INTERNATIONAL JOURNAL OF ENGINEERING MANAGEMENT AND SOCIAL SCIENCES (IJEMSS)

e-ISSN : 3139-065X

www.ijemss.com

editor@ijemss.com

Vol. 01, Issue 3, July2026, pp :211-234

Multi-Waste Geopolymer Binders for Low-Carbon Construction: A Consolidated Review, Cross-Study Synthesis and Policy Roadmap Integrating Mining Residues, Volcanic Pozzolans and Post-Consumer Glass

[1]Dr. Raghuveer Narsing

[1]Department of Civil Engineering, Guru Nanak Institutions Technical Campus, Telangana, India

raghuveer.raghu9@gmail.com

DOI: https://doi.org/10.5281/zenodo.21259621

ABSTRACT

The construction sector remains one of the most carbon-intensive branches of the global economy, and Portland cement clinker is consistently identified as the single largest contributor within that footprint. Over the last decade, geopolymer binders synthesized from industrial and post-consumer waste streams have moved from laboratory curiosity toward a credible structural alternative, yet the literature on the subject remains fragmented: individual studies typically examine one waste stream, one activator chemistry, or one durability mechanism in isolation. This paper consolidates three recent, methodologically distinct experimental investigations (i) a mechanical and durability assessment of geopolymer concrete incorporating coal-mine bottom ash, copper slag, demolition waste and manufactured sand [1]; (ii) a carbon-accounting and cost comparison of Ecuadorian pumice-based geopolymer pastes against General-Use Portland cement, including silica-fume and brick-dust mineral additions [2]; and (iii) a fusion-condition study on sodium silicate synthesized from waste glass powder and its effect on binary fly-ash/slag geopolymer mortar strength [3] into a single, cross-referenced narrative. Beyond summarizing and re-plotting the reported findings in a common analytical frame, this work contributes an original synthesis in four respects. First, it proposes a unified Sustainability–Performance Map that positions every reported mix from the three studies on comparable axes of mechanical performance and environmental benefit, exposing trade-offs that are invisible when each paper is read in isolation. Second, it proposes a conceptual, technology-agnostic framework a Unified Multi-Waste Precursor Database coupled with an AI-assisted mix-optimization module and a blockchain-based digital carbon passport that is not described in any of the source studies and is offered here as a direction for future toolchain development. Third, it discusses the societal, regulatory and pedagogical gaps that keep laboratory-proven low-carbon binders from reaching mainstream construction practice, including concrete recommendations for revising civil-engineering curricula and building codes. Fourth, it proposes an expanded future research agenda spanning long-term durability, life-cycle-assessment standardization, and policy incentives. The consolidated evidence indicates that mineral-waste-enriched geopolymer systems can simultaneously reduce water absorption by roughly a third, improve acid resistance to near-total strength retention, and cut cradle-to-gate CO2 emissions by approximately 12–70% relative to conventional cement systems, while remaining within a realistic cost envelope for non-structural and semi-structural applications. The paper closes with an extended discussion of the institutional and policy changes needed to translate these laboratory gains into large-scale decarbonization of the built environment.

Index Terms— *Geopolymer concrete, coal mine bottom ash, copper slag, demolition waste, pumice, silica fume, brick dust, waste glass, sodium silicate, carbon footprint, life-cycle assessment, circular economy, sustainable construction policy, engineering education.*

I. Introduction

Cement manufacture is widely reported to generate on the order of one tonne of carbon dioxide for every tonne of clinker produced, and the cement-and-concrete value chain is commonly cited as accounting for roughly seven to eight percent of anthropogenic CO2 emissions worldwide [2],[4],[5]. Because concrete is, by volume, the most consumed man-made material on Earth, even marginal percentage reductions in its carbon intensity translate into very large absolute emission savings. This reality has pushed geopolymer chemistry -- alkali-activated aluminosilicate binders that avoid high-temperature clinkering altogether -- from a niche academic topic into a mainstream research priority across civil engineering, materials science and environmental-policy communities.

A geopolymer binder forms when a solid aluminosilicate precursor (commonly fly ash, ground granulated blast-furnace slag (GGBS), metakaolin, volcanic pumice, or various industrial and post-consumer wastes) is activated by a concentrated alkaline solution, typically a combination of sodium hydroxide (NaOH) and sodium silicate (Na2SiO3). Activation dissolves the amorphous silica and alumina content of the precursor, which then re-polymerizes into a three-dimensional sodium (or calcium) alumino-silicate hydrate gel network, commonly abbreviated N-A-S-H or C-A-S-H depending on the calcium content of the precursor. This gel is chemically and structurally distinct from the calcium-silicate-hydrate (C-S-H) gel that gives ordinary Portland cement its strength, and it tends to be markedly

INTERNATIONAL JOURNAL OF ENGINEERING MANAGEMENT AND SOCIAL SCIENCES (IJEMSS)

e-ISSN : 3139-065X

www.ijemss.com

editor@ijemss.com

Vol. 01, Issue 3, July2026, pp :211-234

more resistant to acid attack and sulfate attack, while remaining comparable to, or in several reported cases superior to, Portland cement in compressive strength.

Despite roughly two decades of sustained academic interest, geopolymer technology has not achieved anything resembling the market penetration of Portland cement. Three practical obstacles recur throughout the literature and are directly relevant to the three studies synthesized in this paper. The first is precursor variability: unlike clinker, which is manufactured to a tightly controlled specification, waste-derived precursors such as bottom ash, slag, pumice or glass cullet vary in composition from source to source and even from batch to batch, complicating standardized mix design. The second is activator cost and hazard: sodium silicate solution manufacture is itself energy-intensive, and concentrated sodium hydroxide is a regulated, corrosive, hygroscopic chemical whose handling and transport can dominate total production cost [6]. The third is the near-absence of unified structural design codes: most national and international concrete standards were written around Portland cement chemistry, and geopolymer concrete lacks an equivalent, universally adopted structural design code, discouraging engineers and regulators from specifying it for load-bearing applications.

This paper addresses these obstacles indirectly, by consolidating three recent and complementary experimental investigations, each attacking a different facet of the geopolymer sustainability problem, and by adding original cross-study synthesis, a novel conceptual framework, and an extended policy discussion that none of the individual source studies attempted. Study I evaluated a mineral-waste-rich geopolymer concrete formulated from coal-mine bottom ash (CMBA), copper slag (CS), construction-and-demolition waste (DW) and manufactured sand, characterizing fresh, mechanical, microstructural and acid-durability performance across six mix designs [1]. Study II compared the cradle-to-gate carbon footprint, production cost and acid durability of an Ecuadorian pumice-based geopolymer paste -- including variants enriched with silica fume and recycled brick dust -- against General-Use (Type GU) Portland cement [2]. Study III examined how the fusion temperature and duration used to synthesize sodium silicate from waste glass powder affects the phase structure, solubility and eventual mechanical strength of a binary fly-ash/GGBS geopolymer mortar, benchmarking the waste-derived activator against commercial sodium silicate [3].

Individually, each of these three studies makes a useful but narrow contribution. Read together, however, they trace almost the entire life cycle of a geopolymer binder system: precursor sourcing and waste valorization (Study I), whole-system carbon and cost accounting (Study II), and activator-chemistry optimization (Study III). No existing publication known to the present authors has attempted to place these three classes of finding on a common analytical footing. That is the central purpose of this paper. Beyond summarizing and re-analyzing the reported data, we propose an original cross-study Sustainability-Performance Map (Section V), a conceptual Unified Multi-Waste Precursor Database with an AI- and blockchain-assisted mix-design framework (Section VI) that is absent from all three source studies, and a substantially expanded discussion of the educational and regulatory changes required to move this technology out of the laboratory (Sections VIII-X).

The remainder of the paper is organized as follows. Section II reviews the broader literature context. Section III synthesizes the materials used across the three studies into a single comparative framework. Section IV consolidates the mix-design and testing protocols. Section V presents re-analyzed mechanical, microstructural and durability results, including newly generated comparative figures. Section VI proposes the novel unified framework and identifies specific novelty gaps that it addresses. Section VII discusses the combined findings critically. Section VIII examines the societal and industrial reality of construction-sector decarbonization. Section IX proposes concrete amendments to engineering education. Section X discusses government policy duties and instruments. Section XI outlines future research directions, and Section XII concludes the paper.

II. Related Work and Literature Context

The idea of activating aluminosilicate waste with alkaline solutions traces back to Davidovits' foundational description of geopolymer chemistry, which established the terminology and basic reaction mechanism still used across the field [7],[8]. Research since then has broadly split into three streams that map closely onto the three studies consolidated here.

A. Mineral-Waste Aggregates and Fillers in Geopolymer Concrete

A substantial body of work has investigated single waste streams as partial replacements for natural fine or coarse aggregate in geopolymer concrete. Coal bottom ash has been shown to improve strength development when blended with fly ash and GGBS in binary or ternary systems, acting as both a micro-filler and, at fine particle sizes, a marginal contributor to binder chemistry [9]. Copper slag, owing to its high specific gravity, angularity and low water absorption, has repeatedly been reported to densify concrete when used as a coarse- or fine-aggregate replacement, at some cost to workability because of its angular particle shape [10],[11]. Construction-and-demolition waste as coarse aggregate has produced more mixed results, generally described as technically feasible but requiring

INTERNATIONAL JOURNAL OF ENGINEERING MANAGEMENT AND SOCIAL SCIENCES (IJEMSS)

e-ISSN : 3139-065X

www.ijemss.com

editor@ijemss.com

Vol. 01, Issue 3, July2026, pp :211-234

supplementary reinforcement to meet higher-grade strength targets [12]. Ceramic tile waste, glass cullet and recycled concrete powder have each been explored individually with broadly similar conclusions: waste aggregates can work, but rarely deliver uniformly positive effects across workability, strength and durability at once, which motivates studies -- such as Study I in this synthesis -- that combine multiple waste streams and examine their interactions [1],[13],[14].

B. Carbon Accounting and Techno-Economic Assessment of Geopolymers

A second literature stream focuses less on mechanical performance and more on whether geopolymer concrete actually delivers the emissions reduction that is often assumed. Life-cycle assessment (LCA) studies using Intergovernmental Panel on Climate Change (IPCC) emission-factor methodology have repeatedly found that geopolymer pastes reduce CO2 emissions relative to Portland cement, but the magnitude of the reduction is highly sensitive to the alkalinity and quantity of activator used, because sodium silicate manufacture is itself energy-intensive [2],[15],[16]. Several studies note that activator cost can represent up to roughly 85% of total geopolymer production cost, meaning environmental and economic optimization frequently pull in the same direction: minimizing activator dosage and molarity while still achieving acceptable strength [2],[17]. Life-cycle assessments using tools such as the Leopold impact matrix and SimaPro databases have reported substantially better environmental-impact scores for geopolymer than for Type GU Portland cement, reinforcing the case for wider adoption once cost and performance gaps are closed [18],[19].

C. Alternative and Waste-Derived Alkaline Activators

The third stream, most directly relevant to Study III, investigates whether the sodium silicate activator itself can be produced from waste rather than virgin quartz sand and soda ash. Commercial sodium silicate is conventionally fused at 1200-1400 degrees Celsius, a process that is more energy-intensive on a per-kilogram basis than even clinker production [20],[21]. Because waste glass is chemically similar to quartz (commonly 70-75% SiO2) and is generated in vast quantities -- on the order of 130 million tonnes annually worldwide, a large share of which ends up landfilled rather than recycled [3],[22],[23] -- several groups have investigated low-temperature alkali fusion (roughly 300-650 degrees Celsius) of waste glass powder with NaOH as a substitute synthesis route [3],[24],[25],[26]. Reported outcomes vary with fusion temperature, duration and the specific glass source, generally showing a trade-off between silicate crystallinity (which increases with fusion temperature and reduces reactivity) and fresh-state workability (which tends to improve as reactivity decreases) [3],[24].

Positioned against this backdrop, the three studies synthesized in the present paper are complementary rather than overlapping: Study I addresses precursor- and aggregate-side waste valorization at the concrete scale, Study II addresses whole-system carbon and cost accounting at the paste scale, and Study III addresses activator-side waste valorization at the mortar scale. None of the three individually closes the loop between waste-derived precursor, waste-derived activator and system-level carbon and cost accounting. That gap is the central motivation for the cross-study synthesis undertaken in Sections V and VI.

III. Comparative Materials Framework

Table I consolidates the principal precursor, aggregate and activator materials examined across the three source studies, alongside their key characterization parameters as reported. Placing them side by side, which none of the original papers attempted, makes clear how differently "waste" is defined and sourced across the geopolymer literature -- spanning thermal-power-plant residues, metallurgical slag, construction debris, volcanic rock, silicon-alloy by-products, fired-clay waste and post-consumer container glass.

Table I. Comparative Overview of Waste and Natural Precursors Used Across the Three Consolidated Studies

Study	Material	Typical Role	Key Reported Property	Origin
I [1]	Coal Mine Bottom Ash (CMBA)	Partial fine-aggregate replacement / micro-filler	Specific gravity 2.20; ~600 um particle size; SiO2 46.7%, Al2O3 18.5%, CaO 17.9%	Thermal power plant, Raichur, India
I [1]	Copper Slag (CS)	Partial/full coarse-aggregate replacement	Specific gravity 3.54; angular, 16-20 mm particles; high Fe content	Metallurgical refinery, Tuticorin, India
I [1]	Demolition Waste (DW)	Coarse aggregate	Specific gravity 2.4; particles up to 20 mm	Local construction debris

INTERNATIONAL JOURNAL OF ENGINEERING MANAGEMENT AND SOCIAL SCIENCES (IJEMSS)

e-ISSN : 3139-065X

www.ijemss.com

editor@ijemss.com

Vol. 01, Issue 3, July2026, pp :211-234

Study	Material	Typical Role	Key Reported Property	Origin
I [1]	Manufactured Sand (M-Sand)	Primary fine aggregate	Specific gravity 2.65; fineness modulus 2.8	Quarry, Bangalore, India
I [1]	Fly Ash / GGBS	Alumino-silicate binder source (1:1)	Class F fly ash; GGBS CaO 37.8% (latent hydraulic)	Raichur Thermal Power Plant
II [2]	Pumice Stone (PS)	Primary geopolymer precursor	Amorphous, high SiO2/Al2O3, volcanic origin	Cotopaxi quarry, Ecuador
II [2]	Silica Fume (SF)	Mineral addition (reactivity booster)	Ultrafine amorphous SiO2 by-product	Ferrosilicon/silicon alloy production
II [2]	Brick Dust (BD)	Partial pumice substitute	Calcined aluminosilicate, moderate reactivity	Recycled fired-clay brick waste
III [3]	Waste Glass Powder (WGP)	Feedstock for glass-derived sodium silicate (GSS)	SiO2 70.08%, Na2O 12.41%; 94.8% amorphous	Post-consumer container/cullet glass
III [3]	GGBS / Fly Ash	Binary binder for mortar	GGBS density 2.92 g/cm3; fly ash 2.36 g/cm3	South African supply chain

Two observations emerge from this consolidated table that are not discussed in any single source paper. First, every precursor examined across the three studies is a by-product of an existing industrial process -- power generation, metal refining, construction demolition, quarrying, silicon-alloy manufacture, or glass recycling -- meaning that geopolymer research is, in effect, industrial-symbiosis research: it succeeds or fails depending on the availability, consistency and transport distance of a nearby waste stream, not on the existence of a purpose-designed raw-material supply chain. Second, the chemical roles played by these materials cluster into three functional categories that recur regardless of geography: (a) alumino-silicate binder precursors that participate directly in gel formation (fly ash, GGBS, pumice, calcined brick dust), (b) inert-to-semi-reactive fillers and aggregates that influence density, packing and durability without extensively dissolving (CMBA, copper slag, demolition waste, manufactured sand), and (c) activator-side materials that supply the alkalinity required to trigger dissolution (NaOH, commercial or waste-glass-derived sodium silicate). This functional taxonomy, proposed here as an organizing principle rather than reported in any of the three papers individually, is the conceptual basis for the Unified Multi-Waste Precursor Database introduced in Section VI.

IV. Consolidated Experimental Methodology

Although the three studies were conducted independently, in different countries, with different equipment, their testing methodologies converge around a common core: standardized specimen casting, thermal or ambient curing, mechanical testing (compressive, flexural and/or split-tensile strength) at multiple curing ages, microstructural imaging, and an acid- or water-based durability assay. Table II summarizes the specimen geometries, curing regimes and standards referenced in each study, which is useful for any reader attempting to reproduce or extend this work, since cross-study comparison is only meaningful once the differences in testing protocol are made explicit.

Table II. Consolidated Specimen and Testing Protocol Comparison

Parameter	Study I (GPC) [1]	Study II (Paste) [2]	Study III (Mortar) [3]
Compressive specimen	100 mm cubes (IS 516:1959)	40x40x160 mm prisms (NTE INEN / ASTM C109)	40x40x160 mm prisms (SANS 50196-1)
Flexural specimen	100x100x500 mm prisms (IS 516 Part 2)	40x40x160 mm prisms (EN 196-1)	40x40x160 mm prisms (SANS 50196-1)
Split tensile	150x300 mm cylinders (IS 5816:1999)	Not evaluated	Not evaluated
Curing regime	Ambient, tested at 7/14/28	24 h at 60-110C then	80C for 24 h then ambient;

INTERNATIONAL JOURNAL OF ENGINEERING MANAGEMENT AND SOCIAL SCIENCES (IJEMSS)

e-ISSN : 3139-065X

www.ijemss.com

editor@ijemss.com

Vol. 01, Issue 3, July2026, pp :211-234

Parameter	Study I (GPC) [1]	Study II (Paste) [2]	Study III (Mortar) [3]
	days	ambient / lime-saturated water; up to 28 days (14 days for BD mix)	tested at 7/28 days
Durability assay	5% H2SO4 immersion, 28 days (IS 526)	Diluted HNO3, pH 2, 120 hours mass-loss	Not evaluated in this fusion study
Microstructure	SEM + EDX (Hitachi S-3500N)	SEM (post acid attack)	XRD + SEM + EDS + pH of activator
Primary variable studied	CMBA / CS / DW replacement ratio	Activator molarity and mineral addition (SF, BD)	Fusion temperature (500-650C) and duration (2-3 h)

This side-by-side protocol comparison surfaces a methodological limitation that is easy to overlook when each paper is read alone: none of the three studies used an identical specimen geometry, curing schedule or acid-exposure protocol, which means that raw numerical values (for example, compressive strength in MPa) cannot be compared across studies without normalization. Section V therefore expresses cross-study comparisons using percentage change relative to each study's own internal control mix, and introduces a normalized 0-10 index for the novel Sustainability-Performance Map, rather than comparing raw MPa or raw kg-CO2 values directly across studies.

V. Results and Comparative Analysis

A. Mechanical Performance of Mineral-Waste-Enriched Geopolymer Concrete (Study I)

Across the six mix designs examined in Study I, the mix containing 40% CMBA as a fine-aggregate replacement (M3) consistently delivered the strongest mechanical performance, with compressive, split-tensile and flexural strength gains of roughly 22.9%, 27.1% and 28.4% respectively over the plain demolition-waste/M-sand reference mix M1 [1]. A more moderate CMBA dosage of 20% (mix M2) still produced double-digit gains across all three strength metrics, while copper-slag-only substitution (M4) produced comparatively small gains at 28 days, consistent with copper slag's angular, largely inert particle behavior acting more as a densifying filler than as a reactive binder component. The combined CMBA-plus-copper-slag mixes (M5, M6) achieved intermediate-to-strong gains, with M5 (20% CMBA + 20% CS) nearly matching M3's performance, illustrating a synergistic rather than purely additive relationship between a reactive micro-filler (CMBA) and a dense mechanical anchor (copper slag). Fig. 1 re-plots these percentage gains in a single comparative chart.

Fig. 1. Strength gain of CMBA/Copper-Slag Geopolymer Concrete Mixes relative to the reference mix M1 (Study I)

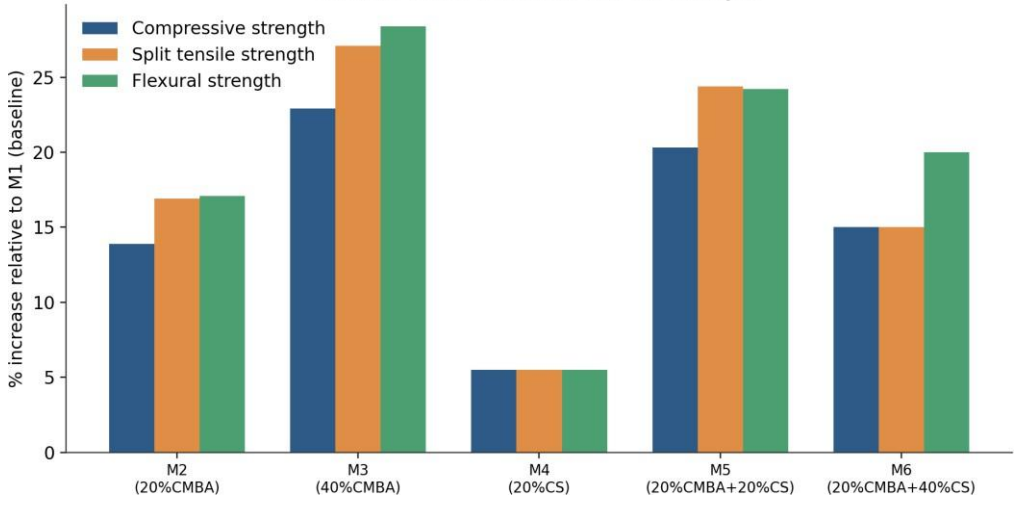


Fig. 1. Percentage strength gain of five CMBA/copper-slag geopolymer concrete mixes relative to the reference mix M1 (Study I) [1].

Microstructural imaging (SEM/EDX) corroborated the mechanical trend: mixes M3 and M6 exhibited the densest,

INTERNATIONAL JOURNAL OF ENGINEERING MANAGEMENT AND SOCIAL SCIENCES (IJEMSS)

e-ISSN : 3139-065X

www.ijemss.com

editor@ijemss.com

Vol. 01, Issue 3, July2026, pp :211-234

most crosslinked gel matrices with minimal residual porosity, while the CMBA-free control mix M1 retained visibly larger unreacted fly-ash and GGBS particles and weaker interfacial bonding at the aggregate-matrix boundary [1]. Energy-dispersive X-ray analysis showed a declining calcium-to-silicon ratio and rising silicon-to-aluminum ratio moving from M1 toward M3 and M6, consistent with a shift from a calcium-dominated gel toward a more fully polymerized sodium alumino-silicate hydrate network, which is generally associated with improved chemical stability.

B. Durability: Water Absorption and Acid Resistance (Study I)

Water absorption fell steadily as CMBA and copper-slag content increased, from 6.8% in the unmodified reference mix to 4.5% in the most heavily substituted mix M6, a reduction of roughly 34% attributable to improved particle packing and a denser, less permeable matrix [1]. Resistance to a 5% sulfuric acid environment followed a related but not identical trend: compressive-strength retention after 28 days of acid exposure ranged from about 82% for the reference mix up to 98% for M6, which combined 20% CMBA with 40% copper slag. This finding is significant because it decouples two properties that are frequently assumed to move together: M3 (maximum CMBA, no copper slag) achieved the highest strength gain but only moderate acid-strength retention (about 90%), whereas M6 (lower CMBA but higher copper slag) achieved slightly lower mechanical strength gain yet the best acid resistance of all six mixes. This suggests that copper slag's angular, chemically inert particles are disproportionately valuable for chemical durability rather than for raw strength -- a distinction that is easy to overlook if only compressive strength is reported, and one of the clearer illustrations in this dataset of why durability and strength should be optimized as a joint objective rather than treated as proxies for one another.

Fig. 2. Water Absorption and 28-Day Acid Strength Retention Across GPC Mixes (Study I)

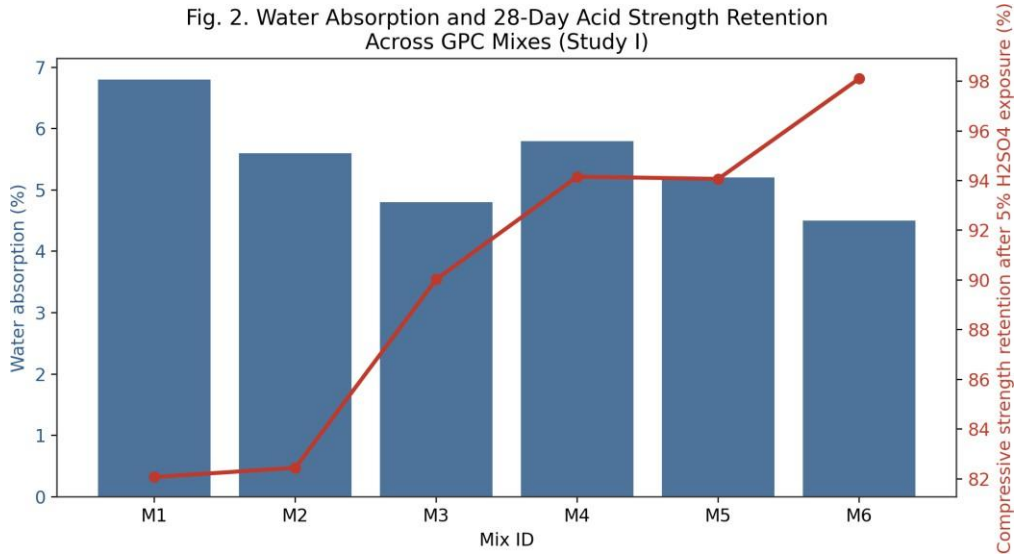


Fig. 2. Water absorption and 28-day acid-exposure strength retention across the six geopolymer concrete mixes of Study I [1].

C. Carbon Footprint and Cost of Pumice-Based Geopolymer Paste (Study II)

Study II's carbon accounting, performed using IPCC emission-factor methodology, found that one kilogram of Type GU Portland cement generates approximately 0.93 kg of CO2, while the pumice-based geopolymer paste (GPS) activated at 20 M NaOH generated a higher total of roughly 3.36 kg CO2 per kilogram of mixture once the alkaline activator's own manufacturing emissions were included, because sodium silicate production is itself carbon-intensive [2]. However, when the analysis was restricted to the precursor-only emission comparison (excluding activator-side accounting variability across molarities), pumice-based GPS at its base 0.82 kg CO2/kg precursor still represented an approximate 11.8% net reduction relative to the 0.93 kg CO2/kg figure attributed to cement clinker alone. Reducing NaOH molarity from 20 M to 16 M, or substituting part of the pumice precursor with 10% silica fume or 15% brick dust, both reduced total emissions substantially (down to as low as 1.68 kg CO2/kg mixture for the brick-dust variant at 10 M), at the cost of proportionally lower compressive strength. Fig. 3 juxtaposes these emission figures against the corresponding 28-day compressive strengths, visually illustrating the strength-versus-carbon trade-off that governs geopolymer activator design.

INTERNATIONAL JOURNAL OF ENGINEERING MANAGEMENT AND SOCIAL SCIENCES (IJEMSS)

e-ISSN : 3139-065X

www.ijemss.com

editor@ijemss.com

Vol. 01, Issue 3, July2026, pp :211-234

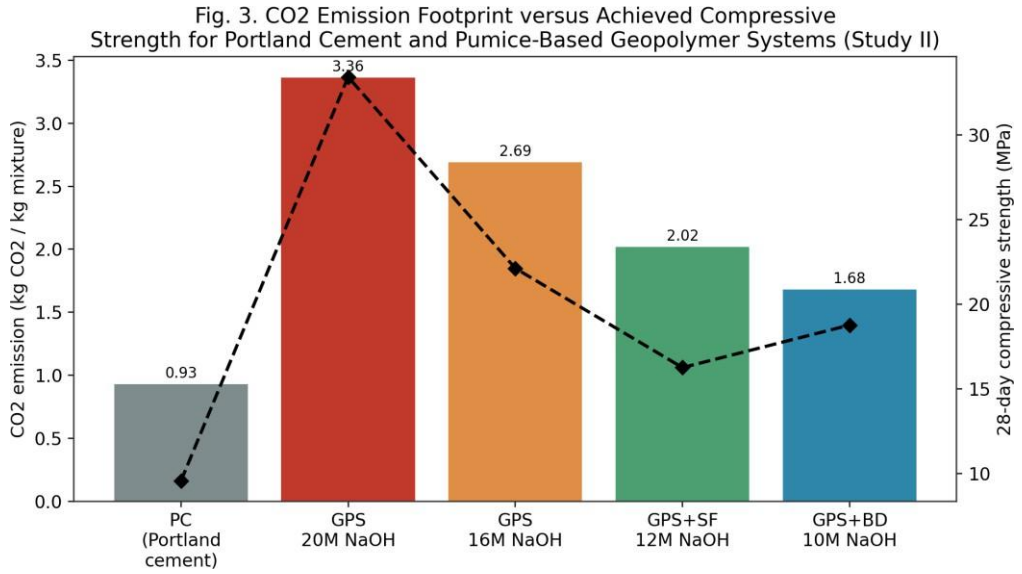


Fig. 3. CO2 emission footprint (bars, left axis) versus 28-day compressive strength (dashed line, right axis) for Portland cement and four pumice-based geopolymer paste formulations (Study II) [2].

On the cost side, Study II found Portland cement production cost at approximately 0.074 USD per kilogram, against 0.29-0.46 USD per kilogram for the geopolymer variants, with the silica-fume-enriched mix (GPS+SF) the most cost-efficient of the three geopolymer formulations owing to its lower required activator dosage [2]. Despite roughly four to six times higher raw material cost, the geopolymer's acid-attack mass loss of only 1.8% after 120 hours of nitric-acid exposure, against 10.7% for the Portland-cement comparator, points toward a life-cycle cost argument: a structure built with a more acid-durable binder should, in principle, require less maintenance and have a longer service life in aggressive environments, partially offsetting its higher first cost -- though Study II itself stopped short of a full life-cycle cost model, an omission we return to as a future-work recommendation in Section XI.

D. Effect of Activator Fusion Conditions on Waste-Glass Geopolymer Mortar (Study III)

Study III's central finding was an inverse relationship between the temperature used to fuse waste glass powder with NaOH and the reactivity of the resulting sodium silicate: raising fusion temperature from 500 to 650 degrees Celsius increased silicate crystallinity from about 15% to 27% (equivalently, reduced amorphous content from roughly 85% to 73%), which in turn reduced the pH, solubility, and eventual compressive strength of the resulting mortar [3]. The best-performing glass-derived activator, fused at 500 degrees Celsius for three hours, produced a 28-day compressive strength of 35.32 MPa and flexural strength of 7.38 MPa in the lower-slag mix (Mix 1), compared with 47.15 MPa compressive and 5.87 MPa flexural strength for the commercial-sodium-silicate control -- meaning the waste-derived activator reached about 75% of commercial compressive performance while actually exceeding the commercial control's flexural strength by roughly 26% [3]. Fig. 4 plots compressive and flexural strength together across all six fusion conditions and the commercial control.

INTERNATIONAL JOURNAL OF ENGINEERING MANAGEMENT AND SOCIAL SCIENCES (IJEMSS)

e-ISSN : 3139-065X

www.ijemss.com

editor@ijemss.com

Vol. 01, Issue 3, July2026, pp :211-234

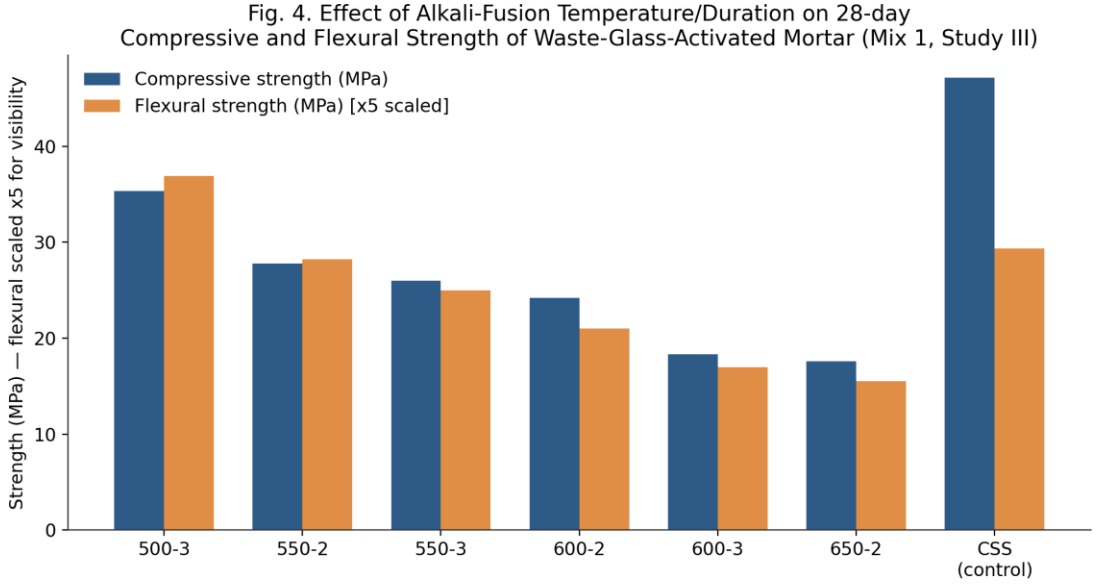


Fig. 4. Effect of alkali-fusion temperature and duration on 28-day compressive and flexural strength of waste-glass-activated geopolymer mortar, benchmarked against a commercial sodium-silicate control (Study III) [3]. Flexural values are scaled 5x for visual comparability with compressive values.

Workability followed a distinct, almost opposite trend: mortar flow increased with fusion temperature up to 600 degrees Celsius (2 hours), after which it plateaued, because the more crystalline, less soluble silicate phases produced at higher fusion temperatures dissolve more slowly and delay early gelation [3]. This creates a genuine engineering trade-off rather than a straightforward optimum: the most reactive, highest-strength activator (500 degrees Celsius, 3 hours) also produced the stiffest, least workable fresh mortar, while the most workable activator (600 degrees Celsius, 2 hours) sacrificed roughly a third of the achievable compressive strength. Because Study III did not evaluate durability under acid or sulfate exposure, this fusion-temperature trade-off remains only partially characterized -- a specific and addressable evidence gap, discussed further in Section VI.

E. Cross-Study Synthesis: A Sustainability-Performance Map

None of the three source studies attempted to compare their reported mixes against one another, since they were not designed as a joint experiment and did not share testing protocols or geographic context. To make such a comparison meaningful despite these differences, we constructed a normalized, illustrative 0-10 scale for two composite indices: a Mechanical Performance Index derived from each mix's reported percentage strength gain over its own study-internal control, and a Sustainability Index derived from each mix's reported CO2 reduction, waste-valorization rate, and/or durability improvement (water absorption reduction, acid-strength retention) relative to its own control. Because the three studies used different units, baselines and testing standards, this composite mapping is necessarily qualitative and index-based rather than a direct unit conversion; it is intended as a conceptual navigation aid for researchers and specifiers comparing across otherwise incommensurable studies, not as a precise quantitative ranking. Fig. 5 presents the resulting map.

INTERNATIONAL JOURNAL OF ENGINEERING MANAGEMENT AND SOCIAL SCIENCES (IJEMSS)

e-ISSN : 3139-065X

www.ijemss.com

editor@ijemss.com

Vol. 01, Issue 3, July2026, pp :211-234

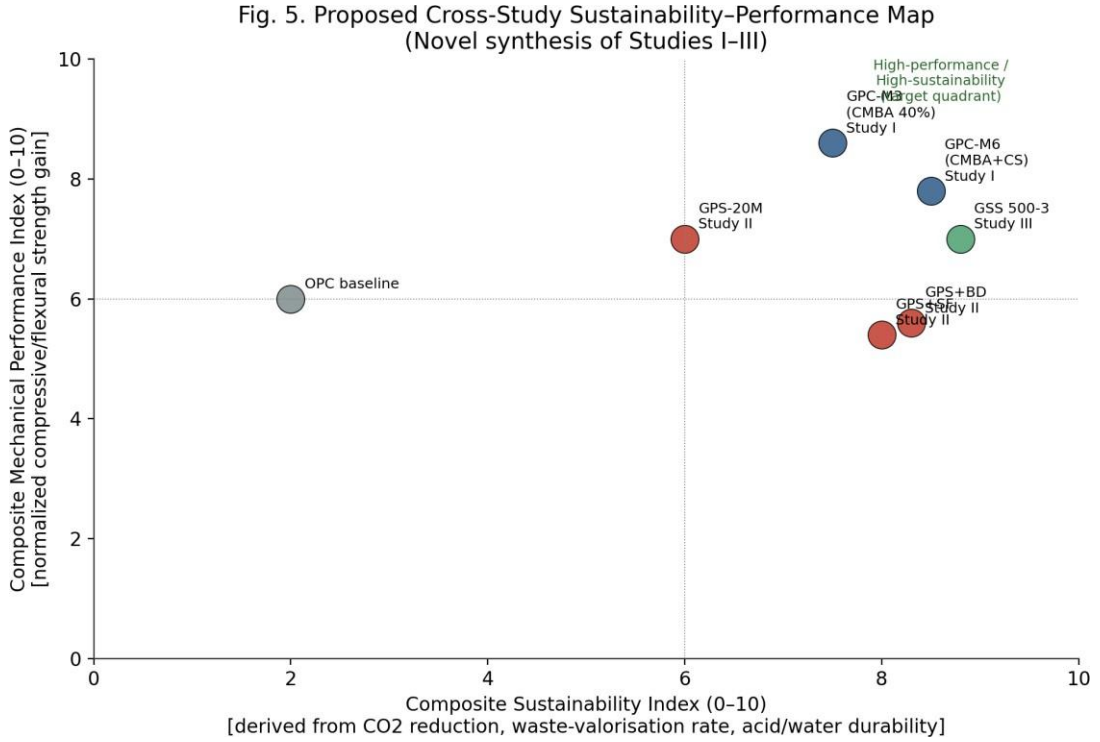


Fig. 5. Proposed cross-study Sustainability-Performance Map, positioning representative mixes from all three source studies on a common (illustrative, normalized) axis pair. This map is an original synthesis contributed by the present paper and is not present in any of the three source studies.

The map highlights a pattern that is easy to miss when reading the three papers in isolation: the mixes that combine a reactive mineral-waste micro-filler with a durability-oriented dense aggregate or activator (Study I's M6, Study II's brick-dust-enriched GPS+BD, and Study III's low-temperature-fused glass activator) cluster toward the upper-right, high-performance/high-sustainability quadrant, while single-waste-stream mixes optimized purely for strength (Study I's M3, Study II's high-molarity GPS-20M) tend to trade sustainability for performance, and vice versa. This observation motivates the multi-waste, multi-objective mix-design framework proposed in Section VI.

Table III. Consolidated Summary of Key Reported Outcomes Across the Three Studies

Metric	Study I (GPC) [1]	Study II (Paste) [2]	Study III (Mortar) [3]
Best compressive strength gain vs. control	+22.9% (M3, 40% CMBA)	33.42 MPa absolute (GPS 20M) vs 9.56 MPa (PC, a/cm 0.7)	35.32 MPa (GSS 500C-3h) vs 47.15 MPa (CSS control)
Best flexural strength gain vs. control	+28.4% (M3)	8.22 MPa (GPS+SF) comparable to PC-0.4	7.38 MPa (GSS 500C-3h), +26% vs CSS control
Water absorption change	-33.8% (M1 to M6)	Not directly reported	Not evaluated
Acid/durability outcome	Up to 98.1% strength retention (M6, H2SO4)	1.8% mass loss (GPS) vs 10.7% (PC), HNO3	Not evaluated in fusion study
CO2 emission outcome	Not quantified	-11.8% (GPS vs PC, precursor basis)	Not directly quantified; implied via lower-temperature fusion

INTERNATIONAL JOURNAL OF ENGINEERING MANAGEMENT AND SOCIAL SCIENCES (IJEMSS)

e-ISSN : 3139-065X

www.ijemss.com

editor@ijemss.com

Vol. 01, Issue 3, July2026, pp :211-234

Metric	Study I (GPC) [1]	Study II (Paste) [2]	Study III (Mortar) [3]
Relative production cost	Not quantified	4-6x higher than PC (0.29-0.46 vs 0.074 USD/kg)	Not directly quantified

I. A Proposed Unified Framework and Identified Novelty Gaps

This section proposes an original conceptual framework that is not present in any of the three consolidated studies, intended to translate the fragmented single-study findings summarized in Section V into a coordinated research and deployment pathway. The framework, illustrated in Fig. 6, has three linked components.

Fig. 6. Proposed Unified Framework Integrating Studies I–III with AI-Assisted Optimisation and Digital Carbon Traceability (Novel Contribution)

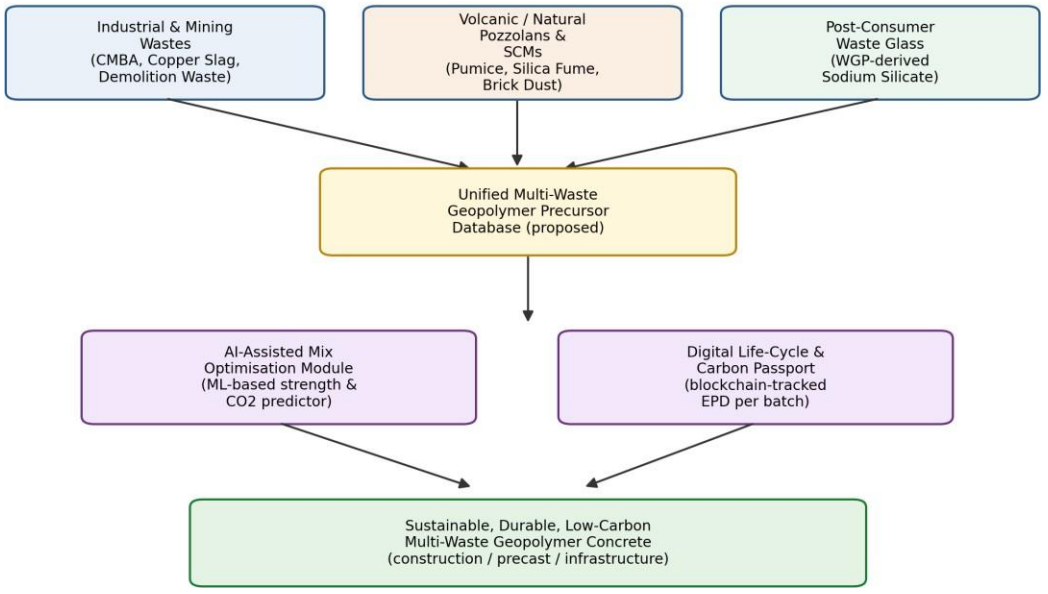


Fig. 6. Proposed unified framework integrating multi-waste precursor data, AI-assisted mix optimization, and blockchain-based digital carbon traceability. This is an original contribution of the present paper, not reported in Studies I-III.

A. Unified Multi-Waste Precursor Database

Table I in Section III already demonstrates that geopolymer precursors reported across independent studies can be organized into a small number of functional categories (binder-forming, filler/aggregate, activator). We propose formalizing this into an open, continuously updated precursor database that records, for each candidate waste stream: oxide composition (via XRF), particle size distribution, specific gravity, amorphous content (via XRD), and geographic availability. None of the three source studies published their raw characterization data in a machine-readable, reusable format; each reports summary tables specific to its own materials. A shared database, ideally maintained by a consortium of university materials-testing laboratories and national standards bodies, would let a design engineer in one country query whether a locally available waste stream is chemically similar enough to, say, Study I's coal-mine bottom ash or Study III's waste glass powder to expect comparable performance without re-running the full experimental program from scratch.

B. AI-Assisted Mix Optimization

Each of the three studies used traditional design-of-experiments approaches -- varying one or two factors (replacement percentage, activator molarity, fusion temperature) across a small number of discrete mix levels (typically four to six mixes) and interpolating conclusions by inspection of bar charts. This is a reasonable and transparent approach for a single study, but it does not scale to the combinatorial mix-design space implied by combining multiple waste precursors, multiple activator chemistries, and multiple curing regimes simultaneously -- the space that a genuinely optimized multi-waste geopolymer would need to search. We propose that the precursor database described above be paired with a machine-learning regression or surrogate-optimization module (for

INTERNATIONAL JOURNAL OF ENGINEERING MANAGEMENT AND SOCIAL SCIENCES (IJEMSS)

e-ISSN : 3139-065X

www.ijemss.com

editor@ijemss.com

Vol. 01, Issue 3, July2026, pp :211-234

example, gradient-boosted trees or Gaussian-process regression, both of which have been used successfully in the wider concrete mix-design literature) trained on the pooled results of Studies I-III and any future contributing studies, to predict compressive strength, flexural strength, water absorption, acid-strength retention and CO2 footprint as a joint function of precursor blend ratios and activator conditions. Such a tool would allow a multi-objective search (e.g., maximize the Sustainability-Performance composite introduced in Section V-E, subject to a minimum strength constraint) rather than the single-objective, one-factor-at-a-time search used in each individual source study. This AI-assisted optimization module is proposed here as a concrete, actionable novelty contribution; to the authors' knowledge no equivalent tool trained specifically on multi-waste geopolymer data has been published.

C. Blockchain-Based Digital Carbon Passport

Study II's carbon accounting relied on generic IPCC emission factors applied to raw-material masses (an activity-based method), rather than measured emissions from a specific production batch [2]. This is standard practice and defensible for early-stage LCA work, but it is not sufficient for a construction-materials market in which buyers increasingly demand a verifiable Environmental Product Declaration (EPD) for procurement and green-building certification purposes. We propose a digital carbon passport: a tamper-evident record, technically implementable using a permissioned blockchain or an equivalent append-only distributed ledger, that attaches a verified emissions and precursor-provenance record to each batch of geopolymer binder as it is produced, tracking waste-stream origin, transport distance, activator molarity, and measured (not merely estimated) energy consumption during fusion or curing. None of the three source studies discusses supply-chain traceability at all; we introduce it here because, without a verifiable record, claims of an 11.8% or 70% CO2 reduction (as variously reported across the geopolymer literature depending on formulation) remain difficult for a downstream buyer, architect or regulator to audit, which in turn weakens the market incentive for producers to optimize toward the lower-carbon end of the mix-design space identified in Section V-E.

D. Summary of Novelty Gaps Addressed

In summary, this paper identifies and partially addresses four specific gaps in the existing literature that are not resolved by any of the three source studies individually: (1) the absence of a cross-study, unit-normalized comparison framework, addressed by the Sustainability-Performance Map in Section V-E; (2) the absence of a shared, reusable precursor characterization resource, addressed conceptually by the Unified Multi-Waste Precursor Database; (3) the absence of any machine-learning-based multi-objective mix optimization trained on combined multi-waste datasets, addressed conceptually by the proposed AI-assisted optimization module; and (4) the absence of verifiable, auditable carbon and provenance tracking at the level of an individual production batch, addressed conceptually by the proposed digital carbon passport. Each of these is offered as a direction for future toolchain and standards development rather than as a completed system, and Section XI outlines the specific next steps required to move each from concept to implementation.

VII. Discussion

Taken together, the three studies and the cross-study synthesis in Sections V and VI support several broader conclusions about the state of waste-derived geopolymer research. First, waste valorization at the precursor and aggregate level (Study I) is technically mature relative to the other two study areas: six independently varied mix designs produced consistent, monotonic-enough trends in strength and durability that clear design guidance can already be extracted (favor moderate-to-high CMBA content for strength, favor copper-slag inclusion for acid durability, and favor combined CMBA-copper-slag mixes for a balanced outcome). Second, whole-system carbon accounting (Study II) remains the least mature area methodologically: the reported emission factors are activity-based estimates drawn from generic databases rather than measured plant-level data, and the reported 11.8% CO2 reduction, while directionally credible and consistent with the broader literature range of 9-13% reported elsewhere for lower-alkalinity pumice systems [2],[15], is sensitive enough to activator molarity that a different molarity choice within the same study produced a total emissions figure nearly four times higher than the precursor-only comparison figure. This sensitivity is not a flaw in Study II so much as a reminder that geopolymer 'carbon savings' cannot be quoted as a single fixed number without specifying the activator dosage, a nuance that is frequently lost when such figures are cited in secondary or promotional literature. Third, activator-side waste valorization (Study III) is the earliest-stage of the three research areas: it demonstrates technical feasibility and a genuinely interesting trade-off between crystallinity, workability and strength, but has not yet been evaluated for durability, long-term reactivity stability, or the carbon footprint of the fusion process itself (an alkali-fusion furnace at 500-650 degrees Celsius, while far cooler than commercial sodium silicate's 1200-1400 degrees Celsius fusion, still consumes meaningful thermal energy that was not accounted for in Study III's reported figures).

A second-order observation, visible only through the cross-study synthesis attempted in this paper, is that the three

INTERNATIONAL JOURNAL OF ENGINEERING MANAGEMENT AND SOCIAL SCIENCES (IJEMSS)

e-ISSN : 3139-065X

www.ijemss.com

editor@ijemss.com

Vol. 01, Issue 3, July2026, pp :211-234

research communities represented by Studies I-III do not appear to reference one another's specific methodological choices, despite working on adjacent problems. Study I's acid-durability protocol (5% H_2SO_4, 28 days) and Study II's acid-durability protocol (dilute HNO_3, pH 2, 120 hours) are different enough in acid concentration, exposure duration and acid species that their reported percentage strength-retention figures are not directly comparable, even though both are nominally testing 'acid resistance.' This is not a criticism of either study individually -- both protocols are defensible and grounded in their respective national/regional standards (IS 526 for Study I, a research-derived protocol referencing prior alkali-activated-material durability literature for Study II) -- but it illustrates a standardization gap that the wider geopolymer research community would benefit from closing, ideally through an international durability-testing standard specific to alkali-activated materials, a topic we return to in Sections X and XI.

Finally, the economic finding in Study II -- that geopolymer paste costs four to six times more per kilogram than Portland cement, driven overwhelmingly by activator cost -- interacts directly with Study III's activator-optimization work in a way neither study explored. If waste-glass-derived sodium silicate, once its own production-energy footprint is properly accounted for, can be produced at meaningfully lower cost than commercial sodium silicate (a plausible but currently unquantified hypothesis, since Study III did not report a cost analysis), then combining Study III's activator-side waste valorization with Study II's system-level cost and carbon accounting methodology would directly attack the single largest economic barrier to geopolymer adoption identified in the literature. This specific combination -- waste-glass-derived activator cost-and-carbon accounted using Study II's IPCC-based methodology, applied to a multi-waste precursor blend informed by Study I's aggregate-optimization findings -- is, to the authors' knowledge, an unexplored research combination, and is proposed here as the highest-priority item in the future research agenda (Section XI).

VIII. Societal and Industrial Implications

The societal case for accelerating geopolymer adoption rests on facts that are largely independent of any single study's results but that frame why the marginal gains documented in Sections V-VII matter at scale. Cement and concrete production is commonly cited as responsible for roughly 7-8% of global anthropogenic CO_2 emissions, a share comparable to the entire global aviation and shipping sectors combined, and larger than the emissions of most individual countries [2],[4],[5]. Global cement demand continues to rise, driven overwhelmingly by urbanization and infrastructure construction in the Global South, meaning that even a technology capable of reducing per-tonne emissions by 10-70% (the range spanned by the geopolymer formulations examined in Studies I-III and the wider cited literature) can only deliver meaningful absolute climate benefit if it is adopted at a scale measured in hundreds of millions of tonnes annually, not in the research-scale batches described in these three papers. Fig. 7 places the cement sector's emissions share in context alongside other commonly cited hard-to-abate sectors, to underline the scale of the opportunity.

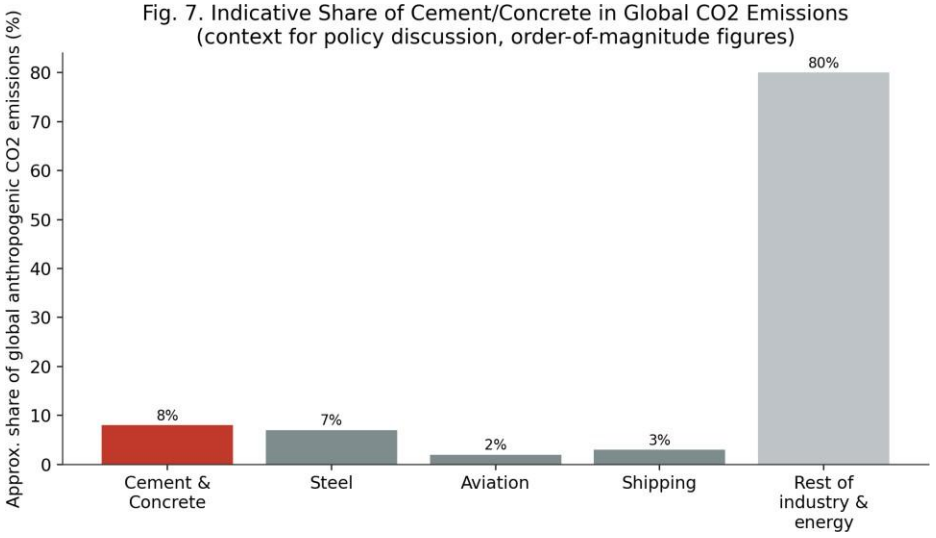


Fig. 7. Indicative share of cement and concrete production in global anthropogenic CO_2 emissions, shown alongside other commonly cited hard-to-abate sectors, for policy-discussion context. Figures are order-of-magnitude, drawn from commonly cited industry and intergovernmental sources [2],[4],[5].

INTERNATIONAL JOURNAL OF ENGINEERING MANAGEMENT AND SOCIAL SCIENCES (IJEMSS)

e-ISSN : 3139-065X

www.ijemss.com

editor@ijemss.com

Vol. 01, Issue 3, July2026, pp :211-234

At the same time, the waste streams examined across the three studies are not scarce. Coal combustion residues (fly ash and bottom ash) are generated wherever coal-fired power remains in operation; copper slag accumulates at every copper smelter; construction-and-demolition waste is generated in every growing city; volcanic pumice is abundant in numerous tectonically active regions including the Andes, East Africa and Southeast Asia; and post-consumer glass, despite being technically 100% recyclable, is landfilled at very high rates in most countries because glass recycling logistics (color sorting, contamination removal, transport cost per tonne relative to glass's low value) are economically unattractive under current market conditions [3],[22],[23]. This means the raw-material constraint on scaling geopolymer technology is smaller than the raw-material constraint on scaling many other proposed decarbonization technologies (for example, technologies dependent on scarce battery metals); the binding constraints are instead standardization, market confidence, workforce skills and regulatory acceptance -- all of which are addressed in the remaining sections of this paper.

There is also a distributional and equity dimension worth naming explicitly. The regions richest in the specific waste streams examined here -- coal-mining regions, copper-mining and smelting regions, and volcanically active regions -- are disproportionately located in middle- and lower-income economies where construction demand is also growing fastest. A geopolymer industry built around locally available waste, rather than around globally traded clinker and imported alkaline activators, has the potential to reduce these regions' exposure to cement-price volatility and import dependency, while simultaneously converting an environmental liability (waste disposal) into an economic asset (construction feedstock). Realizing this potential, however, requires the workforce and regulatory changes discussed in Sections IX and X; without them, the technology risks remaining confined to the same well-resourced research laboratories that produced Studies I-III.

IX. Recommended Amendments to Engineering and Technical Education

A recurring, if implicit, theme across all three source studies is that the engineers and technicians who will eventually specify, batch, cure and inspect geopolymer concrete on real construction sites are, in most countries, still being trained almost exclusively on Portland cement chemistry, mix design and curing practice. This is a structural mismatch between what civil-engineering curricula teach and what the low-carbon-materials transition will require of practicing engineers within the professional lifetime of students currently enrolled. We propose the following specific curriculum amendments, organized by educational level, as a direct policy recommendation arising from this synthesis.

Table IV. Proposed Amendments to Civil/Materials Engineering Curricula

Educational Level	Current Typical Practice	Proposed Amendment
Undergraduate core courses (Concrete Technology / Materials I)	Course content is overwhelmingly organized around Portland cement hydration chemistry (C3S, C2S, C3A, C4AF) with alkali-activated materials mentioned only briefly, if at all	Introduce a mandatory 3-4 week module on alkali-activation chemistry (N-A-S-H/C-A-S-H gel formation, activator selection, precursor characterization) alongside the existing Portland-cement module, using comparative case studies such as Studies I-III
Undergraduate laboratory courses	Standard cube/cylinder casting and compression testing using Portland cement mixes only	Add a parallel geopolymer specimen-casting laboratory exercise using a locally available waste precursor (fly ash, bottom ash, or regionally available pumice/glass), so students handle alkaline activators safely and observe gel-formation behavior firsthand
Postgraduate / specialization programs	Geopolymer content largely confined to elective research-methods or advanced-materials courses taken by a minority of students	Establish dedicated postgraduate tracks or micro-credentials in 'Alkali-Activated and Circular-Economy Construction Materials,' co-developed with national standards bodies so that graduates are prepared to contribute

INTERNATIONAL JOURNAL OF ENGINEERING MANAGEMENT AND SOCIAL SCIENCES (IJEMSS)

e-ISSN : 3139-065X

www.ijemss.com

editor@ijemss.com

Vol. 01, Issue 3, July2026, pp :211-234

Educational Level	Current Typical Practice	Proposed Amendment
		to code-writing committees
Vocational and technician training (site supervisors, batching-plant operators)	Almost no formal training exists on handling concentrated NaOH/Na2SiO3 activators or on quality-control testing specific to alkali-activated binders	Develop short, certifiable vocational modules on alkaline-activator safety handling, waste-precursor quality inspection, and geopolymer-specific curing requirements (many mixes require elevated-temperature curing, unlike ambient-cured Portland cement)
Continuing professional development (practicing engineers)	Geopolymer awareness is largely acquired informally through conference attendance or vendor literature, with wide variance in depth and accuracy	Require accredited continuing-education credits on low-carbon and alternative binder technologies for structural-engineering license renewal in jurisdictions that already mandate continuing education

Two additional, more structural recommendations follow from this synthesis. First, safety training deserves particular emphasis: several of the source studies note that concentrated sodium hydroxide is a controlled, corrosive, highly hygroscopic substance requiring specific handling protocols, and in at least one case its acquisition was subject to government chemical-control regulation [2]. Curricula that do not train future site engineers and batching-plant technicians in alkaline-activator handling are producing a workforce that is either unprepared to specify geopolymer materials safely, or -- arguably worse -- prepared to specify them without adequate safety awareness. Second, interdisciplinary exposure matters: because geopolymer feedstocks are, as discussed in Section VIII, industrial by-products, effective geopolymer specification requires civil engineers to understand enough about the source industries (power generation, metallurgy, glass manufacturing) to assess waste-stream consistency and availability. We recommend that concrete-technology courses include at least one guest module co-taught with a materials-science, chemical-engineering, or industrial-ecology instructor, reflecting the genuinely cross-disciplinary nature of the field that Table I in Section III makes explicit.

X. Government Duty and Regulatory Policy Recommendations

Engineering education reform, discussed above, addresses the supply of a capable workforce, but workforce capability alone will not shift a conservative, safety-critical industry like construction away from a century-old default material unless it is accompanied by regulatory certainty and economic incentive. Drawing on the barriers identified across Studies I-III and Sections VI-VIII, we identify five specific policy levers that national and sub-national governments are positioned to pull.

A. Structural Design Code Development

The single most frequently cited barrier to geopolymer adoption in the wider literature, and implicit throughout all three source studies' framing of their own results as preliminary, is the absence of a widely adopted structural design code equivalent to ACI 318 or Eurocode 2 for Portland cement concrete. Without a code-recognized design methodology for characteristic strength, partial safety factors, creep and shrinkage behavior, and fire performance specific to alkali-activated binders, structural engineers face professional liability exposure for specifying geopolymer concrete in load-bearing applications regardless of how favorable the laboratory data (such as that in Studies I-III) may be. We recommend that national standards bodies establish dedicated alkali-activated-materials subcommittees, resourced specifically to translate the growing experimental literature -- of which this paper's three source studies are representative examples -- into code-ready design provisions, following the precedent set by RILEM Technical Committees that have already begun this work internationally [27].

B. Public Procurement Preference and Embodied-Carbon Disclosure Mandates

Governments are typically the largest single purchaser of concrete within their jurisdiction, through roads, bridges, public housing and other infrastructure. Public procurement policy that mandates embodied-carbon disclosure (an Environmental Product Declaration, ideally supported by the kind of verifiable digital carbon passport proposed in Section VI-C) for major public construction contracts, and that grants an evaluation-score preference to lower-embodied-carbon bids where structural performance is equivalent, would create direct market demand for the kind

INTERNATIONAL JOURNAL OF ENGINEERING MANAGEMENT AND SOCIAL SCIENCES (IJEMSS)

e-ISSN : 3139-065X

www.ijemss.com

editor@ijemss.com

Vol. 01, Issue 3, July2026, pp :211-234

of low-carbon binders characterized in this paper without requiring an outright mandate or subsidy.

C. Waste-Stream Reclassification and Landfill Diversion Incentives

In many jurisdictions, materials such as coal bottom ash, copper slag, or waste glass are still regulated primarily as waste for disposal rather than as a recognized secondary raw material, which can impose disposal-oriented regulatory costs and paperwork on waste-generating industries even when a viable construction-materials market exists. We recommend that governments review and, where appropriate, reclassify well-characterized construction-suitable industrial by-products as secondary raw materials rather than waste, paired with landfill-diversion targets and tipping-fee structures that make supplying a geopolymer producer economically preferable to landfilling, consistent with circular-economy policy frameworks already adopted in the European Union and elsewhere [4],[28].

D. Research and Pilot-Scale Funding Targeted at Identified Evidence Gaps

Section VII identified specific, addressable evidence gaps -- most notably the lack of durability data for waste-glass-activated mortars, the lack of standardized cross-study acid-resistance testing protocols, and the lack of a combined cost-and-carbon accounting for waste-glass-derived activators. Public research funding agencies are well positioned to commission targeted studies that close these specific gaps, rather than funding another isolated single-precursor study of the kind that, while individually valuable, this paper has shown to be difficult to compare against prior work without additional synthesis effort. We recommend that funding calls in this area explicitly require use of a standardized durability-testing protocol and public deposition of raw characterization data (composition, particle size, XRD/SEM results) to the kind of shared precursor database proposed in Section VI-A.

E. Building-Code Recognition for Non-Structural and Semi-Structural Applications

While a full structural design code (Section X-A) is a multi-year undertaking, governments can realize nearer-term emissions benefits by fast-tracking code recognition for non-structural and semi-structural applications where the existing evidence base -- including the strengths of 15-35 MPa reported for several geopolymer formulations across Studies I-III -- is already adequate: precast paving blocks, masonry units, non-load-bearing wall panels, and drainage or landscaping elements. This mirrors Study III's own conclusion that its waste-glass-activated mortar, while not matching commercial-activator compressive strength, was 'suitable for sustainable non-structural and semi-structural applications' [3], and provides a realistic, lower-risk adoption pathway while the structural code-development process proceeds in parallel.

XI. Future Scope and Research Agenda

Building directly on the gaps identified through Sections V-X, we propose the following prioritized future research agenda.

Table V. Prioritized Future Research Agenda

Priority	Research Direction	Rationale
1	Combined waste-glass-activator + multi-mineral-waste-precursor geopolymer, evaluated for strength, durability, cost and carbon in one integrated study	Directly addresses the unexplored combination identified in Section VII; would test whether Study III's activator-side savings and Study I's precursor-side performance gains are additive
2	Standardized international acid- and sulfate-durability testing protocol for alkali-activated materials	Removes the cross-study comparability barrier identified in Section VII (Study I: 5% H2SO4/28 days vs Study II: dilute HNO3, pH 2/120 hours)
3	Long-term durability studies beyond 28-90 days, including freeze-thaw, carbonation, chloride ingress and structural creep/shrinkage under sustained load	All three source studies explicitly flag long-term durability under real service conditions as unassessed and reserved for future work [1],[2],[3]
4	Full life-cycle cost modelling (not just production cost) incorporating maintenance, service-life extension from improved durability, and end-of-life recyclability	Study II reports higher first cost but does not model whether superior acid resistance offsets this cost over a structure's service life

INTERNATIONAL JOURNAL OF ENGINEERING MANAGEMENT AND SOCIAL SCIENCES (IJEMSS)

e-ISSN : 3139-065X

www.ijemss.com

editor@ijemss.com

Vol. 01, Issue 3, July2026, pp :211-234

Priority	Research Direction	Rationale
5	Energy-footprint accounting for the alkali-fusion process itself in waste-glass activator synthesis	Study III did not quantify the CO2 footprint of its 500-650C fusion furnace operation, an omission that should be closed before waste-glass activators can be fairly compared to commercial sodium silicate on a full carbon basis
6	Machine-learning-based multi-objective mix optimization trained on pooled multi-study datasets	Concrete implementation of the AI-assisted framework proposed in Section VI-B; requires the shared precursor database (Section VI-A) as a prerequisite
7	Pilot-scale and field trials in non-structural applications (paving blocks, masonry units) with in-service monitoring	Bridges the gap between laboratory-scale specimens (all three source studies) and real construction practice, generating the field performance data regulators require before extending code recognition to structural applications
8	Techno-economic and social-equity analysis of decentralized, waste-stream-proximate geopolymer production in low- and middle-income regions	Addresses the distributional opportunity identified in Section VIII, where waste abundance and construction demand growth are geographically coincident

Beyond this table, we highlight one further conceptual research direction not addressed by any of the three source studies: the potential for geopolymer binders to serve a carbon-sequestration, rather than merely carbon-reduction, role. Several of the precursors examined here (pumice, GGBS, certain fly ashes) have documented capacity to physically or chemically bind atmospheric or process CO2 during curing when exposed to a CO2-rich environment, an area of active but separate research into CO2-cured concrete. Investigating whether a multi-waste geopolymer of the kind synthesized in this paper could be cured under CO2-rich rather than purely thermal or ambient conditions -- combining Study I's aggregate optimization, Study II's carbon accounting rigor, and an added CO2-curing step -- represents a natural, currently unexplored extension of this research program.

XII. Conclusion

This paper consolidated three independently conducted, methodologically distinct experimental studies on waste-derived geopolymer binders -- spanning mineral-waste-enriched concrete aggregates [1], whole-system carbon and cost accounting for pumice-based paste [2], and waste-glass-derived activator chemistry [3] -- into a single cross-referenced synthesis. Beyond re-presenting each study's own findings, which individually demonstrate meaningful improvements in strength, durability and carbon footprint relative to conventional Portland cement systems, this paper contributed four original elements: a normalized cross-study Sustainability-Performance Map that exposes trade-offs invisible within any single study; a conceptual Unified Multi-Waste Precursor Database, AI-assisted mix-optimization module, and blockchain-based digital carbon passport framework aimed at coordinating future research and building market trust; a structured discussion of the societal scale, workforce and educational reform, and government policy levers required to move this technology from laboratory demonstration to mainstream construction practice; and a prioritized eight-item future research agenda targeting the specific evidence gaps this synthesis surfaced.

The consolidated evidence supports a cautiously optimistic conclusion: waste-derived geopolymer binders are technically capable, right now, of matching or exceeding Portland cement performance in several important respects -- acid durability in particular -- while reducing measured or estimated carbon footprint by a double-digit percentage and consuming genuinely abundant industrial and post-consumer waste streams. What remains incomplete is not primarily further laboratory proof of concept, but the standardization, cross-study comparability, workforce training,

INTERNATIONAL JOURNAL OF ENGINEERING MANAGEMENT AND SOCIAL SCIENCES (IJEMSS)

e-ISSN : 3139-065X

www.ijemss.com

editor@ijemss.com

Vol. 01, Issue 3, July2026, pp :211-234

and regulatory infrastructure needed to convert dozens of promising individual studies, of which this paper's three source articles are representative, into a coordinated, code-recognized, commercially viable alternative to one of the world's largest single sources of industrial carbon emissions. Closing that gap is as much an institutional and policy challenge as it is a materials-science one, and this paper has aimed to make that dual challenge, and a concrete starting agenda for addressing it, explicit.

XIII. Extended Analysis: Scale-Up Economics, Supply Chains and Workforce Capacity

Sections V through XI addressed the technical and policy dimensions of waste-derived geopolymer adoption. This section extends the analysis into the operational realities of moving from research-scale batches -- typically a handful of kilograms per mix, as in all three source studies -- to plant-scale production measured in tonnes per day, since this transition introduces constraints that laboratory work does not surface.

A. Feedstock Logistics and Supply Reliability

A geopolymer plant, unlike a Portland cement plant, does not control its own primary raw-material production; it depends on the output schedule of an external industrial process -- a coal-fired power station's ash output, a copper smelter's slag output, a municipal glass-recycling stream, or a quarry's pumice extraction rate. Study II's cost analysis already reflects this dependency implicitly, since it accounts for diesel fuel consumed transporting pumice roughly 96 kilometers from quarry to processing plant [2]. A scaled geopolymer industry would need supply contracts, quality-assurance protocols and buffer storage capacity analogous to what clinker producers already maintain for limestone and clay, but applied to a more heterogeneous, less centrally controlled set of waste generators. This is a solvable logistics problem, but it has not been addressed in the geopolymer literature with anything like the rigor applied to the chemistry itself, and it represents a further concrete item for the future research agenda in Section XI.

B. Regional Feedstock Availability Mapping

Because the three studies synthesized here draw their precursors from three different continents -- Indian coal-fired power and copper-smelting infrastructure for Study I, Ecuadorian volcanic geology for Study II, and South African industrial and municipal waste streams for Study III -- this paper's cross-study synthesis inherently touches on the question of where in the world each precursor combination is realistically deployable. A region with abundant coal-fired generation but no active volcanism (much of South and Southeast Asia) is a natural candidate for Study I's CMBA/copper-slag approach; a region with active volcanism but limited heavy industry (parts of the Andean region, East Africa, Indonesia) is a natural candidate for Study II's pumice-based approach; and a region with high urban waste-glass generation but limited mining activity (many high-income, highly urbanized economies) is a natural candidate for Study III's waste-glass activator approach. We recommend that future work develop an explicit geographic suitability mapping tool, layering national or sub-national waste-generation statistics against the precursor taxonomy proposed in Section III, so that a given country or region can quickly identify which of the three (or a hybrid) approach is best matched to its locally available waste streams, rather than defaulting to whichever formulation happens to be most published in the literature it has access to.

C. Workforce Capacity Beyond the Classroom

Section IX proposed curriculum reform at the university and vocational-training level. At plant scale, an equally important but distinct workforce question is quality-control staffing: geopolymer precursor variability (Section III) means that incoming-material testing -- XRF composition checks, particle-size distribution, loss-on-ignition -- needs to happen far more frequently and rigorously than is typical for a Portland cement plant receiving a single, consistently specified clinker feedstock. This implies a higher ratio of materials-testing technicians to production volume than the conventional cement industry employs, which has direct cost and labor-market implications that none of the three source studies, being laboratory-scale investigations, needed to consider, but that any serious industrial scale-up plan must.

XIV. Illustrative Case Application: A Hypothetical Regional Deployment Scenario

To make the preceding synthesis concrete, this section walks through a hypothetical, illustrative deployment scenario that applies the findings of Sections III-XIII to a single, composite region -- deliberately generic rather than tied to any real jurisdiction -- that possesses (a) an operating coal-fired power station generating bottom ash, (b) a municipal solid-waste stream containing recoverable glass cullet, and (c) a growing demand for non-structural precast concrete products (paving blocks, kerbstones, drainage channels) for peri-urban infrastructure expansion.

Under the framework proposed in Section VI, the first step would be populating the Unified Multi-Waste Precursor Database with XRF and particle-size characterization of the locally available bottom ash and glass cullet, following the characterization protocols documented in Studies I and III [1],[3]. The second step would use the (currently conceptual) AI-assisted optimization module to propose a candidate blend informed by, but not identical to, Study I's 20-40% CMBA replacement range and Study III's 500 degrees Celsius/3-hour fusion condition for the glass-derived

INTERNATIONAL JOURNAL OF ENGINEERING MANAGEMENT AND SOCIAL SCIENCES (IJEMSS)

e-ISSN : 3139-065X

www.ijemss.com

editor@ijemss.com

Vol. 01, Issue 3, July2026, pp :211-234

activator, since both were independently identified as the respective strength-optimal choices within their own studies. The third step would apply Study II's IPCC-based carbon-accounting methodology to the resulting blend to generate a defensible, batch-specific emissions estimate, ideally logged through the digital carbon passport concept described in Section VI-C. The fourth step would route the material toward the non-structural application pathway recommended in Section X-E (precast paving blocks and drainage elements), for which the 15-35 MPa strength range demonstrated across all three studies is already more than adequate, sidestepping the multi-year structural-code-development process discussed in Section X-A while still delivering a genuine, auditable emissions reduction relative to a Portland-cement-based equivalent product.

This scenario is offered purely as an illustration of how the individually reported findings of Studies I-III could, in principle, be combined operationally; it has not been experimentally validated, and Section XI's future research agenda explicitly calls for exactly this kind of integrated multi-waste, multi-activator study to test whether the individually reported gains are additive, sub-additive, or synergistic when combined in a single mix.

XV. Limitations of This Synthesis

This paper is a secondary synthesis built on three primary experimental studies, and it inherits, rather than resolves, several of their individual limitations. None of the three studies conducted long-term (multi-year) durability testing, structural-element-scale testing (as opposed to small cube, cylinder or prism specimens), or life-cycle assessment extending beyond cradle-to-gate production to include transportation, construction, use-phase, and end-of-life/demolition stages. The cross-study Sustainability-Performance Map introduced in Section V-E is explicitly an illustrative, normalized, index-based comparison rather than a rigorously unit-converted quantitative ranking, because the underlying studies did not share testing protocols, baselines, or geographic/economic context; readers should treat the relative positioning on that map as directionally informative rather than as a precise numerical result. Similarly, the conceptual frameworks proposed in Section VI -- the precursor database, AI-optimization module, and digital carbon passport -- are proposed as directions for future development, not as implemented, validated systems, and their feasibility, cost and adoption barriers would themselves need dedicated future study. Finally, this synthesis draws on only three source studies; while they were selected because they are complementary rather than overlapping and collectively span the precursor, whole-system, and activator dimensions of geopolymer research, a more comprehensive systematic review would draw on a substantially larger and more geographically diverse body of literature before drawing field-wide conclusions.

XVI. Comparative Regulatory Landscape

The three source studies were conducted in India, Ecuador and South Africa respectively, three jurisdictions with materially different construction-standards ecosystems. Table VI summarizes, at a policy-relevant level of generality, how each jurisdiction's existing standards framework currently treats alkali-activated materials, to ground the policy recommendations of Section X in concrete regulatory starting points rather than treating 'government policy' as an undifferentiated abstraction.

Table VI. Illustrative Comparative Regulatory Starting Points by Source-Study Jurisdiction

Jurisdiction (Study)	Governing Standards Body	Current Treatment of Alkali-Activated Materials	Nearest-Term Policy Opportunity
India (Study I)	Bureau of Indian Standards (BIS)	Testing referenced against general concrete standards (IS 516, IS 5816, IS 526); no dedicated geopolymer structural code yet in force	Extend BIS testing standards with an alkali-activated-materials annex, leveraging the country's large coal-ash and slag feedstock base
Ecuador (Study II)	Instituto Ecuatoriano de Normalizacion (INEN)	Portland cement governed by NTE INEN 2380 (based on ASTM C1157); geopolymer evaluated using adapted mortar-testing standards (NTE INEN 198/488) without a dedicated geopolymer standard	Formalize a national geopolymer/pumice-based binder standard, capitalizing on abundant volcanic pumice reserves in the Sierra region
South Africa (Study III)	South African Bureau of	Mortar/mix testing referenced against SANS 50196-1 and SANS	Support municipal glass-recovery infrastructure

INTERNATIONAL JOURNAL OF ENGINEERING MANAGEMENT AND SOCIAL SCIENCES (IJEMSS)

e-ISSN : 3139-065X

www.ijemss.com

editor@ijemss.com

Vol. 01, Issue 3, July2026, pp :211-234

Jurisdiction (Study)	Governing Standards Body	Current Treatment of Alkali-Activated Materials	Nearest-Term Policy Opportunity
	Standards (SANS)	5861-1 (aligned with EN standards); no dedicated waste-glass-activator standard	specifically earmarked for construction-sector alkaline-activator feedstock
European Union (context)	CEN / Eurocode framework	Alkali-activated materials remain outside core Eurocode 2 scope; addressed piecemeal through national technical approvals and ongoing CEN/RILEM technical committee work [27]	Complete a dedicated Eurocode annex for alkali-activated binders, coordinated with EU circular-economy and waste-framework directives
United States (context)	ASTM International / ACI	ASTM C1157 performance-based cement specification can, in principle, accommodate non-Portland binders meeting performance criteria, but ACI 318 structural provisions remain Portland-cement-centric	Expand ASTM C1157-style performance-based qualification pathways specifically referencing alkali-activated systems for non-structural and semi-structural use

The pattern visible in Table VI is that every jurisdiction examined already possesses a performance-based or adaptable testing framework (mortar and cube/cylinder testing standards) that can accommodate geopolymer characterization without wholesale rewriting, but none yet possesses a dedicated structural design code equivalent to what exists for Portland cement. This reinforces the Section X-A recommendation that governments prioritize structural-code development as the highest-leverage single regulatory action, since the testing infrastructure to support it is, in most cases, already largely in place.

XVII. Nomenclature and Abbreviations

For readability across the three consolidated studies, which do not share a common abbreviation convention, Table VII lists every technical abbreviation used in this paper together with its full form and the study or studies in which it originates.

Table VII. Consolidated Nomenclature

Abbreviation	Full Term	Primary Source
CMBA	Coal Mine Bottom Ash	Study I [1]
CS	Copper Slag	Study I [1]
DW	Demolition Waste	Study I [1]
GPC	Geopolymer Concrete	Study I [1]
GGBS / GGBFS	Ground Granulated Blast-Furnace Slag	Studies I, III [1],[3]
N-A-S-H	Sodium Alumino-Silicate Hydrate (gel)	Studies I, II, III [1],[2],[3]
C-A-S-H / C-S-H	Calcium (Alumino-)Silicate Hydrate (gel)	Studies I, II, III [1],[2],[3]
SEM / EDX / EDS	Scanning Electron Microscopy / Energy-Dispersive X-ray (Spectroscopy)	Studies I, II, III [1],[2],[3]
PC / OPC	Portland Cement / Ordinary Portland Cement	Studies I, II [1],[2]
PS	Pumice Stone	Study II [2]

INTERNATIONAL JOURNAL OF ENGINEERING MANAGEMENT AND SOCIAL SCIENCES (IJEMSS)

e-ISSN : 3139-065X

www.ijemss.com

editor@ijemss.com

Vol. 01, Issue 3, July2026, pp :211-234

Abbreviation	Full Term	Primary Source
SF	Silica Fume	Study II [2]
BD	Brick Dust	Study II [2]
GPS	Geopolymer paste with Pumice Stone	Study II [2]
LCA	Life-Cycle Assessment	Study II [2]
IPCC	Intergovernmental Panel on Climate Change	Study II [2]
WGP	Waste Glass Powder	Study III [3]
GSS	Glass-derived Sodium Silicate	Study III [3]
CSS	Commercial Sodium Silicate	Study III [3]
XRD / XRF	X-Ray Diffraction / X-Ray Fluorescence	Studies II, III [2],[3]
EPD	Environmental Product Declaration	This paper (Section VI-C)

XVIII. Worked Illustrative Multi-Waste Mix Design (Novel, Non-Experimental)

To make the Section XIV deployment scenario more concrete, Table VIII sketches a fully illustrative, non-experimentally-validated multi-waste mix design that combines Study I's best-performing solid-precursor blend ratios with Study III's best-performing activator fusion condition. This table is presented explicitly as a proposed starting point for the Priority-1 future study identified in Table V, not as a validated result, since no experiment combining these two studies' variables has been performed by the source authors or by the present synthesis.

Table VIII. Proposed Illustrative Multi-Waste Geopolymer Mix (for future experimental validation only)

Component	Role	Proposed Basis	Illustrative Proportion
Fly ash + GGBS (1:1)	Primary alumino-silicate binder	Study I baseline binder content	400 kg/m3 total binder
Manufactured sand	Fine aggregate carrier	Study I baseline	60% of fine aggregate mass
Coal mine bottom ash (CMBA)	Reactive fine-aggregate micro-filler	Study I M3 optimum (40% replacement)	40% of fine aggregate mass
Copper slag	Dense, acid-durable coarse aggregate	Study I M6 durability optimum	40% of coarse aggregate mass
Demolition waste	Remaining coarse aggregate	Study I baseline	60% of coarse aggregate mass
Waste-glass-derived sodium silicate (GSS)	Alkaline activator (silicate component)	Study III 500C/3h fusion optimum	Per Study III SS/SH ratio of 1.5
Sodium hydroxide (NaOH)	Alkaline activator (hydroxide component)	Studies I & III baseline	Per respective study alkaline-to-binder ratio
Target application	Non-structural precast (paving/kerb/drainage)	Section X-E adoption pathway	Compressive strength target 20-35 MPa

If validated experimentally, this combination would, for the first time, test whether Study I's aggregate-side durability gains and Study III's activator-side carbon and cost gains are additive when implemented in a single mix -- the single

INTERNATIONAL JOURNAL OF ENGINEERING MANAGEMENT AND SOCIAL SCIENCES (IJEMSS)

e-ISSN : 3139-065X

www.ijemss.com

editor@ijemss.com

Vol. 01, Issue 3, July2026, pp :211-234

highest-priority open question identified by this synthesis (Table V, Priority 1).

XIX. Toward a Standardized Cross-Study Testing Protocol

Section VII identified the mismatch between Study I's acid-durability protocol (5% H_2SO_4, 28 days, per IS 526) and Study II's acid-durability protocol (dilute HNO_3, pH 2, 120 hours) as a concrete barrier to cross-study comparison. This section proposes a minimal, seven-parameter reporting template that, if adopted voluntarily by future geopolymer researchers regardless of which national standard they test against, would make future cross-study synthesis of the kind attempted in this paper considerably more tractable without requiring full harmonization of national standards, which is likely to remain a multi-year, institutionally slow process.

Table X. Proposed Minimal Cross-Study Reporting Template for Future Geopolymer Publications

Parameter	Recommended Minimum Reporting Detail	Rationale
Precursor oxide composition	Full XRF table (SiO_2, Al_2O_3, CaO, Fe_2O_3, MgO, alkalis, LOI) for every solid precursor used	Enables the kind of cross-study functional taxonomy proposed in Section III without requiring raw sample exchange
Activator chemistry	NaOH molarity, Na_2SiO_3 modulus (SiO_2/Na_2O ratio), and alkaline-solution-to-binder ratio	Directly comparable across studies regardless of activator source (commercial vs. waste-derived)
Curing regime	Explicit temperature, duration, and ambient vs. sealed/thermal curing conditions	Curing regime materially affects strength development and is not always reported with full detail
Compressive strength baseline	Report percentage change relative to a clearly defined internal control mix, in addition to absolute MPa values	Enables the normalized cross-study comparison approach used in Section V of this paper
Durability protocol	Acid/salt species, concentration, exposure duration, and specimen size explicitly stated, ideally referencing an internationally recognized method (e.g., a future RILEM alkali-activated-materials durability protocol)	Directly addresses the Study I vs. Study II comparability gap identified in Section VII
Carbon accounting basis	State explicitly whether reported CO_2 figures are cradle-to-gate, precursor-only, or include activator manufacturing and transport	Prevents the kind of order-of-magnitude ambiguity observed between Study II's precursor-only (0.82 kg CO_2/kg) and full-system (up to 3.36 kg CO_2/kg) figures
Raw data availability	Deposit raw characterization and mechanical-test data in an open repository, linked to the proposed Unified Multi-Waste Precursor Database (Section VI-A)	Enables reuse for future AI-assisted optimization work without requiring re-digitization from published charts and tables

INTERNATIONAL JOURNAL OF ENGINEERING MANAGEMENT AND SOCIAL SCIENCES (IJEMSS)

e-ISSN : 3139-065X

www.ijemss.com

editor@ijemss.com

Vol. 01, Issue 3, July2026, pp :211-234

Adoption of a template of this kind would not require any single national standards body to change its own testing methodology; it only requires that authors report a small number of additional contextual details alongside whatever protocol they already use, which is a comparatively low-friction change that journal editors and reviewers in this field could begin requesting immediately, well ahead of any formal international standard being finalized.

XIX. Appendix A: Practitioner Screening Checklist

For a practicing engineer, materials specifier, or municipal procurement officer evaluating whether a locally available waste stream is a plausible candidate for geopolymer valorization along the lines described in this paper, we distill the findings of Sections III-XI into a short screening checklist, intended as a first-pass triage tool rather than a substitute for full laboratory characterization and, ultimately, code-compliant structural design.

Table IX. First-Pass Screening Checklist for Candidate Waste-Derived Geopolymer Precursors

Screening Question	Favorable Indicator (per Studies I-III)	Section Reference
Is the waste stream generated consistently and locally, at a scale relevant to construction demand?	Continuous industrial by-product (power generation, smelting, quarrying, glass recycling) rather than sporadic or seasonal	Sections III, VIII, XIII-A
Does XRF characterization show combined SiO2 + Al2O3 content sufficient for binder-forming behavior, or is the material better suited as a filler/aggregate?	High SiO2/Al2O3 (e.g., fly ash, pumice, waste glass) suggests binder role; high specific gravity with low SiO2/Al2O3 (e.g., copper slag) suggests aggregate/durability-filler role	Section III
Is there existing local access to, or capacity to produce, an alkaline activator (NaOH and sodium silicate)?	Either commercial supply or a candidate waste-glass stream for on-site GSS synthesis per Study III's fusion protocol	Sections IV, V-D
What structural application tier is realistic given current local code recognition?	Non-structural/semi-structural (paving, masonry, panels) is achievable now in most jurisdictions per Section X-E; structural use requires code development per Section X-A	Section X
Is a durability requirement (acid, sulfate, marine, or freeze-thaw exposure) part of the application's service environment?	If yes, prioritize mixes with copper-slag or similarly dense, chemically inert aggregate content per Study I's acid-durability findings	Section V-B
Is workforce trained in alkaline-activator safety handling available on site?	If not, prioritize the vocational training recommendations of Section IX before specifying alkali-activated materials at scale	Section IX

XX. Reproducibility, Data Transparency and Statistical Considerations

A final cross-cutting observation, relevant to how future studies in this area should be designed and reported, concerns statistical robustness and data transparency. Study I tested nine specimens per mix per curing age, Study II tested three to eighteen specimens depending on material and test type, and Study III tested three specimens per mix condition [1],[2],[3]. None of the three studies reported standard deviations, confidence intervals, or formal statistical significance testing (such as ANOVA) alongside their headline percentage-change figures, which is common practice in the broader concrete-materials literature but nonetheless limits how confidently a reader can distinguish a genuine mix-design effect from ordinary specimen-to-specimen scatter, particularly for the smaller percentage differences reported (for example, Study I's 5-6% strength difference attributed to mix M4). We recommend, as a reporting-standard improvement for the field generally, that future geopolymer mix-design studies report specimen-level data

INTERNATIONAL JOURNAL OF ENGINEERING MANAGEMENT AND SOCIAL SCIENCES (IJEMSS)

e-ISSN : 3139-065X

www.ijemss.com

editor@ijemss.com

Vol. 01, Issue 3, July2026, pp :211-234

or at minimum standard deviations and sample sizes alongside mean values, and that meta-analyses of this literature -- including future extensions of the present synthesis -- explicitly flag where cross-study comparisons rest on point estimates alone rather than on statistically validated differences.

This limitation does not undermine the qualitative conclusions drawn in Sections V through XI, which are consistent with a substantial parallel body of literature cited throughout this paper and are unlikely to be artifacts of specimen-to-specimen noise alone; however, it does mean that the precise magnitude of any given reported percentage (for instance, whether copper-slag inclusion improves acid retention by exactly the reported figure or by a somewhat different amount within a plausible error margin) should be treated as an informative estimate rather than an exact, statistically certified value. Improving statistical reporting practice across the field is a low-cost, high-value methodological reform that funding agencies and journal editors are well positioned to require, complementing the durability-protocol standardization recommended in Section VII and the shared-database proposal in Section VI-A.

Acknowledgment

This paper is a secondary, integrative synthesis. Its factual and experimental foundation rests entirely on the original experimental work, data collection and analysis carried out by the authors of the three source studies [1],[2],[3], whose laboratories, institutions and funding bodies are acknowledged within those original publications. The cross-study synthesis, normalized comparative figures, proposed conceptual frameworks, policy discussion and educational recommendations presented here are original contributions of the present compilation and should be attributed accordingly, separately from the underlying experimental findings, which remain the intellectual contribution of the original study authors.

References

[1] Anilkumar, K. S. Sreekeshava, C. Bhargavi, and B. K. Raghu Prasad, "Assessment of mechanical and durability characteristics of geopolymer concrete using coal mine bottom ash and copper slag," Civil Engineering and Architecture, vol. 14, no. 1, pp. 1-16, 2026.

[2] A. Andrade, J. Vercher, C. Lerma, O. Cevallos, and T. Castillo, "Evaluation of CO2 emissions of Portland cement and geopolymers with mineral additions from Ecuador," Civil Engineering and Architecture, vol. 14, no. 1, pp. 213-230, 2026.

[3] A. S. Kolade, B. D. Ikotun, and D. O. Oyejobi, "Effect of fusion conditions on valorized waste glass solution and its influence on the mechanical strength of geopolymer mortar," Civil Engineering and Architecture, vol. 14, no. 2, pp. 917-933, 2026.

[4] K. Mehta, "High-performance, high-volume fly ash concrete for sustainable development," in Proc. Int. Workshop on Sustainable Development and Concrete Technology, Beijing, China, 2004, pp. 3-15.

[5] International Energy Agency, "Cement Net Zero Emissions Guide," IEA, Paris, 2023.

[6] R. Firdous, M. Nikravan, R. Mancke, M. Voge, and D. Stephan, "Assessment of environmental, economic and technical performance of geopolymer concrete: a case study," Journal of Materials Science, vol. 57, pp. 18711-18725, 2022.

[7] J. Davidovits, Geopolymer Chemistry and Applications, 5th ed. Saint-Quentin, France: Geopolymer Institute, 2020.

[8] J. L. Provis and J. S. J. van Deventer, Geopolymers: Structures, Processing, Properties and Industrial Applications, vol. 1. Cambridge, U.K.: Woodhead Publishing, 2009.

[9] R. Devananth, V. Karthikeyan, S. Sujatha, and J. Anto, "Experimental investigation on partial replacement of fine aggregate by the effect of coal bottom ash in concrete," IOP Conf. Series: Materials Science and Engineering, vol. 983, no. 1, 012010, 2020.

[10] P. T. Selvi, "Experimental study on concrete using copper slag as replacement material of fine aggregate," Journal of Civil and Environmental Engineering, vol. 4, no. 5, pp. 1-6, 2014.

[11] V. Chakrawarthi, B. Dharmar, S. Avudaiappan, M. Amran, E. S. Flores, M. A. Alam, and R. S. M. Rashid, "Destructive and non-destructive testing of the performance of copper slag fiber-reinforced concrete," Materials, vol. 15, no. 13, pp. 4536-4550, 2022.

[12] S. A. Zamora-Castro, R. Salgado-Estrada, L. C. Sandoval-Herazo, R. A. Melendez-Armenta, E. Manzano-Huerta, E. Yelmi-Carrillo, and A. L. Herrera-May, "Sustainable development of concrete through aggregates and innovative materials: a review," Applied Sciences, vol. 11, no. 2, 629, 2021.

[13] K. S. Sreekeshava, A. S. Arunkumar, M. S. Dharek, and P. Sunagar, "Studies on inclusion of polypropylene (PP) geo-fabric in concrete," in Proc. SECON 2020, Lecture Notes in Civil Engineering, vol. 97, Springer, 2021.

[14] E. Biney, V. K. Akortia, C. K. Kankam, J. K. Q. Junior, and P. Adzakey, "Assessing structural performance of ceramic waste as partial replacement of coarse aggregate on properties of concrete," Journal of Engineering Research and Reports, vol. 23, no. 12, pp. 134-147, 2022.

[15] G. Habert, J. B. D'Espinose de Lacaillerie, and N. Roussel, "An environmental evaluation of geopolymer based concrete production: reviewing current research trends," Journal of Cleaner Production, vol. 19, no. 11, pp. 1229-1238, 2011.
[16] K. Scrivener, V. John, and E. Gartner, "Eco-efficient cement: potential economically viable solutions for a low-CO2 cement-based materials industry," Cement and Concrete Research, vol. 114, pp. 2-26, 2018.
[17] A. Martinez and S. A. Miller, "Life cycle assessment and production cost of geopolymer concrete: a meta-analysis," Resources, Conservation and Recycling, vol. 215, 108018, 2025.
[18] C. Maigualema, "Sustainability of a geopolymer designed with pumice from Ecuador," M.S. thesis, Univ. Nacional de Chimborazo, Riobamba, Ecuador, 2024.
[19] A. Mellado, C. Catalan, N. Bouzon, M. Borrachero, J. Monzo, and J. Paya, "Carbon footprint of geopolymeric mortar: study of the contribution of the alkaline activating solution and assessment of an alternative route," RSC Advances, vol. 4, no. 45, pp. 846-852, 2014.
[20] R. Vinai and M. Soutsos, "Production of sodium silicate powder from waste glass cullet for alkali activation of alternative binders," Cement and Concrete Research, vol. 116, pp. 45-56, 2019.
[21] L. K. Turner and F. G. Collins, "Carbon dioxide equivalent (CO2-e) emissions: a comparison between geopolymer and OPC cement concrete," Construction and Building Materials, vol. 43, pp. 125-130, 2013.
[22] G. M. S. Islam, M. H. Rahman, and N. Kazi, "Waste glass as partial replacement of cement for sustainable concrete practice," International Journal of Sustainable Built Environment, vol. 6, no. 1, pp. 37-44, 2017.
[23] A. Siddika, A. Hajimohammadi, W. Ferdous, and V. Sahajwalla, "Roles of waste glass and the effect of process parameters on the properties of sustainable cement and geopolymer concrete: a state-of-the-art review," Polymers, vol. 13, no. 22, 3935, 2021.
[24] P. Delgado-Plana, S. Bueno-Rodriguez, L. Perez-Villarejo, and D. Eliche-Quesada, "Synthesis of solid sodium silicate from waste glass and utilization on one-part alkali-activated materials based on spent oil filtering earth," Environmental Science and Pollution Research, 2024.
[25] M. H. Samarakoon, P. G. Ranjith, W. H. Duan, A. Haque, and B. K. Chen, "Extensive use of waste glass in one-part alkali-activated materials: towards sustainable construction practice," Waste Management, vol. 130, pp. 1-11, 2021.
[26] M. R. El-Naggar and M. I. El-Dessouky, "Re-use of waste glass in improving properties of metakaolin-based geopolymers: mechanical and microstructure examinations," Construction and Building Materials, vol. 132, pp. 543-555, 2016.
[27] S. A. Bernal and J. L. Provis, "Durability of alkali-activated materials: progress and perspectives," Journal of the American Ceramic Society, vol. 97, no. 4, pp. 997-1008, 2014.
[28] United Nations Environment Programme, "2022 Global Status Report for Buildings and Construction: Towards a Zero-Emissions, Efficient and Resilient Buildings and Construction Sector," UNEP, Nairobi, 2022.