be increased to over 8 MPa through composite modification.
5. **Dependence on high-temperature curing:** Some systems require high-temperature curing at 60–90 °C to achieve optimal strength, increasing energy consumption and equipment investment.
6. **Poor workability:** Fresh paste has low workability due to high viscosity of the activator solution, often requiring superplasticizers, further raising costs.
7. **Insufficient long-term data:** Measured long-term durability data for 20–30+ years is limited. Carbonation, freeze-thaw cycling, chloride ion penetration and creep behavior still require in-depth research.
8. **Batch stability:** Scaling up from laboratory to industrial production, maintaining quality consistency and process controllability remains a challenge.

(II) Economic Constraints

The main economic constraints include four items:

- **High activator cost:** Alkali activators (especially water glass) account for approximately 30%–50% of total material cost. Potassium-based activators are even more expensive, directly weakening cost competitiveness relative to cement.

- **Safety and equipment investment:** Strong alkali activators are highly corrosive, requiring special equipment and strict safety protection, increasing operating costs and complexity.
- **Activator's own environmental footprint:** The production process of activators such as water glass itself has high energy consumption. Developing greener, low-cost solid activators or natural mineral activators is a future research challenge.
- **Transportation costs and geographic mismatch:** Industrial waste slag production is concentrated in heavy industrial areas such as North China and Northwest China, while regions with large building material demand are on the eastern coast, increasing logistics costs and transportation carbon emissions.

(III) Standards and Industrialization Obstacles

Although the standard system is improving, in bidding, quality acceptance and other links, geopolymers are still often regarded as an "unconventional material", lacking unified pricing basis and policy-mandated application requirements. Design codes and test methods are mostly based on ordinary Portland cement systems, and engineers, contractors and regulators face uncertainty when adopting it. The industry has strong path dependence, and building trust in new materials still takes time. Meanwhile, full-process economic analysis (covering raw materials, activators, curing energy consumption, labor, maintenance and full-life-cycle performance) is still insufficient, leading to low industrial investment willingness.

VIII. Development Recommendations

Based on the above analysis, the following four aspects of recommendations are proposed:

1. **Break through performance shortcomings through composite modification:** Improve problems such as high brittleness, large shrinkage and poor workability through fiber reinforcement and toughening, shrinkage-reducing agent shrinkage control, and compound activator setting time optimization. Meanwhile, develop room-temperature curing systems to reduce dependence on high-temperature curing.

2. **Ensure product stability through raw material homogenization: Establish online detection and dynamic proportioning mechanisms for solid waste raw materials. Perform calcination activation pre-treatment for low-activity raw materials such as coal gangue and red mud, and control fineness by grinding fly ash and slag to specific surface area $\geq 400 \text{ m}^2/\text{kg}$, reducing batch fluctuation from the source.**
3. **Lower economic thresholds with low-cost green activators: Develop low-alkali alternatives, solid activators and natural mineral activators. Explore self-production of water glass using waste such as waste glass, and promote a reduction in activator cost proportion.**
4. **Promote market acceptance through standards and demonstration projects: Actively participate in the formulation of standards related to solid waste-based geopolymers. Demonstrate first in scenarios with high requirements for early strength rapid hardening and relatively loose requirements for long-term data, such as municipal roads, foundation pit backfilling, and emergency repair projects. Gradually accumulate engineering performance and durability data, then extend to structural engineering.**

IX. Conclusion

1. Geopolymer cementitious materials are a class of three-dimensional network inorganic polymeric materials formed by alkali-activated polycondensation using silico-aluminous solid waste as precursors. Their structure takes silicon-oxygen tetrahedra and aluminum-oxygen tetrahedra as basic units, with covalent and ionic bonds as the main bonding forces. This is the physicochemical root of their high strength, high stability and high durability.
2. At the performance level, geopolymer presents distinct characteristics of "early strength rapid hardening, high strength, high temperature resistance, corrosion resistance, high durability, volume stability, and strong immobilization": 4-hour strength can reach approximately 70% of final strength, 28-day compressive strength can reach 55.6–136 MPa; no oxidation or decomposition at 1000–1200 °C; mass loss only 3% after 60 days of H_2SO_4

(pH=0) immersion; linear shrinkage only 1/5–1/8 of ordinary cement; heavy metal immobilization rate $\geq 90\%$.

3. At the advantage level, the core value is concentrated in three points: first, low-carbon environmental protection, with production energy consumption approximately 1/6–1/4 of cement and carbon emissions reduced by 60%–80%; second, outstanding resource utilization attributes, capable of large-scale consumption of industrial solid wastes such as fly ash, coal gangue, slag, steel slag, red mud and tailings; third, obvious advantages in construction efficiency and application scenarios, with rapid hardening and early strength supporting rapid road and airport repair, and high temperature and corrosion resistance opening up incremental markets in metallurgy, refractories and marine engineering.
4. At the bottleneck level, alkali activator cost accounting for 30%–50% of total material cost, drying shrinkage and brittleness, raw material composition fluctuation, insufficient long-term durability data, and imperfect standard and pricing systems are the main factors restricting large-scale promotion.
5. Comprehensively judging, geopolymers cementitious materials already have engineering implementation conditions in scenarios such as road engineering, foundation pit and foundation treatment, emergency repair engineering, precast components, hazardous waste and nuclear waste immobilization. It is an important technological carrier for solid waste resource utilization and low-carbon transformation of the construction industry. With the maturation of composite modification technology, breakthroughs in low-cost activators, and improvement of the standard system, its application boundary for replacing Portland cement is expected to continue expanding.

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