

Wastewater Treatment Plant Secondary Sludge as a Sustainable Partial Cement Replacement for Concrete Applications

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www.jrasb.com || June 2026

Date of Submission: 01-06-2026

Date of Publication: 12-06-2026

ABSTRACT

The cement industry accounts for roughly 8% of anthropogenic carbon dioxide emissions, making supplementary cementitious materials (SCMs) that can lower the clinker factor without compromising performance a pressing priority. Secondary sludge, the biological residue produced in large quantities at municipal and industrial wastewater treatment plants, is increasingly difficult and costly to dispose of. This chapter reviews its use as a partial cement replacement through a unifying source–processing–performance–mechanism framework, covering the compositional variability of sludge, the pre-treatments that render it reactive, the mechanical and durability performance of sludge-modified concrete, and the underlying hydration mechanisms. Synthesis of the evidence indicates that replacing up to about 10% of cement with optimally processed sludge ash preserves more than 90% of the compressive strength while delivering measurable environmental benefits; beyond this level, porosity rises, strength declines, and durability deteriorates. Three barriers most strongly limit adoption: the absence of standardised characterisation procedures, the scarcity of multi-year field durability data, and the narrow geographical scope of existing life-cycle assessments. Coordinated field trials and harmonised testing standards will be decisive in moving the material into routine practice.

Keywords- Secondary sludge; sewage sludge ash; supplementary cementitious material; concrete; cement replacement; pozzolanic reactivity; durability; life-cycle assessment.

I. INTRODUCTION

Cement is among the most widely produced and most carbon-intensive materials in human history. Global output stands at roughly four billion tonnes per year, and the industry contributes close to 8% of anthropogenic carbon dioxide emissions (Nicoara et al., 2020). About 60% of that footprint is chemically unavoidable, arising from the decomposition of limestone into lime and carbon dioxide above 1450 °C. The most direct way to curb these emissions is to reduce clinker content by substituting supplementary cementitious materials (SCMs). Fly ash, blast-furnace slag, and silica fume have served this purpose for decades, but their supply is dwindling as coal-fired power stations are decommissioned and steelmaking shifts to electric-arc furnaces, prompting a search for alternatives.

Semi-solid biological sludge from wastewater treatment has attracted growing attention as one such alternative. It is produced in enormous volumes—more than 100 million tonnes of dry solids annually—and these quantities rise with urban growth and stricter effluent regulations (Al-Obaidi et al., 2021; Azeem et al., 2023). Disposal is difficult: landfilling is increasingly restricted, land application raises concerns about heavy metals and pathogens, and incineration is capital-intensive and carries a carbon penalty. Incorporating sludge into concrete offers two complementary benefits—it is diverted from landfill and can displace a portion of the clinker.

This is not new territory. Halliday et al. (2012) conducted one of the first systematic investigations of the pozzolanic properties of UK sewage sludge ash, and Vouk et al. (2018) clarified the influence of combustion temperature on reactivity. Activity has since accelerated, producing a substantial body of evidence (Al-Obaidi et al., 2021; Alam et al., 2023; He et al., 2024). The literature nonetheless remains poorly integrated: studies of sludge chemistry, pre-treatment, mechanical

performance, and environmental impact are often conducted in isolation. This review provides that connection, following a source–processing–performance–mechanism logic from the origin of the sludge, through the performance of the resulting concrete, to the hydration chemistry that underpins it. Drawing on more than 80 studies published between 2012 and 2025, it addresses sludge composition (Section 1), pre-treatment routes (Section 2), mechanical performance and durability (Section 3), hydration mechanisms (Section 4), and the environmental and economic picture (Section 5), before evaluating the evidence and identifying research gaps (Section 6) and concluding (Section 7). The overall workflow is summarised in Figure 1.

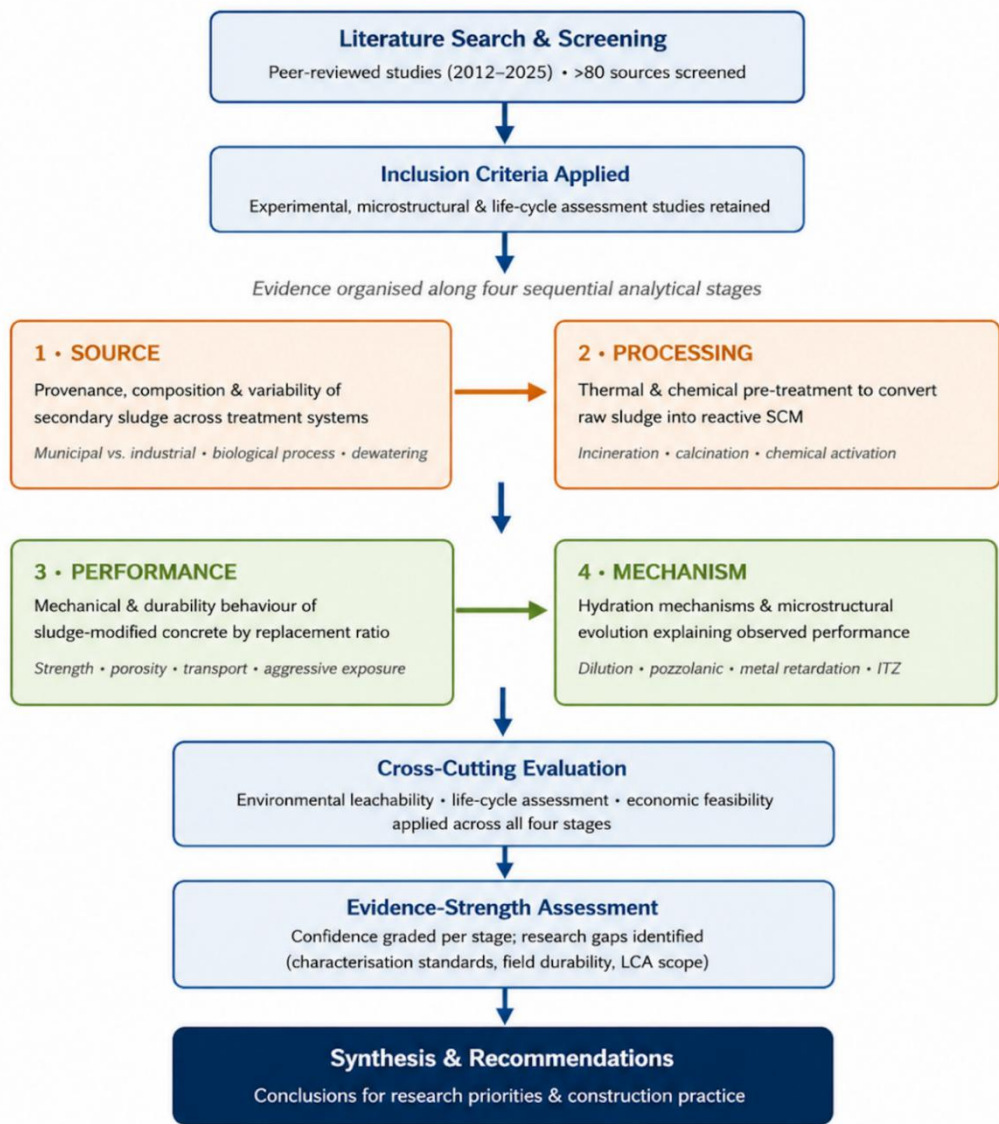


Figure 1. Methodological workflow adopted in this review, tracing the utilisation pathway from sludge source to concrete performance.

II. SLUDGE PROVENANCE, COMPOSITION, AND VARIABILITY ACROSS WASTEWATER TREATMENT SYSTEMS

2.1 Municipal versus Industrial Secondary Sludge

Composition is the single most important factor governing the suitability of secondary sludge as a cement replacement, and also one of its most variable. The solids from activated-sludge treatment of domestic wastewater are mostly inorganic, typically containing 50–70% volatile solids alongside 20–35% SiO₂, 8–18% Al₂O₃, 5–15% Fe₂O₃, and 5–12%

CaO (Al-Obaidi et al., 2021; Azeem et al., 2023). After thermal removal of the organic fraction, the residue is an ash rich in reactive aluminosilicate phases. The combined $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$ content generally falls between 50% and 70%, which usually meets the 50% minimum for natural pozzolans (Class N) in ASTM C618 but not the 70% threshold for fly ash. Municipal sewage sludge ash (SSA) is therefore a moderate-reactivity SCM rather than a direct fly-ash substitute.

Industrial sludges are far more heterogeneous. Those from textile, electroplating, tannery, and chemical processes can carry much higher concentrations of zinc, copper, chromium, lead, and nickel (Oliva et al., 2019; Xin et al., 2019), and their oxide profiles are skewed—electroplating sludge may contain 30–50% Fe_2O_3 with under 10% SiO_2 , while tannery sludge can hold up to 5% Cr_2O_3 . Vouk et al. (2018) showed that SSA chemistry tracks the wastewater, treatment chemicals, and combustion conditions, reporting 25–42% SiO_2 and 5–18% P_2O_5 in ash from two Croatian plants. High- Fe_2O_3 ashes are less reactive than high- Al_2O_3 ones, and elevated P_2O_5 retards hydration by precipitating calcium phosphate on clinker grains. Municipal sludge can thus be treated as a candidate SCM requiring only routine characterisation, whereas industrial sludge demands source-specific screening of oxide chemistry and heavy-metal content—a distinction existing reviews seldom draw.

2.2 Influence of the Biological Treatment Process

The biological treatment process itself influences sludge composition. Conventional activated-sludge (CAS) systems operating at solids retention times (SRT) of 5–10 days yield a high organic fraction (65–75%) dominated by quartz and clay minerals. Extended-aeration systems (SRT 20–30 days) promote endogenous respiration, lowering the organic fraction to 55–65% and enriching the inorganic residue. Membrane bioreactors (MBRs) produce finer, higher-ash sludge by retaining colloidal particles that would otherwise pass through clarifiers (Azeem et al., 2023; Gao et al., 2020). Oliva et al. (2019) found that MBR sludge yielded 12–18% more ash than CAS sludge from the same catchment, with about 15% higher amorphous content, because finer particles vitrify more readily during incineration. High-retention, high-shear processes therefore generate a more reactive ash, so the choice of treatment technology exerts an indirect but significant influence on valorisation potential.

2.3 Effects of Dewatering and Stabilisation

The final treatment steps further modify reactivity. Anaerobic digestion converts much of the volatile solids to biogas, raising the ash-to-organic ratio; this lowers the loss on ignition and limits porosity from organic decomposition, though it may leave recalcitrant humic substances that interfere with C-S-H nucleation (Kaszycki et al., 2021; Michalska et al., 2022). Lime stabilisation adds calcium that can supplement the CaO available for pozzolanic reaction—Gu et al. (2022) reported slightly higher early-age strengths for lime-stabilised ash—but excess lime leaves free CaO, causing unsoundness through delayed expansion. Finally, dewatering moisture content governs the energy balance of thermal treatment: drying a 20%-solids cake requires roughly three times the energy of a 35%-solids cake (Gao et al., 2020), a difference that can determine whether the pathway is net carbon-positive or negative—an often-overlooked consideration discussed in Section 5.

III. THERMAL AND CHEMICAL PRE-TREATMENT PATHWAYS

3.1 Incineration and Sewage Sludge Ash

Incineration is the most industrially mature route. In a fluidised-bed incinerator operating at 800–900 °C, the organic fraction is combusted and the inorganic fraction becomes a fine ash (SSA) representing 30–40% of the dry mass. Its main advantage is throughput—hundreds of tonnes per day from a single unit. Temperature and cooling rate govern reactivity: Vouk et al. (2018) found that the amorphous content fell from about 55% to below 30% as the temperature rose from 800 to 1000 °C, with mortar strength dropping from 42 to 31 MPa (against 52 MPa for the control). Juala et al. (2022) confirmed that rapid quenching from 800 °C raised the amorphous content and the strength activity index by about 20%. Because industrial incinerators run at 850–950 °C to destroy micropollutants, a trade-off arises between throughput and reactivity. Oliva et al. (2019) addressed this with a dual-fired design—combustion at 900 °C followed by a quench below 700 °C—which raised the amorphous content from 38% to 62% and the 28-day activity index from 72% to 88% at laboratory scale, though industrial scale-up remains uncertain. Consequently, SSA from existing municipal incinerators is likely less reactive than ash from dedicated facilities, a distinction important when interpreting the wide variability in published data.

3.2 Low-Temperature Calcination

Calcination at 500–700 °C trades throughput for better phase control and lower energy use. The clay minerals are dehydroxylated without full vitrification, yielding a reactive, partially dehydroxylated aluminosilicate. Zhang et al. (2024) found that ash calcined at 600 °C gave the highest compressive strength across all replacement levels (10–40%) and curing ages, owing to its higher specific surface area and more reactive dehydroxylated phases that nucleate C-S-H. The energy savings are substantial: Gao et al. (2020) estimated 1.8–2.2 MJ kg⁻¹ for 600 °C calcination versus 3.5–4.5 MJ kg⁻¹ for incineration at 850 °C, equating to a 40–55% reduction in carbon dioxide emissions relative to Portland cement. Calcination achieves less volume reduction (40–50% versus 60–65%), and residual carbon may impart an unwanted grey or black colour. Xia et al. (2023) showed that co-combusting sludge with silica-rich rice husk raised the ash SiO_2 content to 58–65% and the

28-day activity index to 92% at 20% replacement, approaching coal fly ash, through formation of a more reactive amorphous phase.

3.3 Chemical Activation and Co-Processing

Chemical activation provides a non-thermal route. Alkali activation with sodium hydroxide or silicate dissolves the aluminosilicate fraction and precipitates a strength-giving gel: Guo et al. (2023a) reported 35–42 MPa at 28 days for alkali-activated composites with 30% sludge, against 18–24 MPa for water-cured equivalents. Lime activation is a lower-cost variant—Zhou et al. (2020) found that adding 10% CaO raised the 28-day strength at 20% SSA replacement from 28 to 38 MPa, with the CaO/SSA ratio critical (below 0.1 gave weak activation, above 0.2 caused free-CaO expansion). Acid leaching can remove 80–90% of zinc and copper before cementing (Zhi et al., 2024), though acid cost and leachate management remain obstacles. Blending sludge with other by-products raises overall reactivity and dilutes heavy metals: Guo et al. (2023b) found that an equal-parts SSA:slag:fly-ash mixture reached a 28-day activity index of 95%, against 72% for SSA alone.

IV. MECHANICAL PERFORMANCE AND DURABILITY OF SLUDGE-MODIFIED CONCRETE

4.1 Compressive and Flexural Strength

The relationship between replacement ratio and compressive strength is the most thoroughly documented property: above about 10% replacement, strength declines approximately linearly. At 5% replacement, the 28-day strength is 92–98% of the control—within normal batch variation (Kaish et al., 2021; Shamaki et al., 2021)—falling from 85–93% at 10% to 60–78% at 20%, depending on sludge type, water-to-binder ratio, and curing (Alam et al., 2023; Amminudin et al., 2020; Rabie et al., 2019). Zhang et al. (2024) reported that at a water-to-binder ratio of 0.4, the 10% mix reached 48.2 MPa (92% retention) and the 20% mix only 34.6 MPa (66%), against 52.5 MPa for the control; counterintuitively, the loss was greater at low ratios, attributed to poor workability and compaction. Flexural strength follows a comparable pattern—Kaish et al. (2021) observed reductions of 8–15% at 10% and 25–35% at 20% alum-sludge replacement—while the flexural-to-compressive ratio stayed broadly constant. Crucially, Shamaki et al. (2021) found the loss at 20% replacement about 30% greater than dilution alone predicts, implying that sludge actively inhibits hydration or adds porosity.

4.2 Water Absorption, Porosity, and Transport Properties

Sludge consistently increases water absorption and porosity. Rabie et al. (2019) measured a rise in 28-day absorption from 5.2% (control) to 7.8% (20% dry sludge) and 9.4% (20% wet sludge), the higher wet-sludge value reflecting added mixing water. Lv et al. (2024) recorded porosity rising from 18.5% (control) to 24.7% (20% SSA) and 31.2% (30% SSA), with the pore distribution shifting towards larger capillary pores (100–1000 nm) at the expense of gel pores. These changes raise transport properties that govern durability: sorptivity is typically 30–80% higher at equal replacement, and the chloride diffusion coefficient increases by a factor of 1.5–3.0 at 20% replacement (K et al., 2024; Kadhim et al., 2021). Without additional protection such as increased cover or corrosion inhibitors, sludge-modified concrete is therefore unsuitable for embedded steel in chloride-rich environments.

4.3 Long-Term Durability Under Aggressive Exposure

Durability data are scarcer than mechanical data, and the losses are proportionally larger. After freeze–thaw cycling (ASTM C666), the relative dynamic modulus drops 20–40% at 10–15% replacement, worsening as replacement rises (Devi et al., 2023; K et al., 2024), driven by the larger capillary-pore volume admitting more freezable water. Alam et al. (2023) found that ettringite-driven sulphate expansion at 20% replacement was up to twice the control's after 12 months in 5% sodium sulphate, because higher permeability admits more sulphate while diluted clinker supplies less buffering $\text{Ca}(\text{OH})_2$. With chloride resistance also falling 1.5–3.0-fold, sludge-modified concrete beyond about 10% replacement is unlikely to meet EN 206 or ACI 318 durability provisions for exposure classes XS2 and XS3. This does not preclude non-structural uses such as pavers, blocks, and low-rise masonry, but for structural reinforced concrete the acceptable level is confined to roughly 5–10%.

V. HYDRATION MECHANISMS AND MICROSTRUCTURAL EVOLUTION

5.1 The Dilution Effect

The dominant cause of strength loss is dilution—the reduction in clinker volume fraction as binder is replaced by less reactive material. If the ash contributes no hydrates, the quantity of C-S-H, portlandite, ettringite, and AFm phases falls in proportion to the mass substituted. Zhang et al. (2024) reported chemically bound water (a proxy for hydrate volume) decreasing from 14.8% (control) to 12.1% (20% SSA) and 9.8% (30% SSA), with portlandite falling more modestly (3.8% to 3.2% at 20%) owing to partial pozzolanic consumption. Comparison with a rule-of-mixtures model suggests dilution accounts for roughly half the loss at 10–20% replacement; the remainder arises from incomplete pozzolanic compensation, heavy-metal retardation, and ITZ deterioration. Only dilution is independent of sludge type and therefore sets a fundamental lower bound on strength loss.

5.2 Pozzolan Reactivity and Secondary C-S-H

Sludge ash can partly offset this loss through the pozzolanic reaction ($\text{amorphous SiO}_2 + \text{Ca(OH)}_2 + \text{H}_2\text{O} \rightarrow \text{C-S-H}$). Using selective dissolution, Xia et al. (2023) estimated 15–22% of SSA reacted by 28 days and 25–35% by 90 days, against 40–55% for fly ash, reflecting SSA's lower amorphous content (40–60% versus 70–90%) and its inert crystalline phases. Guo et al. (2023b) found the secondary C-S-H had a lower Ca/Si ratio (1.0–1.5) than primary C-S-H (about 1.7); by precipitating in the capillary pore space it partly refills dilution-induced porosity, explaining the modest strength gain between 28 and 90 days. El-Didamony et al. (2015) concluded that for fired drinking-water sludge a filler effect—acceleration of hydration by additional nucleation sites—dominated over the pozzolanic reaction, implying that even low-reactivity ash may confer benefit through physical means.

5.3 Heavy-Metal Retardation and ITZ Deterioration

Heavy metals, particularly zinc, copper, and lead, introduce a distinct chemical interference. Above roughly 10–50 mg L⁻¹ in the pore solution they precipitate insoluble compounds on cement grains, forming a diffusion barrier that slows clinker dissolution (Niu et al., 2015; Wang et al., 2015); zinc is the most potent, with 0.1% by mass appreciably extending setting time. Zhang et al. (2024) observed the main hydration peak for 20% SSA paste delayed 4–6 hours and the 72-hour heat of hydration reduced 10–15%, linked to a zinc content (0.12%) too low to pose an environmental concern but enough to affect early kinetics. The effect compounds the early-age strength deficit and may require an accelerating admixture or extended curing, though it typically dissipates within 7–14 days. Organic matter further weakens the interfacial transition zone (ITZ) by depositing on grain and aggregate surfaces and suppressing C-S-H formation (Ho and Huynh, 2023; Shuldyakov et al., 2018); because the ITZ governs load transfer and ion ingress, its deterioration amplifies losses in strength and durability beyond what bulk-paste properties predict.

VI. Environmental Leachability, Life-Cycle Assessment, and Economic Feasibility

6.1 Heavy-Metal Immobilisation and Leaching

The foremost environmental concern is leaching of heavy metals during service and at end of life. The matrix immobilises them by physical encapsulation within low-permeability hydrates and by chemical fixation in C-S-H, ettringite, and AFm. Leaching tests indicate effective immobilisation at 20–30% replacement: Alamin et al. (2024) found TCLP leachate concentrations of zinc, copper, chromium, and lead one to two orders of magnitude below hazardous-waste thresholds, and Wang and Shui (2023) reported chromium and lead release below 1% of total content after 64 days (NEN 7345). Long-term stability under matrix degradation is less certain—Müllauer et al. (2012) showed that carbonation can lower the pore-solution pH below 9 and remobilise metals—and field data spanning decades are absent. Until multi-year field studies exist, risk assessment must rely on conservative assumptions and accelerated tests, introducing uncertainty into life-cycle assessment.

6.2 Life-Cycle Assessment

Life-cycle assessment (LCA) weighs the benefit of valorisation against the processing it requires, but the evidence is limited in coverage and consistency. Habibi et al. (2022) reported GWP reductions of 5–30% for SCM concretes depending on type, transport distance, and allocation, while Mekky et al. (2025) found 12–18% reductions at 10% sludge replacement. The net balance is highly sensitive to the system boundary and allocation: treating sludge as a waste (cut-off) maximises the apparent saving by charging only the extra processing to the concrete, whereas economic allocation reduces it. Yang et al. (2023) showed that the benefit of using incinerated ash depended on whether incineration was accounted for within the waste or concrete system—an unresolved ambiguity. Most LCAs also reflect European or East Asian conditions; region-specific factors such as grid carbon intensity and transport distance can alter the net result by a factor of two or more.

6.3 Economic Feasibility and Scale-Up Barriers

Viability depends on cement savings against processing, quality-control, and compliance costs. Processing—dewatering, thermal treatment, and grinding—costs an estimated €30–60 per tonne of ash, weighed against displaced cement (€80–120 per tonne) and avoided disposal (landfill gate fees of €20 to over €100 per tonne). The case is strongest where avoided landfill costs exceed about €40 per tonne, cement prices are high, and plants are co-located, yielding net savings of €10–20 per cubic metre; carbon pricing and landfill taxes can shift this either way (Nicoara et al., 2020; Pešta et al., 2020). The principal barriers, however, are logistical and regulatory: sludge variability frustrates quality control in the absence of a standardised characterisation protocol comparable to ASTM C618; co-location is awkward because concrete and treatment plants are usually sited apart; and approving a new SCM requires years of testing and assessment.

VII. RESEARCH GAPS AND FUTURE DIRECTIONS

The evidence is distributed unevenly across the framework. The source and nature of sludge are understood with medium confidence: its variability is well established, but bulk chemistry correlates poorly with SCM reactivity, so standardised characterisation methods—modelled on the fly-ash and slag specifications—are needed for cross-study comparison and quality control. Pre-treatment pathways carry moderate confidence: laboratory effects of temperature and

cooling rate are well characterised but not yet translated to industrial scale, and pilot trials at 10–100 tonnes per day are required. Mechanical performance is high-confidence for the strength–replacement relationship, providing a basis for conservative non-structural design, but long-term durability data are limited and mostly short-term; multi-year field exposures are the most significant gap.

Hydration mechanisms carry moderate confidence: dilution, pozzolanic reaction, and metal retardation are each supported, but no study has partitioned the strength loss quantitatively among them, and the roles of organic matter in suppressing C-S-H nucleation and weakening the ITZ remain unproven—advanced techniques such as NMR spectroscopy and nanoindentation could supply the needed detail. Environmental and economic assessment is low-confidence: the LCA base is small and European-dominated, long-term field-leaching data are unavailable, and economic analyses rest on assumptions that may not generalise. Three cross-cutting priorities follow: standardised characterisation protocols, multi-year field durability studies, and region-specific LCAs. Coordinated, multi-site, multi-year programmes addressing these concurrently would transform isolated laboratory studies into an evidence base able to support standards and deployment.

VIII. CONCLUSIONS

Applying a source–processing–performance–mechanism framework, this chapter draws five principal conclusions. First, the composition of secondary sludge is highly variable and is the chief determinant of suitability; municipal sludge supports moderate pozzolanic reactivity after thermal treatment, whereas industrial sludge requires source-specific screening. Second, the three pre-treatment routes embody a trade-off among throughput, reactivity, and energy: incineration (800–900 °C) maximises volume reduction but crystallises mineral phases; calcination (550–650 °C) preserves reactive phases at roughly half the energy cost; and chemical activation delivers competitive reactivity without heat, at the expense of reagent and effluent costs.

Third, mechanical performance is governed by a replacement threshold—above 90% strength is retained at 5–10%, but beyond about 15% porosity rises and durability deteriorates, confining use to non-structural elements; durability losses are proportionally greater than strength losses and limit structural use. Fourth, four mechanisms account for the strength loss—dilution, incomplete pozzolanic compensation, heavy-metal retardation, and ITZ deterioration—of which dilution is dominant and sets a lower bound that processing alone cannot overcome. Fifth, the environmental case is supported by good heavy-metal immobilisation and GWP reductions of 10–30% at 10% replacement, but evidence for long-term performance remains thin. Realising the material's potential depends on closing three gaps: standardised characterisation, multi-year field durability data, and region-specific LCAs. A coordinated, multi-site programme addressing these concurrently would move sludge-based SCMs from the laboratory into mainstream construction practice.

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