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Treatment, Replacement Basis and Contaminant Release in Cementitious Mixtures Containing Mswi Fly Ash and Apc Residues: A Quantitative Review of Accessible Experimental Evidence

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Abstract

Municipal solid waste incineration (MSWI) residues are investigated as cementitious constituents, but treatment benefits can be misinterpreted when fly ash and air-pollution-control (APC) residues, replacement denominators, and leaching conditions are combined. This review asks what source-verified, matched comparisons show about treatment, compressive strength and product contaminant release. A prospective extraction and analysis protocol preceded numerical extraction. Six targeted queries were executed in Crossref and OpenAlex on 7 October 2026, retrieving the first 100 records per query and provider. After deduplication and documented machine-assisted title triage, complete accessible original papers were assessed. Confirmed fly ash, APC residues and unresolved collection streams were separated. Exact printed values were extracted without graph-coordinate digitization; censored results were retained. Within-study ratios were calculated only for interpretable comparisons. Search restrictions and a subsequent focus on cement-containing systems are disclosed. The bounded search yielded 1,200 metadata records and 763 unique candidates. Of 98 reports sought, 28 were retrieved and 11 included; 70 reports remained inaccessible. The dataset contains 55 exact strength means, six source-reported relative strength results and 573 product-leaching entries, including controls and censored entries. In one APC study, incremental milling after washing at 35% replacement increased 28-day strength from 22.3 to 32.4 MPa while Cd, Cr and Zn extract concentrations decreased by 98.0%, 91.4% and 38.3%, respectively. In confirmed fly ash, combined washing and electrodialysis increased late-interval Pb release from 3.4 to 14 mg/m² in acidic-start water, despite reductions in selected other endpoints. Heating previously washed ash produced opposing responses by analyte and extraction method. A UHPC series showed strength retention declining from 94.3% to 60.7% across 6–24% ash by total binder mass; these doses correspond to 7.79–31.17% displacement of reference OPC. No strength study met strict confirmed-fly-ash classification, and no pooled estimate or confidence interval was justified. Treatment cannot be assigned a universal strength or environmental benefit. The strongest joint matched comparison concerned a single APC stream, whereas confirmed-fly-ash evidence was leaching-only. Replacement basis, reference mixture and exposure protocol must remain explicit. The evidence supports study-specific tradeoffs and improved experimental reporting, rather than an optimal replacement percentage or construction-safety claim.

Keywords: MSWI Fly Ash, Air-Pollution-Control Residue, Cement Replacement, Compressive Strength, Contaminant Leaching, Comparator Validity, Quantitative Evidence Review.

INTRODUCTION

Reuse of municipal solid waste incineration residues in construction has attracted extensive research, encompassing mineral additions, binders, aggregates and immobilization matrices. Reviews already cover the construction applications of MSWI ashes, treatment technologies and residue valorisation [1–3]. An adjacent systematic review and meta-analysis addresses MSWI bottom ash in concrete [4]. These existing syntheses make a broad claim of novelty for "MSWI ash in cementitious materials" untenable. They also show why an analysis must define its residue and substitution role before drawing conclusions about treatment.

The term "fly ash" is used inconsistently in experimental publications. Entrained combustion particles collected upstream of sorbent injection can differ from bag-filter mixtures that contain lime, activated carbon and acid-gas reaction products. Both may contain contaminant-bearing particles, but their composition,

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soluble salts and response to processing need not be interchangeable. Bottom ash, boiler deposits and coal fly ash are separate materials. Chemical composition alone cannot identify the collection stream, and a fine particle size does not convert milled bottom ash into fly ash. This review therefore retains the authors' original terminology while assigning an independently justified collection-stream category.

Treatment and replacement also describe different interventions. A washed-ash mortar compared with neat cement measures the behavior of the complete ash-containing formulation; it does not identify the effect of washing. A treated-ash mixture compared with an otherwise matching raw-ash mixture can identify a treatment-package contrast. A dose series describes replacement-associated behavior within its particular ash, binder, water demand and curing conditions. Across-study comparisons may confound all these factors. Combining the three estimands obscures whether an apparent benefit comes from contaminant removal, improved particle packing, a reactive co-binder, a changed water ratio or a different reference cement.

Environmental interpretation creates another difficulty. An aqueous batch extract from crushed mortar, an acetic-acid extraction and an interval maximum from a partially renewed monolith test are different endpoints. Concentrations inmg/L, mass-normalized releasemg/kg and area-normalized releasemg/m² cannot be pooled as equivalent quantities. A reduction relative to raw ash may include dilution by the cementitious matrix. Conversely, lower concentrations of one metal do not imply lower release of all analytes. Laboratory compliance assertions require an applicable criterion and a test configuration consistent with that criterion; neither establishes service-life exposure or structural suitability.

Yan and Keokhumcheng [5] examined implementation concerns through five professional interviews. Their qualitative contribution motivates attention to treatment, performance and environmental acceptance, but it does not provide a new experimental dataset for this review. Here, experimental observations were collected independently from original publications. No interview transcript, thematic table, figure or secondary numerical claim from that article was used as a new finding.

The initial question was how treatment method and cement replacement percentage influence strength and leaching. Scoping showed that the broad subject was already reviewed and that accessible studies offered few isolated treatment contrasts with adequate variance. We consequently refined the operational question: in separately classified MSWI fly ash and APC residues used in cement-containing matrices, what do matched comparisons and documented replacement series show about strength and analyte-specific product release? This refinement is comparator-focused and does not establish that the exact synthesis is unprecedented. Several closely related reviews were identified but could not be assessed in full text. The contribution is the transparent audit of collection streams, replacement bases, source discrepancies and paired outcomes within a bounded evidence set.

METHODS

Protocol, Scope And Reporting

A dated prospective protocol specified eligibility, extraction fields, comparison types, missing-data handling and conditional analysis before numerical extraction. It was not registered, and no registration identifier is claimed. The accompanying amendment log records the later focus on cement-containing paste, mortar and concrete; non-Portland alkali-activated systems and non-cement replacement were retained as contextual leads rather than combined with the focused synthesis. This restriction followed scoping and some initial extraction and is explicitly post-protocol.

PRISMA 2020, PRISMA-S and SWiM informed reporting of selection, searches and synthesis without meta-analysis [6–8]. Figure 1 uses reconciled selection accounting. These frameworks do not make a limited metadata search exhaustive. The work is described as a bounded quantitative evidence review, because retrieval caps, source-access restrictions and automated title rules limit the completeness expected of a full systematic review.

Search Execution and Novelty Assessment

Crossref and OpenAlex were searched on 7October 2026 using six executed queries: "municipal solid waste incineration fly ash cement treatment compressive strength leaching review" ; "municipal solid waste incineration fly ash meta-analysis" ; "municipal solid waste incineration fly ash systematic review" ; "municipal solid waste incineration fly ash concrete washing leaching compressive strength" ; "municipal

solid waste incineration fly ash cement carbonation leaching strength" ; and "municipal solid waste incineration fly ash thermal treatment mortar leaching" . Two pages of 50 records were saved for each query-provider pair:24 successful pages, totaling 1,200 downloaded records. Queries were metadata relevance searches rather than controlled database Boolean searches. Provider ordering and caps affect recall. Initial failed requests and separate broad probes are retained, but failed requests were not treated as zero-result searches and provider-estimated totals were not counted as downloaded records.

Supplementary targeted discovery explored washing, carbonation, thermal processing and relevant reviews. Four accessible review full texts were read for novelty and scope assessment [1–4]. These contextual discovery logs are separate from the primary 1,200-record selection denominator. All 11 included experimental reports were present in the primary metadata set; supplementary discovery therefore added no otherwise missing included study to Figure 1. Full-text sources were original publisher articles or an archived original article in PubMed Central. Search snippets, reviews and abstracts did not supply experimental numbers. Scopus and Web of Science were not searched, and no access to them is implied.

The exact requests, retrieval timestamps, query pages, raw responses and deduplication groups are archived. Because this search does not exhaust the topic, "no matching review found in accessible full text" is weaker than "no matching review exists" . We use the former interpretation and make no first-review claim.

Eligibility and Selection

Eligible focused reports described original cement-containing paste, mortar or concrete with an identifiable MSWI-fly-labelled/APC binder constituent, a replacement or binder-composition design, and compressive strength or release from a hardened product. Reports lacking dispersion could contribute narrative or point-valued results. Co-binder and manufactured blended-cement designs were included descriptively when their ash role was documented; they were not assigned an isolated ash-treatment effect.

Wrong ash streams, sand/aggregate substitution without eligible binder substitution, asphalt, soil stabilization, brick manufacture, raw-ash-treatment-only reports, reviews and non-Portland geopolymers were excluded from the focused outcome synthesis. Bottom-ash and coal-ash arms within otherwise relevant papers were not extracted as eligible fly-ash outcomes. A paper with product release but no strength remained eligible. Full-text inaccessibility was recorded as "not retrieved" , not as a scientific exclusion.

DOIs were normalized and duplicate records grouped by DOI or title/author information. Documented automated title rules excluded obvious non-primary or wrong-topic records and prioritized potentially relevant or uncertain MSWI/APC titles for retrieval. The rule requiring identifiable municipal-incineration/APC terminology can miss papers with nonspecific titles; no dual independent human title/abstract screen is claimed. Retrieved original papers received source-level eligibility adjudication and a principal exclusion reason. Extraction assistants and a root verification pass supported checking, but they are not independent human reviewers. Record-level decisions and access errors remain available for reassessment.

Extraction and Ash Classification

Linked datasets preserve study identifiers, DOI, collection stream, treatment sequence, mix design, replacement denominator, specimen, age, sample-size statements, strength, dispersion, leaching method, analyte, result qualifier, units, limits and exact source location. A source-verification log connects each numerical observation to the retained full text. Original reported strings and normalized numerical fields are separate. Exact printed prose values, tables and numerical figure labels were used; no curve heights were reverse-engineered and no pixel-coordinate digitization was performed. Unlabelled curves contribute narrative results rather than invented point estimates.

Three retained stream categories were used: confirmed entrained MSWI fly ash; APC residue identified through gas-cleaning/sorbent collection; and author-labelled fly ash with an unresolved collection point. Ash-free controls retain their own status. Ebert et al. [12] investigated two confirmed fly-ash streams and one APC stream in the same paper; these were separated at observation level. High chloride or calcium was not used alone to assign APC identity.

Replacement was recorded in the authors' original basis. When mix masses permitted an additional denominator, it was calculated and labelled. For an ash massm_a, total binderm_b, and OPC mass in the ash-free reference$m_{c,0}$ (Eq.1):

$$p_b = 100m_a/m_b, \qquad p_{c,0} = 100m_a/m_{c,0} \tag{1}$$

These expressions are equal only when the reference binder is entirely OPC and substitution is mass-for-mass. Treated-powder replacement may include reagents; a pre-calcination feed fraction is not necessarily the final ash-origin mass fraction after volatile loss. Unknown yields and reagent denominators were not filled in.

Leaching Harmonization and Censoring

Raw-ash extracts were retained in original detailed extractions as context and excluded from the product-leaching dataset. Aqueous concentrations, mass-normalized release and area-normalized release were separate endpoints. For compatible aqueous units, 1 µg/L=0.001 mg/L, 1 ng/mL=0.001 mg/L and 1 µg/mL=1 mg/L. These are dimensional conversions, not evidence that extraction methods are equivalent. No conversion betweenmg/L andmg/kg was applied without a fully supported mass balance, andmg/m² interval maxima were not summed into cumulative release.

ND, blq, ELQ and dashes were retained with their source meaning. Some dashes indicated either below detection or no increment over the initial solution concentration. If a detection/quantification limit was unknown, no zero, half-limit or small positive substitute was assigned. A reported limit was recorded when available, but ambiguous limits did not yield fabricated finite treatment ratios. Exact zero was distinguished from a censored value. Unknown product age, pH, extraction duration, liquid-to-solid ratio and replication remained unknown rather than borrowed from a cited standard.

Comparison Validity and Quantitative Synthesis

For positive quantified outcomes under an interpretable within-study comparison, the response ratio and descriptive percentage change were (Eq.2):

$$R = y_t/y_c, \qquad \log R = \ln(y_t) - \ln(y_c), \qquad \Delta\% = 100(R-1) \tag{2}$$

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Comparison Validity and Quantitative Synthesis

For positive quantified outcomes under an interpretable within-study comparison, the response ratio and descriptive percentage change were (Eq.3):

$$R = y_t/y_c, \qquad \log R = \ln(y_t) - \ln(y_c), \qquad \Delta\% = 100(R-1) \tag{3}$$

For strength, a ratio above 1 denotes a larger reported mean. For leaching, it denotes larger release under the specified analyte/protocol/exposure conditions. Ratios are point comparisons, not significance tests. Original and comparator observation IDs and a shared-control identifier are stored with every derived effect. Multiple analytes, windows and dose arms sharing a comparator were not counted as independent studies.

Three comparison types were kept distinct: incremental treatment of an otherwise matched ash-containing mixture; complete incorporation/formulation versus an ash-free cementitious reference; and within-series replacement association. Combined washing/electrodialysis was a package, while milling or heating an already washed ash was an incremental treatment. Washed ash was not relabelled “untreated” . CaO-containing packages and alternative binder formulations were not interpreted as isolated milling, thermal or carbonation effects.

No inverse-variance model, pooled dose slope, statistical heterogeneity estimate or sampling confidence interval was calculated. Independent production-batch replication was not established sufficiently, and numerical SD or labelled dispersion was generally absent for the decisive comparisons. Technical specimen replication was recorded without treating it as independent ash batches. Undefined “±” quantities and unidentified error bars were not converted into SD. Each numerical ratio was checked independently with Decimal arithmetic; arithmetic agreement does not validate an experiment or establish uncertainty.

Quality, Joint Outcomes and Sensitivity Analyses

Applicability was judged in separate domains: ash identity, treatment reproducibility, comparator validity, independent replication/variance and product-leaching reporting. Judgments were adequate, some concern, major concern or unclear, with “not measured” where applicable. No unvalidated aggregate score or quality weight was assigned. Adequacy was purpose-specific: a paper could support a within-protocol release contrast while failing to identify a treatment effect on strength.

Joint interpretation required strength and product-leaching results from the same identifiable experimental series. This does not require that both were measured on the identical specimen, nor imply a synchronized age when the source omitted it. Strict-stream, matched-treatment, 28-day-age, replacement-basis and reporting-quality restrictions were examined descriptively. They test which claims remain supported, rather than recalculate an unavailable pooled estimate. The manuscript, CSV tables and figures were cross-checked against the same dataset; a separate claims register links the highlighted numerical findings to observations and equations.

RESULTS

Selection and the Accessible Evidence Set

The 1,200 metadata records formed 763 unique candidate groups after 437 duplicate records were removed. Title-rule triage excluded 665 groups and 98 reports were sought. Twenty-eight full texts were assessed, 70 reports were not retrieved, and 17 assessed reports were excluded, leaving 11 included reports/studies(Figure 1). Full-text reasons included wrong replacement target or product, wrong ash/matrix, no eligible hardened-product outcome, non-primary review and a non-Portland alkali-activated system outside the focused scope. Access failures are listed individually. These counts describe downloaded records and actual decisions, not provider-estimated literature totals.

The included studies span 2019–2025 [9–19]. Table 1 describes their streams, matrices and available outcomes, and Table 2 records treatment and denominator caveats. The structured outcome dataset contains 55 exact strength means and 573 product-leaching entries; 314 release entries are quantified and 259 are censored or otherwise lack a usable numerical value. The 573 entries include ash-free controls and multiple analytes/windows, so they are neither 573 independent experiments nor 573 treatment effects. Six additional relative strength results are preserved from source-reported percentages [18].

Eight studies contribute exact strength means, and one additional study contributes source-reported relative strength. Eight have numerical product-release entries; Wang et al. [10] additionally report product release in unlabelled graphs and qualitative tables, but concentrations were not digitized. Six reports provide exact numerical strength and numerical product-leaching observations in the same experimental series(Table 6). Qiu et al. [19] report strength qualitatively and product-release values, but mapping the strength series to the leaching formulations was insufficient for an exact joint comparison. Figure 2 separates outcome availability from valid comparator availability.

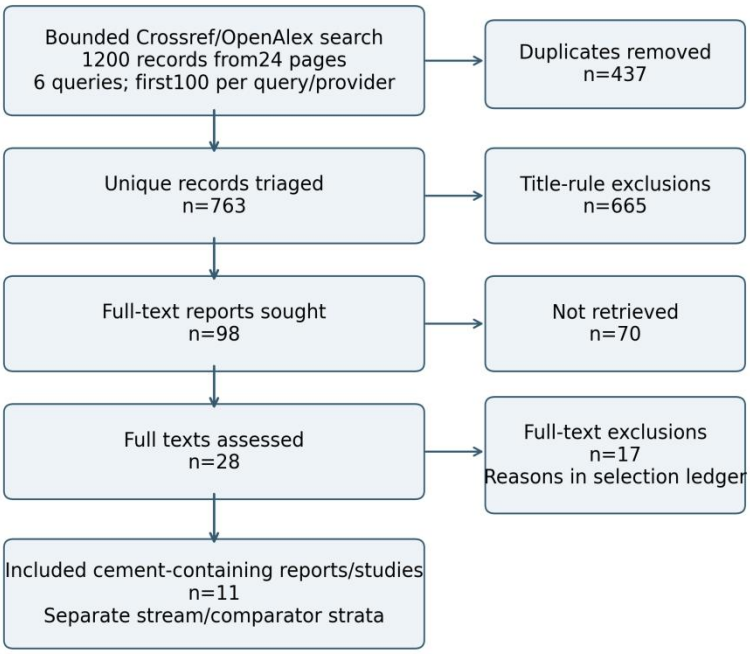


Figure 1. Reconciled Selection of the Bounded Crossref/Openalex Evidence Set. Supplementary Discovery Supplied Context and Source Access but No Additional Included Study Absent from this Metadata Set

Table 1. Included Reports, Ash-Stream Classification and Outcome Availability

Study	Ash Stream	Cementitious Matrix	Outcome Availability
Czop 2019	APC	CEM I mortar	Strength + product release
Wang 2020	Unresolved	OPC–slag paste	Strength + qualitative product release
Pan 2022	APC	OPC mortar	Strength + product release
Ebert 2022	Confirmed FA + APC	CEM I mortar	Product release only
Czop 2022	Unresolved	CEM I mortar	Strength + product release
Marieta 2023	APC	Clinker–SCM mortar	Strength + product release
He 2023	Unresolved	Prepared clinker cement mortar	Strength + product release
Poranek 2024	APC	CSA–OPC–zeolite mortar	Strength; raw ash release only
Liu 2025	Unresolved	UHPC, OPC/SF/slag	Strength + product release
Song 2025	Unresolved	Recycled-aggregate concrete	Reported relative strength only
Qiu 2025	APC	OPC–slag paste	Strength narrative + product release

Table 2. Treatment Sequences, Replacement Bases and Principal Design Caveats

Study	Reported Dose (%)	Treatment/Design and Interpretation
Czop 2019	30 nominal	No deliberate ash pretreatment; cement encapsulation; Water masses and ash mass incompletely reported
Wang 2020	20 in OPC arms	Binder-composition design; ash not pretreated; OPC28–70%; ash 20% fixed; no ash-free reference
Pan 2022	35/50/65 treated powder	Two washes; 500rpm milling 10 h; optional CaO; CaO 0/15/30/45% denominator unresolved
Ebert 2022	10 cement mass	Three washes + electrodialysis 28d,1A; AMA/NUU confirmedFA; RYA APC; no strength
Czop 2022	4/8/18 nominal	Binder nanomaterial addition; no ash pretreatment; Ash mass missing; water/cement changes; nano identity inconsistent
Marieta 2023	40 treated SCM	Hydrothermal 200°C, 1 h; composite calcination 1000–1050°C; SCB2 40% composite =22% nominal pre-calcination ash feed; binder control differs
He 2023	5/10/15 total cement	Previously washed; 500 °C, 1 h air/CO2/N2; Exact ash strengths only 15%; leaching 15%; no exact washed reference strength
Poranek 2024	5.8 nominal	No ash pretreatment; blend/zeolite encapsulation; Dose arithmetic unresolved; aerated pair has changed AEA
Liu 2025	6/12/18/24 total binder	Harmless treatment not specified; Equals 7.79–31.17% reference OPC displaced; product test mapping unresolved
Song 2025	5/10/15/20 cement mass	Harmless treatment not specified; No numeric absolute graph means or product release; particle-size series
Qiu 2025	30 paste-strength design	850 °C, 4 h; milling + TEA–STPP surface modifier; Leaching systems and strength series not fully mapped; no isolated thermal effect

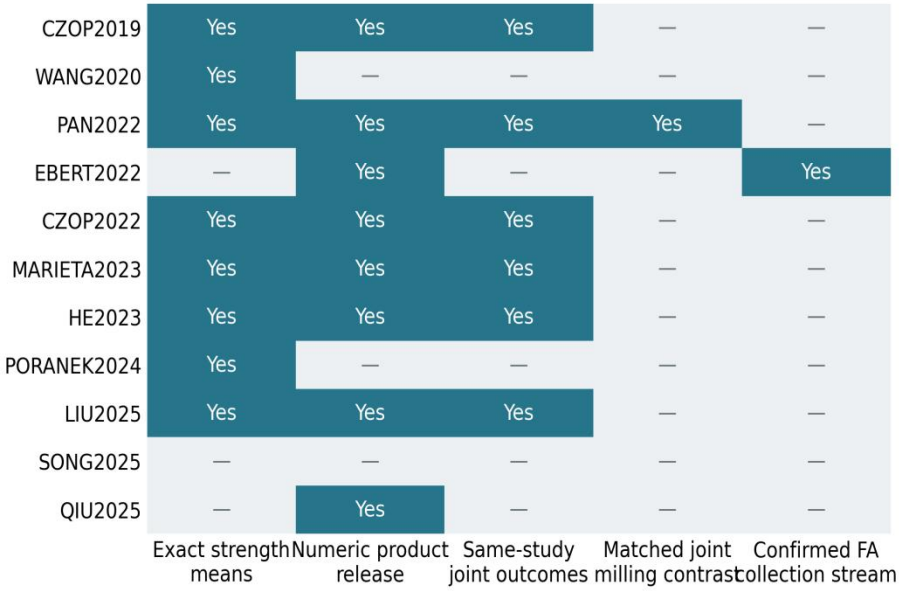


Figure 2. Availability of exact strength means, numerical product release, joint observations and a matched joint contrast. Absence indicates unavailable evidence under the stated definition, not a failed experiment or quality score. Song 2025 contributes relative results only; Wang 2020 has qualitative product-release evidence

Ash-Stream and Replacement-Basis Audit

Only Ebert et al. [12] explicitly distinguished pure upstream fly ash from gas-cleaning products: AMA and NUU were electrostatically collected fly ashes, whereas RYA included APC material. Five other reports concerned identifiable APC residues [9, 11, 14, 16, 19]. Five used an MSWI-fly-ash label without a sufficiently resolved collection stream [10, 13, 15, 17, 18]. Consequently, strict confirmed-fly-ash sensitivity retains one report and two ash streams, with product release but no compressive-strength measurements. A combined strength–leaching conclusion for confirmed fly ash cannot be established from this set.

Replacement denominators varied substantially. Liu et al. [17] used 6, 12, 18 and 24% ash relative to an 800 g total binder containing OPC, silica fume and slag. Reference OPC was 615.92 g, so 48–192 g ash displaced 7.79–31.17% of that reference OPC mass, rather than 6–24%. This difference changes the interpretation of a nominally "low" replacement range. The analyzed strength values remain in the original binder basis, with the alternative OPC denominator documented separately.

Marieta et al. [14] incorporated 40% treated SCM in both SCB1 and SCB2. SCB1 used hydrothermally treated ash, but SCB2 used a calcined composite whose pre-calcination feed contained 55% treated ash, 35% fiberglass and 10% mortar waste. Forty percent of that composite corresponds to 22% nominal pre-calcination ash feed in the binder; unknown thermal mass losses prevent an exact final ash fraction. Treating both formulations as 40% fly ash would be erroneous. Pan et al. [11] similarly report replacement by mechanochemically treated powder, which includes CaO where added; the exact incorporated original-ash/reagent split is not established.

In Wang et al. [10], the OPC-containing CB series maintains 20% ash while varying OPC and slag. The arm C28B42 comprises 20% ash, 28% OPC, 42% slag and 10% gypsum(Table 2 of that source); it is not a 30%-ash mix. A source prose description elsewhere reverses the cement/slag proportions for an "optimal" balance. We retain the actual arm composition and avoid transferring its strength to another formulation. Czop 2019, Czop 2022 and Poranek 2024 contain additional water, missing-mass or nominal-dose inconsistencies [9, 13, 16]. These observations remain visible but cannot support a universal cement-replacement curve.

Compressive Strength: Incorporation, Treatment and Dose

Table 3 and Figure 3 present selected exact 28-day outcomes. In the washed APC series of Pan et al. [11], 35% washed powder produced 22.3 MPa against 64.8 MPa for the cement reference. Incremental milling without CaO increased the reported mean to 32.4 MPa, a 45.3% increase over the washed comparator but only 50.0% of the ash-free reference. Thus, improvement relative to an impaired ash mixture did not restore cement-reference strength. At 35% treated-powder replacement, CaO-containing formulations reached 45.7, 51.6 and 32.7 MPa for the nominal 15, 30 and 45% CaO packages. These are different treatment formulations at one replacement rate, not a dose progression. Within the same MFA30 package, increasing replacement from 35 to 65% reduced strength from 51.6 to 43.5 MPa, a 15.7% decrease. Only this pair supports that specific dose association.

The UHPC series of Liu et al. [17] showed a monotonic decrease in exact 28-day strength from 159.2 MPa in the reference to 150.1,134.6,111.3 and 96.7 MPa at 6, 12, 18 and 24% ash by total binder. Corresponding retention was 94.3, 84.5, 69.9 and 60.7%. The series supports an incorporation association in its low-water OPC/silica-fume/slag formulation; it does not isolate an undocumented "harmless" pretreatment. It cannot establish a broadly transferable optimum or acceptable structural dose.

He et al. [15] reported 36.0, 39.8 and 37.2 MPa at 15% ash in prepared cement after heating previously washed ash at 500°C for 1 h in air, CO2 orN2, respectively. The 48.1 MPa reference gives retention of 74.8, 82.7 and 77.3%. Exact washed-only strength was not available from printed values, so these incorporation ratios do not measure thermal strength gains. A difference among atmosphere-specific means likewise lacks estimable sampling uncertainty.

Czop 2019 reported 27.0 MPa for the nominal 30% fly-labelled APC mortar against 45.0 MPa for CEMI [9]. Its Table 1 changes cement from 450 to 315 g and water from 225 to 135 g while declaring a constant water/cement ratio elsewhere; ash mass is not printed. The 60.0% retention is therefore a formulation comparison, not a clean ash-dose effect. Czop 2022 similarly reports 71.37 and 35.06 MPa at nominal 4 and 18% ash versus 87.74 MPa for the reference [13], with missing ash mass, changed water

content and conflicting nano-material descriptions. The nominal nano-containing results cannot identify an isolated nanosilica treatment effect.

Other formulations illustrate why absolute strength alone is insufficient. Wang's C28B42 paste reached 52 MPa at 28 days without an ash-free reference [10]. Marieta's SCB1 and SCB2 yielded 17.98 and 25.32 MPa against 53.30 MPa for a commercial CEMIII/A slag-cement reference [14]; different binders and ash/composite fractions preclude a thermal-treatment effect. Poranek's non-aerated blend produced 49.5 MPa versus 53.2 MPa for its reference, with nominal-dose and binder-composition caveats [16]. Song et al. [18] reported 28-day changes that differed between particle-size series: at 10% replacement, one series was 18.2% below its reference while another was 1.9% above. Absolute means were not reconstructed from unlabelled plots. These source-reported relative results remain a separate evidence type.

Table 3. Selected Exact 28-Day Strength Observations and Descriptive Reference Ratios. Ratios Do Not Imply Isolated Treatment Effects

Study / Series	Ash-containing Means (MPa)	Reference (MPa)	Retention (%)
Czop 2019, 30% nominal	27.0	45.0	60.0; water/mix confounding
Wang 2020, C28B42	52	No ash-free reference	Not calculated
Pan 2022, 35% washed / milled	22.3 /32.4	64.8	34.4 /50.0
Pan 2022, MFA30, 35%/65%	51.6 /43.5	64.8	79.6 /67.1
Czop 2022, 4%/18% nominal	71.37 /35.06	87.74	81.3 /40.0; formulation confounded
Marieta 2023, SCB1/SCB2	17.98 /25.32	53.30, CEMIII/A	33.7 /47.5; different binders
He 2023, 15%, air/CO2/N2	36.0 /39.8 /37.2	48.1	74.8 /82.7 /77.3
Poranek 2024, non-aerated	49.5	53.2	93.0; blend/dose caveats
Liu 2025, 6/12/18/24% binder	150.1 /134.6 /111.3 /96.7	159.2	94.3 /84.5 /69.9 /60.7

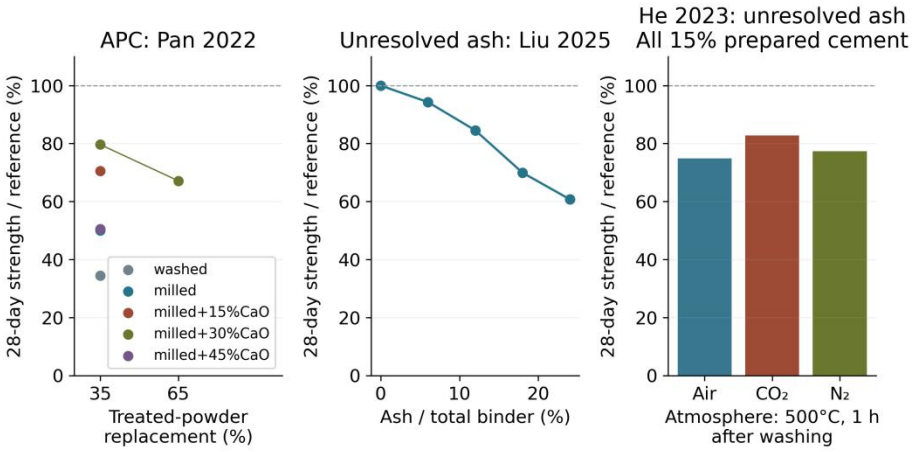


Figure 3. Selected 28-day strength retention relative to each study's ash-free reference. Panels retain distinct replacement denominators and formulations; no common dose curve or confidence interval is implied. Pan's CaO-containing series replaces treated powder rather than a verified pure-ash mass

Product Release Depends on Treatment, Analyte and Exposure

Table 4 summarizes the protocol-specific results. In Pan's matched 35% APC comparison [11], milling after washing decreased Cd from 0.25 to 0.005 mg/L, Cr from 2.643 to 0.228 mg/L and Zn from 0.506 to 0.312 mg/L. Ratios were 0.020, 0.0863 and 0.6166, respectively. Leaching age and several extraction details were not stated. Table 4 of the source prints Cu/Ni headings inconsistent with the standards ordering in its earlier table; both analytes were therefore excluded from treatment-specific inference. An unexplained "SN19" row was preserved without mapping it toSN9. ND values with unknown limits were not assigned zero. The washed reference's Cd and Cr also exceeded the source's own displayed standard values 0.15 and 1.5 mg/L, contradicting its blanket compliance statement. These displayed landfill-oriented values were not adopted as construction-product criteria.

Ebert et al. [12] tested 10% substitution in monolithic mortar with acidic-start water, NaCl solution orNa 2SO4 solution. Reported values were interval maxima over 0–4, 4–16 and 16–70 days, not cumulative release. The initial water pH of 4 did not mean a persistently acidic exposure: final reported pH across conditions was 11.4–12.5. Combined washing and electrodialysis produced 49 quantified matched analyte/solution/window ratios:31 lower, 16 higher and 2 unchanged. These dependent cells describe that experiment and are not a success-rate statistic across independent studies.

For confirmed AMA fly ash, late-interval Pb increased from 3.4 to 14 mg/m² in acidic-start water, a 4.12-fold ratio, and from 5.4 to 19 mg/m² inNaCl, a 3.52-fold ratio. In the same late acidic-start interval, Cr decreased from 1.1 to 0.78 mg/m². Treatment therefore had opposing analyte responses within one confirmed ash stream. Censored endpoints could indicate reduced release but could not yield a finite numerical ratio without a limit. Figure 5 displays only quantified late-window pairs and keeps the stream and solution visible.

Heating previously washed ash in He et al. [15] generated 29 quantified matched product-release ratios across three atmospheres, six analytes and two methods; 15 were lower, 13 higher and 1 unchanged. Again these are dependent measurements, not independent evidence votes. For air treatment, Ni increased threefold in the aqueousHJ557 extraction, from 0.0015 to 0.0045 mg/L, but decreased from 0.0192 to 0.0134 mg/L in theHJ/T300 acetic-acid-buffer test. Air-treatment Cd in the acid-buffer test increased from 0.0121 to 0.0199 mg/L. These contrasts demonstrate protocol-dependent direction rather than a universal thermal immobilization benefit (Figure 6).

Czop 2019's nominal 30% APC mortar released Ba at 2.44 mg/kg in intact specimens and 72.83 mg/kg after crushing [9]. The different exposure forms should not be treated as interchangeable or as proof of unchanged environmental performance after demolition. In Czop 2022 [13], Ba remained 15.20 or 35.50 mg/L in non-nano mortars and 8.70 or 17.80 mg/L in nano-containing formulations. The source-cited comparison limit was not independently verified as an applicable construction standard. Values reported asCr<0.50 mg/L cannot establish compliance with a 0.10 mg/L criterion. Chloride also increased from 0.14 to 0.28 mg/L in the nominal 4% nano-containing pair, contrary to a blanket statement that all releases decreased.

Liu et al. [17] reported Cd concentrations of 0.002, 0.007, 0.70 and 0.80 mg/L as binder-basis ash increased from 6 to 24%. The source's claim of universal compliance conflicts with the 18 and 24% values relative to its own cited 0.15 and 0.04 mg/L criteria. Two methods were cited but only one unmapped product table was available; product age and key extraction conditions were absent. The values support a source-specific high-dose concern, not a verified legal pass/fail decision for an intended construction use.

Qiu et al. [19] reported Pb at 5.5,212.5 and 80.1 μg/L in OPC, MSWIFA+OPC andMSWIFA+BFS+OPC, respectively. Their normalized concentrations are 0.0055, 0.2125 and 0.0801 mg/L. The slag-containing system had lower Pb than the ash–OPC system, but the formulations differ, and their relationship to the strength/grinding series is incompletely resolved. We therefore do not assign a pretreatment response ratio. Marieta's product extracts likewise remain formulation-specific, with analyte-dependent units and ELQ censoring preserved [14]. Poranek's reported leaching concerns the original APC material, not hardened mortar [16], so it cannot support a joint product-safety assertion.

Table 4. Protocol-specific Product-Release Results Selected for Interpretation; No Construction-Safety Threshold is Assigned

Study / Condition	Protocol / Unit	Verified Contrast or Concern
Czop 2019, 30% nominal	Water, L:S10, 24 h; mg/kg	Ba intact 2.44 vs crushed 72.83; exposure form matters
Pan 2022, washed→milled 35%	HJ/T300; mg/L; ageNR	Cd 0.25→0.005; Cr 2.643→0.228; Zn 0.506→0.312
Ebert 2022, AMA, 16–70d	ModifiedNEN7345; mg/m² interval maximum	Pb raw→treated 3.4→14 in acidic-start water; 5.4→19 inNaCl
Czop 2022	EN12457-4, L:S10, 24 h; mg/L	Ba 15.20/35.50 without nano; 8.70/17.80 with nano; control absent
Marieta 2023	EN12457-4; variable rawng/mL orµg/mL	Raw values retained; µg/mL=mg/L; ng/mL×0.001=mg/L; ELQ censored
He 2023, 15%, air vs washed	HJ557 vsHJ/T300; mg/L	Ni water 0.0015→0.0045; acid 0.0192→0.0134
Liu 2025, 6/12/18/24% binder	HJ557/HJ/T300 unmapped; mg/L	Cd 0.002 /0.007 /0.70 /0.80; source compliance claim contradicted
Qiu 2025, OPC/ash+OPC/ash+slag+OPC	Author-labelledTCLP; rawµg/L	Pb 5.5 /212.5 /80.1 µg/L; changing formulation precludes isolated milling effect

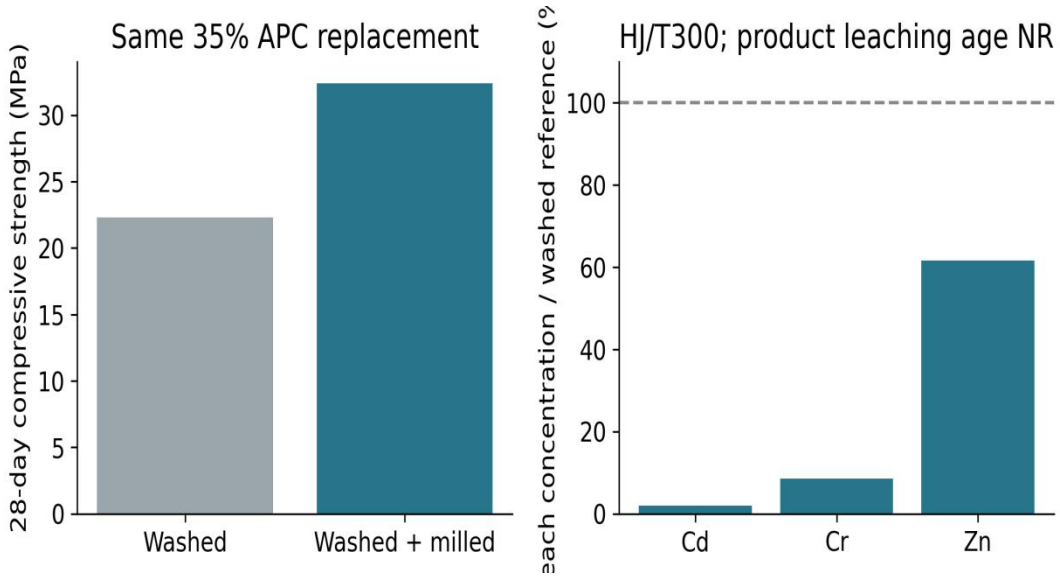


Figure 4. Joint matched comparison for milling previously washed APC residue without addedCaO in Pan 2022. Both mortars contain 35% treated powder. Strength is measured at 28 days; leaching age is unknown. Cd/Cr/Zn concentration ratios are specific to the reportedHJ/T300 test and do not establish service-life safety

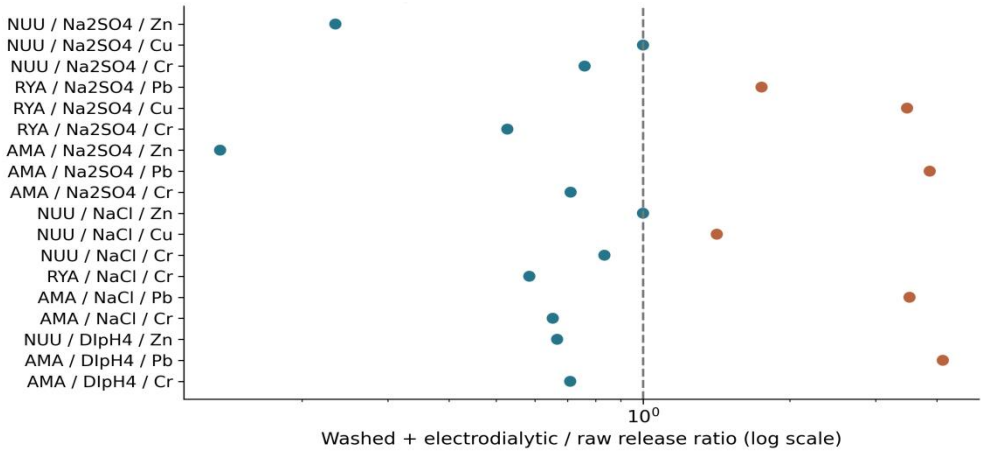


Figure 5. Quantified 16–70 day treatment/raw ratios in Ebert 2022. Release is a modified-monolith interval maximum inmg/m². Values above 1 denote increased release after the combined washing/electrodialysis package; ratios sharing controls remain dependent

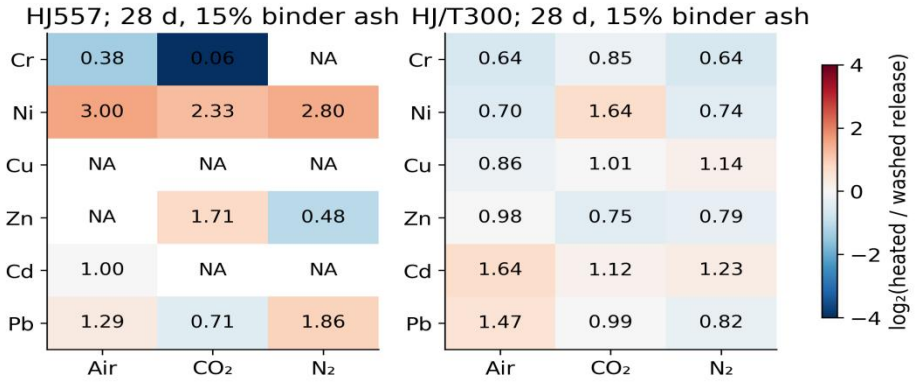


Figure 6. Incremental heating versus previously washed ash in He 2023, at 15% binder replacement and 28-day product age. Numbers are point ratios; color represents log 2ratio. NA denotes unavailable quantified pairs and is not zero. Aqueous and acid-buffer results remain separate

Joint Interpretation, Quality and Sensitivities

Pan's milling comparison is the clearest matched joint result in the retrieved set: strength increased 45.3% while quantified Cd, Cr and Zn release decreased 98.0%, 91.4% and 38.3%(Figure 4; Table 6)[11]. This is a single APC experiment with previously washed ash, not proof of an equivalent result for confirmed pure fly ash. Its strength endpoint was 28 days, while its product-leaching age was unspecified. The treatment improved a poor reference mix but left the milled mortar at half the cement-reference strength.

The other five exact joint reports have weaker causal interpretation. Liu's replacement series combines declining strength retention with higher Cd at larger doses, but missing pretreatment and test mapping limit generalization [17]. He's atmosphere series supplies exact treated strength and matched leaching, but lacks an exact washed-strength baseline [15]. Czop 2019 and Czop 2022 contain mixture or labeling conflicts [9, 13]. Marieta changes ash-containing SCM composition and compares against a different cement [14]. Joint availability therefore must not be mistaken for joint causal identification.

Table 5 records domain judgments. No included report supplied the independent-batch and fully labelled numerical variance needed for robust pooling of the decisive strength–release contrasts. Treatment specification was particularly weak where ash was called "harmless" without a reproducible procedure [17, 18]. Product tests were absent for two strength reports [16, 18], and several release protocols or limits were incomplete. These gaps constrain the estimands rather than justify exclusion of inconvenient outcomes.

The strict confirmed-fly-ash restriction removes all exact strength and matched joint conclusions, retaining only two fly-ash streams within Ebert's leaching study. Restricting to identifiable matched treatment packages retains Pan, Ebert and He; release direction remains metal- and protocol-specific. Restricting product age to a known 28-day baseline removes Pan's leaching, Liu's product table and Qiu's product table from age-matched interpretation; Pan's joint milling result consequently cannot be described as a synchronized 28-day joint test. Restricting attention to compositions without major mixture conflicts removes the Czop formulation comparisons but does not eliminate the opposing Pb and Ni release responses in Ebert and He.

Replacement-range sensitivity is constrained by inconsistent denominators and treatment packages: there is no common low-dose band or sufficiently replicated within-treatment curve to pool. The MFA30 pair and Liu series remain separate within-study associations. No 90-day pooled comparison is possible; Poranek's reported later-age strength cannot supply absent product-release outcomes. These restrictions reduce the supported claims substantially, and no numerical precision is recovered by counting multiple analytes or shared-reference arms as independent studies.

Table 5. Quality and Applicability Judgments by Domain. Adequacy is Limited to the Specified Estimand

Study	Identity	Treatment	Comparator	Independent Replication / Variance	Product Leaching
Czop 2019	adequate	adequate / no pretreatment	major concern for isolated effect	unclear / insufficient	some concern
Wang 2020	unclear	adequate / no pretreatment	major concern for isolated effect	unclear / insufficient	narrative, graph values not extracted
Pan 2022	adequate	some concern	adequate for matched package	unclear / insufficient	major concern
Ebert 2022	adequate	adequate / no pretreatment	adequate for matched package	unclear / insufficient	some concern
Czop 2022	unclear	some concern	major concern for isolated effect	unclear / insufficient	some concern
Marieta 2023	adequate	adequate / no pretreatment	major concern for isolated effect	unclear / insufficient	some concern
He 2023	unclear	some concern	adequate for matched package	unclear / insufficient	some concern
Poranek 2024	adequate	adequate / no pretreatment	major concern for isolated effect	unclear / insufficient	not measured
Liu 2025	unclear	major concern	major concern for isolated effect	unclear / insufficient	major concern
Song 2025	unclear	major concern	major concern for isolated effect	unclear / insufficient	not measured
Qiu 2025	adequate	some concern	major concern for isolated effect	unclear / insufficient	major concern

Table 6. Joint Strength–Product-Leaching Interpretation Within Individual Reports

Study	Joint Finding	Inference Limit
Czop 2019	27.0 MPa at nominal 30%; intact/crushed release differs	Water/composition confounding; intact-water method ambiguous
Pan 2022	Milling washedAPC: strength+45.3%; Cd−98.0%, Cr−91.4%, Zn−38.3%	Single APC source; leaching ageNR; Cu/Ni headings ambiguous
Czop 2022	Strength falls in nominal dose series; Ba remains detectable/high	Nano chemistry and mix masses inconsistent; no isolated nano treatment

Study	Joint Finding	Inference Limit
Marieta 2023	17.98/25.32 MPa and protocol-specific product release	SCB formulations, doses and control binder differ
He 2023	15% heat-treated strength 74.8–82.7% reference; release changes by metal/protocol	No exact washed strength mean: joint isolated heat effect not estimable
Liu 2025	Strength retention declines 94.3→60.7%; Cd rises at 18–24% binder	Pretreatment and leaching conditions unresolved; no ash-free release control

DISCUSSION

What Treatment-Dependent Evidence Actually Establishes

The retrieved experiments support a narrower conclusion than “pretreatment improves MSWI fly ash” . A treatment package can improve one endpoint while worsening another. Incremental milling after washing produced a favorable strength/Cd/Cr/Zn combination in one APC source, but washing/electrodialysis increased quantified Pb release in confirmed fly ash. Incremental heating produced different directions under aqueous and acid-buffer extraction. Treatment classification alone is consequently insufficient for predicting joint performance.

Several mechanisms are plausible but cannot be inferred solely from the response ratios. Washing can change soluble-salt content and metal associations; milling can change particle size, surface area and hydration interactions; heating or carbonation can alter phases, alkalinity and species availability. Cementitious encapsulation can affect transport and sorption while dilution reduces the inventory per unit product. The included microstructural observations may support authors’ mechanistic explanations, but this review does not create new phase/speciation measurements or attribute every change to a single mechanism. A valid mechanism test would require controlled material accounting and direct chemical evidence.

The most favorable matched joint observation concerned APC residue, while the strict confirmed-fly-ash set offered no strength endpoint. This distinction is a central applicability boundary. An APC result may be useful for managing that APC stream, but its title cannot justify transferring the finding to upstream fly ash. Future reviews should preserve process-defined streams and investigate them separately rather than use the generic term as a pooling criterion.

Replacement Percentage is Not a Portable Dose

Apparent disagreement between studies can reflect denominator changes rather than material behavior. Six percent of a total binder is a larger share of the OPC it replaces when substantial silica fume or slag is already present. Forty percent of a processed composite is not 40% original ash. A treated powder containing CaO also changes the balance between waste loading and added reactive material. Reporting only a nominal percentage hides these differences and can produce an unjustified “optimal 10–20%” recommendation.

Reference choice matters equally. A51.6 MPa treated-ash mortar may appear attractive in absolute terms yet retain 79.6% of its own cement reference. A32.4 MPa milled mortar improves substantially over its washed comparator while retaining only 50.0% of its cement reference. Conversely, a high-strength UHPC reference makes substantial absolute strength compatible with a large relative loss. Both absolute means and within-study ratios are necessary, together with the formulation that generated them. Neither defines structural suitability without the applicable product standard and durability/exposure requirements.

Water and co-binder changes further restrict interpretation. If replacement changes water/binder conditions or nano-material additions, the result concerns the formulation package. Shared-reference normalization does not remove that confounding. Similarly, variable binder formulations can provide valuable practical designs without identifying the marginal effect of ash treatment. The present separation of incorporation, treatment and replacement association prevents these useful but different results from becoming a falsely common causal estimate.

Environmental Assessment Requires Exposure-Specific Evidence

The leaching findings show why strength cannot serve as a proxy for environmental acceptability. Stronger products can still release selected analytes, and a treatment reducing one metal can mobilize another. An intact monolith and crushed material can expose different transport pathways and surface areas. Acid-buffer tests, alkaline final solutions and saline immersion interrogate different aspects of release. Reporting them as "heavy metals leaching" without these conditions loses the information needed for interpretation.

Source compliance statements also require numerical auditing. In several included papers, a blanket pass statement conflicted with displayed values or a censoring limit could not establish the claimed pass. Detecting such inconsistencies does not establish a different legal classification. The appropriate conclusion is that the source's general statement is not demonstrated by the presented table. Construction-product assessment requires a jurisdiction, intended use, applicable protocol, relevant limit and exposure scenario; landfill or drinking-water limits cannot be substituted automatically.

Unknown detection limits are especially consequential. An ND result does not establish absence, quantify a reduction or support an exact finite ratio. Substituting zero would overstate immobilization and can make log ratios undefined; substituting half an unreported limit would fabricate a measurement. The censored entries are therefore retained as evidence of a reporting boundary. The quantified subset is informative but selectively omits low/unknown endpoints, so counts of lower versus higher release cannot be interpreted as treatment effectiveness probabilities.

Implications for Experimental Design and Evidence Synthesis

A decisive experiment should collect a clearly identified ash stream, allocate a homogenized batch to treatments, record process yield and reagent carryover, and compare untreated, washed-only and further-treated material at identical binder formulation and replacement basis. An ash-free reference remains necessary for incorporation effects. Independent processing and production batches should be distinguished from multiple specimens made from one batch, with numerical variance and its definition reported.

Strength and product-release testing should be linked to the same mixture and documented curing state. Full leaching parameters, censoring limits and exposed form should be reported, together with raw concentrations and any blank or cumulative-release correction. Long-term or altered-form tests are needed before extrapolating to ageing, demolition or field use. Energy use, secondary waste streams and treatment yield would also be required for environmental-benefit claims; the present performance/release dataset cannot establish carbon savings or a lifecycle advantage.

For future synthesis, these practices would permit fewer but more interpretable independent comparisons. A hierarchical meta-analysis might then account for study, ash batch, shared reference, dose and analyte/protocol strata, but the current dataset cannot identify such a model reliably. Providing a complex pooled estimate now would conceal missing variance and structural noncomparability. The verified observations and comparison exclusions are a reproducible basis for updating the review when additional originals or independent experiments become available.

Limitations

The largest limitation is evidence coverage. Searches used two metadata services, relevance-ordered caps and targeted phrases, with no Scopus/Web of Science access or exhaustive pagination. Automated title rules can omit relevant records, and 70 of 98 sought reports were inaccessible. Several close reviews could not be read in full, so novelty is not established. The focus on cement-containing systems was a disclosed post-protocol refinement; conclusions do not cover all MSWI-based alkali-activated materials or all thermal treatment routes.

Screening and extraction were AI-assisted with source verification, not dual independent human review. Original numerical labels were favored over unlabelled curves, introducing availability-based selection within studies. No graph-coordinate digitization was performed, and absent absolute means were not reconstructed from author percentages. Reviewer judgment remains necessary for classifications and ambiguous reporting. Source-verified transcription also does not confirm the original experiment's analytical accuracy or independence.

The accessible set is small and heterogeneous. Ash-stream identity was unresolved in five reports, treatment conditions were incomplete in some, independent-batch variance was insufficient, and several mixtures changed co-binders or water content. Quantified analyte/window comparisons share controls and may be correlated. Censoring limits and leaching conditions were often absent. Consequently, inferential confidence intervals, pooled effects, dose thresholds, heterogeneity and publication-bias statistics were not estimable. Descriptive sensitivity restrictions cannot repair inaccessible evidence or establish transportability.

The analysis addresses published performance and release endpoints, not dioxin destruction, occupational exposure, full contaminant inventories, field durability, lifecycle emissions or regulatory product approval. It cannot establish environmental safety, carbon savings, structural suitability or an optimal replacement percentage. Before submission as a systematic review, search coverage and screening would require strengthening; the current article should retain its bounded-review designation.

CONCLUSION

Within 11 accessible cement-containing studies, the strongest matched joint result was incremental milling of previously washed APC residue at 35% treated-powder replacement: reported 28-day strength increased from 22.3 to 32.4 MPa and Cd, Cr and Zn concentrations decreased under the reported extraction. The milled mixture nevertheless retained only 50.0% of the ash-free reference strength, and product-leaching age was unspecified.

This result does not generalize to all residues or treatments. Confirmed-fly-ash evidence supplied no strength data and showed increased late Pb release after a washing/electrodialysis package. Incremental heating gave analyte- and protocol-dependent responses. Strength–release interpretation must therefore remain tied to collection stream, comparator, replacement basis and exposure condition.

Replacement percentages require explicit denominators and formulation accounting. Reported binder percentages, reference-cement displacement and processed-composite fractions are not interchangeable. The evidence supports specific within-study associations and identifies reporting gaps; it does not support a pooled treatment ranking, an optimum dose or a construction-safety claim. The extraction dataset, source links and descriptive code permit transparent reassessment and updating.

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