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LIFECYCLE-STATE ENVIRONMENTAL COMPLIANCE OF SEDIMENT–FLY ASH ONE-PART GEOPOLYMERS: A SECONDARY REANALYSIS INTEGRATING DEMOLITION, CARBONATION, AND SERVICE-STATE LEACHING

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Environmental qualification of waste-derived binders is commonly reported in separate test domains such as crushed material, carbonated material, and intact monoliths, even though these states correspond to different stages of one product life cycle. As a result, a practical question remains insufficiently resolved for circular construction: can a geopolymer be environmentally acceptable during service while becoming problematic after end-of-life fragmentation? This manuscript presents a transparent secondary reanalysis of a complete benchmark dataset for one-part sediment–fly ash geopolymers containing 0, 15, 30, and 50% dredged sediment. Rather than introducing new experiments, the study recalculates and integrates precursor batch leaching, crushed-mortar leaching at 7, 28, and 56 days, carbonation-conditioned crushed-mortar leaching at 60 and 180 days, and 64-day dynamic surface leaching of monoliths within a single lifecycle-state framework. Four state-sensitive metrics are used to organize the comparison: threshold utilization ratio, activation remobilization factor, carbonation recovery factor, and service-state safety margin. Internal cross-checking of the recalculated ratios confirms a clear divergence between demolition-state and service-state behavior. Mean crushed-state arsenic and selenium concentrations exceeded non-hazardous-waste thresholds by 21–29% and 20–38%, respectively, whereas molybdenum, antimony, and chromium remained well below the same limits. Relative to precursor powders, activation increased arsenic release by factors of 7.85–25.81 and selenium release by factors of 2.18–3.34, while chromium release fell to 0.04–0.17 of precursor values. Carbonation lowered pH by 2.61–2.71 units and reduced arsenic by 22.5–50.6%, but did not provide a comparable benefit for selenium at higher sediment contents. In contrast, all 64-day monolith releases remained below Dutch Soil Quality Decree limits; arsenic reached only 19.3–24.0% of the allowable value and sulfates 4.5–24.9%. The contribution is therefore methodological and regulatory rather than experimental: qualification protocols for sediment-based geopolymers should distinguish service-state safety from end-of-life fragmentation risk and treat carbonation as a selective, not universal, remediation pathway.

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INTRODUCTION

Waste-derived geopolymer binders continue to attract interest because they reduce clinker demand while creating opportunities to valorize industrial and dredged residues in construction materials (Amran et al., 2021; Davidovits, 1991; Li et al., 2022; Provis & van Deventer, 2009; Turner & Collins, 2013). Among these residues, dredged sediments are particularly important because they are produced in large quantities, are costly to manage, and are increasingly constrained by environmental disposal regulations (Amar et al., 2021; Benzerzour et al., 2017; Lirer et al., 2017). When sediments are thermally activated and blended with fly ash, they can serve not only as fillers but also as reactive aluminosilicate precursors that alter gel chemistry, pore structure, and strength development (E. Mahfoud, Maherzi, et al., 2023; E. Mahfoud, Ndiaye, et al., 2023; Mahfoud et al., 2023). For circular construction, however, mechanical viability alone is not sufficient. The material must also remain environmentally acceptable across the states in which it will actually exist during use, demolition, and possible reuse.

That requirement is more demanding than conventional single-test qualification. European assessment frameworks distinguish between batch leaching of crushed material and dynamic surface leaching of monoliths because the underlying transport regimes are fundamentally different (Eikelboom et al., 2001; Sun & Vollpracht, 2020; Weiler et al., 2022). Crushed-state tests simulate fragmentation and maximize exposure of pore solution to leachant, whereas monolith tests are controlled more strongly by diffusion, near-surface dissolution, and wash-off from an intact body (Paulus et al., 2016; Sun & Vollpracht, 2020). In waste-based geopolymers, this distinction is especially consequential because contaminant retention may arise from several concurrent mechanisms, including chemical incorporation, precipitation, adsorption, and physical encapsulation (Izquierdo et al., 2009; Palomo & Palacios, 2003; Zhang et al., 2008). A material can therefore appear compliant in one lifecycle state while showing a more restrictive response in another.

This issue is especially pronounced for oxyanion-forming species such as arsenic and selenium. Previous studies have shown that strongly alkaline pore solutions can mobilize oxyanions even when many cationic species remain well stabilized (Álvarez-Ayuso et al., 2008; Izquierdo et al., 2009; Škvára et al., 2012; Tigue et al., 2018; Yliniemi et al., 2015). Yet the literature often reports crushed-state and monolith-state outcomes as adjacent datasets rather than as linked lifecycle states of the same product. The practical consequence is that service-state safety and end-of-life fragmentation risk are frequently discussed in parallel but not interpreted together.

The benchmark experimental study by Mahfoud et al. (2023) is unusually well suited for resolving that disconnect. It reports a complete dataset for four optimized one-part geopolymer mortars with 0, 15, 30, and 50% sediment, including mechanical performance, pore structure, gel chemistry, crushed-state leaching at three curing ages, carbonation-conditioned crushed-state leaching, and dynamic surface leaching of monoliths. The original study already established two important observations: sediment addition improved strength and mesopore refinement, while oxyanion behavior diverged sharply from the behavior of most cationic trace species (Mahfoud et al., 2023). What remained underdeveloped was a lifecycle interpretation that linked those datasets to separate regulatory decisions for service, demolition, and post-conditioning states.

Accordingly, the objective of the present manuscript is to provide a transparent secondary reanalysis of the full experimental matrix reported by Mahfoud et al. (2023). The contribution is not new laboratory testing. Instead, it is a consistency-checked lifecycle interpretation that reorganizes the benchmark data into four states, recalculates state-sensitive metrics, and asks a narrower but more practically relevant question: *how does the regulatory and mechanistic interpretation of the* *same binder system change as it moves from precursor powders to demolition-state fragments, carbonation-conditioned fragments, and service-state monoliths?* Three hypotheses guide the analysis. First, demolition-state fragmentation will reveal a selective oxyanion vulnerability not visible in the monolithic service state. Second, carbonation will provide selective recovery for arsenic but not necessarily for selenium. Third, environmental acceptability in this binder family must therefore be interpreted as state-dependent rather than as a fixed intrinsic property.

EXPERIMENTAL BASIS AND ANALYTICAL FRAMEWORK

Benchmark experimental platform

This manuscript is a secondary analysis of the complete experimental matrix reported by Mahfoud et al. (2023), complemented where necessary by the optimization background reported by E. Mahfoud, Maherzi, et al. (2023). The benchmark platform consists of four one-part geopolymer mortars prepared from thermomechanically treated fly ash–sediment precursor blends and a solid sodium silicate/NaOH activator. The mixtures were optimized for mechanical performance at four sediment incorporation levels: 0, 15, 30, and 50% sediment, identified as FA100r3.5, FA85SD15r3.5, FA70SD30r3.5, and FA50SD50r5, respectively (Mahfoud et al., 2023). The mortars were cast as $4 \times 4 \times 16$ cm^3 prisms, thermally cured for 72 h at 50 °C, and stored at 20 °C before testing (Mahfoud et al., 2023).

The original program included: (i) precursor characterization by BET, particle-size analysis, XRF, XRD, MIP, and SEM/EDS; (ii) flexural and compressive strength at 7 and 28 days; (iii) batch leaching on precursor powders and crushed mortars at 7, 28, and 56 days according to EN 12457-2; (iv) carbonation-conditioned batch leaching after 60 and 180 days at 3% CO_2; and (v) dynamic surface leaching of monoliths up to 64 days according to EN 16637-2 (Mahfoud et al., 2023). The source study reported that sediment addition increased compressive strength from about 19 to 29 MPa, increased mesoporosity below 50 nm from 1.6 to 3.5%, and raised the Ca/Si ratio of gel phases from 0.04 to 0.18, consistent with coexistence of N–A–S–H and C–A–S–H products (Mahfoud et al., 2023).

Because the present contribution depends on a published benchmark dataset, additional care was taken with numerical consistency. All derived ratios reported below were recalculated from the published concentrations or normalized releases, all narrative percentage ranges were cross-checked against the recalculated values before rounding, and the updated figures were regenerated directly from the verified tables. These checks do not create new experimental evidence, but they do improve transparency and reduce the risk of internal inconsistency in the lifecycle interpretation.

Lifecycle-state interpretation

To convert the original experimental matrix into a lifecycle-oriented analytical framework, the dataset was reorganized into four states, each corresponding to a materially distinct stage in product life (Table 1):

(i) *Precursor state.* Untreated environmental baseline of the aluminosilicate powders prior to activation.

(ii) *Demolition state.* Crushed-mortar leaching at 7, 28, and 56 days, representing fragmentation at end of life or reuse as granular material.

(iii) *Post-conditioning state.* Carbonation-conditioned crushed mortars after 60 and 180 days, representing partial neutralization prior to reuse or disposal.

(iv) *Service state.* Dynamic surface leaching of intact monoliths up to 64 days, representing in-service environmental exposure.

Table 1: Lifecycle interpretation of the experimental states used in the reanalysis.

State	**Experimental basis**	**Primary unit**	**Interpretive role**
Precursor state	Batch leaching of FA, FA85SD15, FA70SD30, FA50SD50 powders	mg/kg	Baseline release potential before alkali activation
Demolition state	Batch leaching of crushed mortars at 7, 28, and 56 days	mg/kg	End-of-life fragmentation and granular reuse/disposal risk
Post-conditioning state	Batch leaching of crushed mortars after 60 and 180 days of carbonation at 3% CO_2	mg/kg	Recovery potential after partial neutralization
Service state	Dynamic surface leaching of intact monoliths over 64 days	mg/m^2	In-service compliance of the construction product

Derived metrics

To formalize the transition between states, four derived metrics were calculated for each analyte i and mixture m.

First, the *threshold utilization ratio* (TUR) compares a measured concentration to the applicable regulatory limit:

$$\mathrm{TUR}_{i,s,m} = \frac{C_{i,s,m}}{L_{i,s}}, \tag{1}$$

where $C_{i,s,m}$ is the measured concentration in state s and $L_{i,s}$ is the corresponding threshold. For demolition-state calculations, French inert-waste and non-hazardous-waste thresholds reported by Mahfoud et al. (2023) were used. For service-state calculations, Dutch Soil Quality Decree limits for monolithic materials were used (Mahfoud et al., 2023; Rijkswaterstaat Environment, 2008).

Second, the *activation remobilization factor* (ARF) quantifies the change in leaching caused by geopolymerization:

$$\mathrm{ARF}_{i,m} = \frac{\bar{C}_{i,\mathrm{dem},m}}{C_{i,\mathrm{prec},m}}, \tag{2}$$

where $C_{i,\mathrm{prec},m}$ is precursor powder leaching and

$$\bar{C}_{i,\mathrm{dem},m} = \frac{1}{3} \sum_{t \in \{7,28,56\}} C_{i,t,m} \tag{3}$$

is the mean demolition-state concentration across the three crushed-mortar ages.

Third, the *carbonation recovery factor* (CRF) measures the fractional reduction after 180 days of carbonation:

$$\mathrm{CRF}_{i,m} = 1 - \frac{C_{i,\mathrm{carb180},m}}{\bar{C}_{i,\mathrm{dem},m}}. \tag{4}$$

Positive values indicate improvement; negative values indicate a worsening relative to the mean demolition-state concentration.

Fourth, the *service-state safety margin* (SSM) expresses the remaining distance to the Dutch monolith limit:

$$\mathrm{SSM}_{i,m} = 1 - \frac{C_{i,\mathrm{serv64},m}}{L_{i,\mathrm{serv}}}. \tag{5}$$

Higher values indicate greater regulatory headroom.

The reanalysis concentrates on arsenic, selenium, molybdenum, antimony, and chromium in the crushed-state comparisons because these species best capture the contrast between oxyanion-sensitive and relatively stable release behavior in the source dataset. Monolith-state comparisons focus on the principal analytes reported with Dutch limit values at 64 days.

Analytical scope

The objective is interpretive rather than inferential, but the analysis is more than a narrative summary. It contributes a structured lifecycle comparison, recalculates all derived metrics from the benchmark values, and aligns each material state with the regulatory benchmark that is most relevant for that state. No new laboratory experiments were performed, no attempt is made to convert laboratory leaching values into field exposure concentrations, and the manuscript should therefore be evaluated as a secondary analysis rather than as an original experimental report. The central question is whether the environmental classification of these materials remains stable across service, demolition, and post-conditioning states. The answer depends on cross-state interpretation, not on any single test in isolation.

RESULTS

Material baseline: why this system is suitable for lifecycle analysis

The benchmark system combines practical engineering relevance with a strong environmental contrast across states. Sediment addition increased compressive strength from approximately 19 to 29 MPa, refined the sub-50 nm pore fraction from 1.6 to 3.5%, and increased gel-phase Ca/Si from 0.04 to 0.18 (Mahfoud et al., 2023). These changes indicate that sediment incorporation does not simply dilute the fly ash binder; it shifts the reaction chemistry toward mixed N–A–S–H/C–A–S–H assemblages, consistent with the source study's SEM/EDS interpretation (Mahfoud et al., 2023; Yip & van Deventer, 2003; Yip et al., 2005). At the same time, the same mixtures display non-uniform contaminant behavior across precursor, crushed, carbonated, and monolithic states. This combination of mechanical relevance and environmental divergence makes the dataset well suited to a lifecycle-state analysis.

Figure 1 summarizes the analytical framework used here. The contribution is not the addition of new specimens, but the integration of all reported states into a single decision-oriented logic: precursor powders define the pre-activation baseline; crushed mortars represent demolition-state exposure; carbonated crushed mortars test post-conditioning recovery; and monolith leaching represents service-state exposure. Taken together, these states provide three mutually reinforcing layers of evidence already embedded in the benchmark program: mechanical and microstructural performance, demolition-state leaching, and service-state leaching.

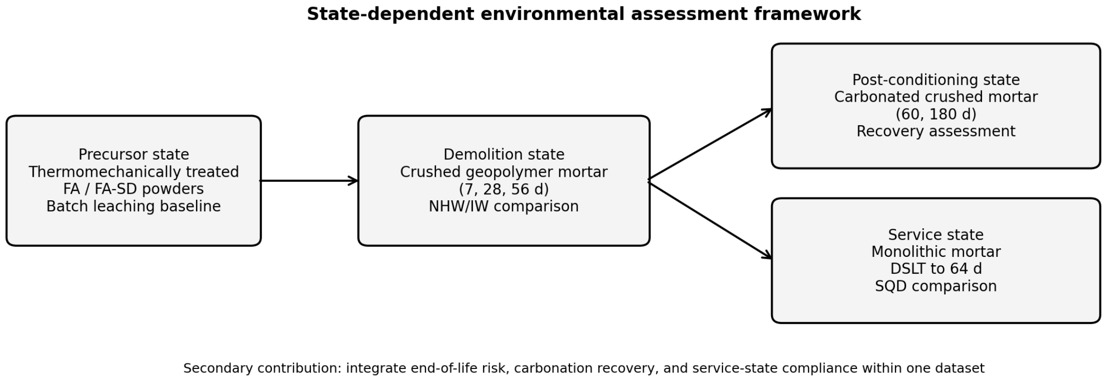

Figure 1: Lifecycle-state framework used to reinterpret the benchmark dataset.

Demolition-state behavior reveals selective oxyanion vulnerability

Table 2 shows the activation remobilization factors. The pattern is highly selective and numerically consistent across all four mixtures. Arsenic exhibited the largest activation-induced increase, with ARF values of 7.85 for FA100r3.5, 14.79 for FA85SD15r3.5, 25.02 for FA70SD30r3.5, and 25.81 for FA50SD50r5. Selenium also increased systematically, though less dramatically, with ARF values from 2.18 to 3.34. By contrast, molybdenum decreased to 0.32–0.38 of precursor values in all mixtures, and chromium dropped even more sharply to 0.04–0.17 of precursor release. Antimony behaved intermediately: it decreased at low sediment content but rose modestly above precursor levels at 30 and 50% sediment.

Table 2: Activation remobilization factors (ARF) comparing the mean crushed-state concentration to precursor-powder leaching. Values above 1 indicate increased release after activation.

Mixture	**As**	**Se**	**Mo**	**Sb**	**Cr**
FA100r3.5	7.85	2.18	0.32	0.62	0.07
FA85SD15r3.5	14.79	2.58	0.38	0.84	0.17
FA70SD30r3.5	25.02	2.75	0.34	1.41	0.04
FA50SD50r5	25.81	3.34	0.37	1.39	0.11

This divergence is reinforced when the mean demolition-state concentrations are normalized by the non-hazardous-waste threshold (Table 3). Arsenic exceeded the threshold in all four mixtures by 21–29%, and selenium exceeded it by 20–38%. In contrast, molybdenum remained at only 6–7% of the threshold, antimony at 10–13%, and chromium at less than 1%. The demolition state therefore does not indicate broad environmental failure of the material. Instead, it isolates a specific oxyanion-centered vulnerability that remains visible regardless of sediment level.

Table 3: Mean demolition-state threshold utilization ratios (TUR) relative to the French non-hazardous-waste threshold. Values above 1 indicate exceedance.

Mixture	As	Se	Mo	Sb	Cr
FA100r3.5	1.21	1.20	0.07	0.10	0.00
FA85SD15r3.5	1.29	1.33	0.06	0.13	0.00
FA70SD30r3.5	1.25	1.37	0.07	0.12	0.00
FA50SD50r5	1.29	1.38	0.06	0.12	0.00

Two points deserve emphasis. First, the exceedance is not driven by sediment alone, because the 0% sediment binder already exceeds the arsenic and selenium thresholds once activated. Second, higher sediment contents do not eliminate the problem and, for selenium, tend to aggravate it. This pattern is consistent with the mechanistic interpretation advanced by Izquierdo et al. (2009), Tigue et al. (2018), and Yliniemi et al. (2015): strongly alkaline pore solutions favor the mobilization of oxyanion-forming species even when cationic trace metals remain tightly retained.

Figure 2 visualizes this state dependence using threshold-normalized concentrations reconstructed from the verified tables. Both arsenic and selenium are comparatively modest in the precursor powders, increase after activation in the crushed state, and then diverge under carbonation. Arsenic is strongly responsive to carbonation; selenium is not.

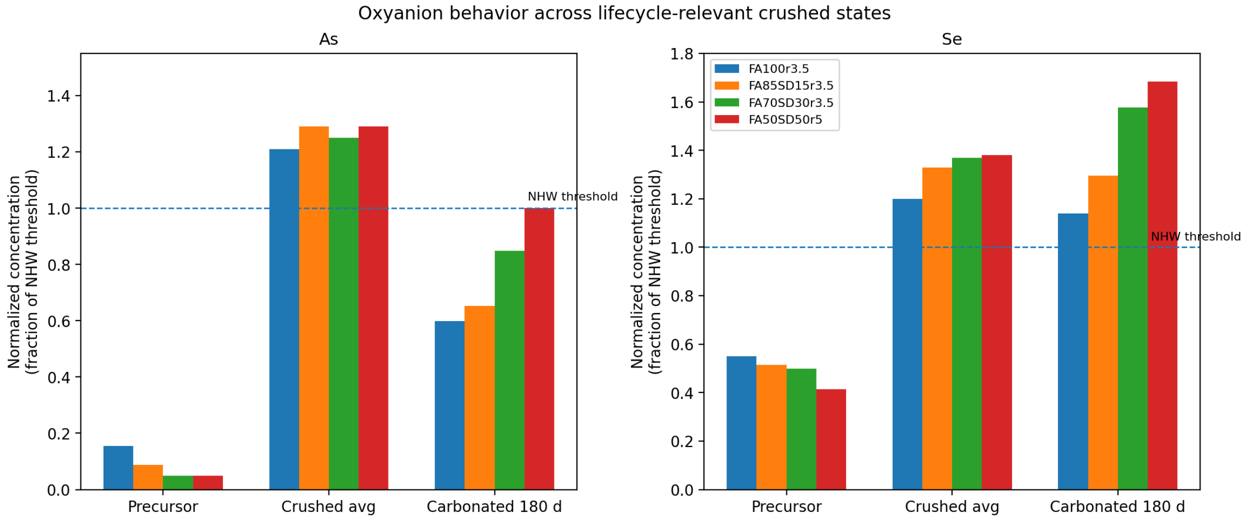

Figure 2: Oxyanion behavior across precursor, demolition-state, and post-conditioning crushed states.

Carbonation is a selective end-of-life remediation pathway

Carbonation changed the chemistry of the crushed-state eluates in two ways. First, the pH fell substantially, by 2.61–2.71 units after 180 days. Second, arsenic release decreased in every mixture, but the magnitude of recovery depended strongly on composition. Table 4 shows that the 180-day carbonation recovery factor for arsenic was 0.51 for FA100r3.5 and 0.49 for FA85SD15r3.5, but only 0.32 for FA70SD30r3.5 and 0.23 for FA50SD50r5. In other words, carbonation roughly halved arsenic release at low sediment contents but achieved only partial improvement at higher sediment contents.

Table 4: Carbonation response after 180 days. Positive recovery factors indicate reduced leaching relative to the mean demolition-state value; negative selenium values indicate a worsening after carbonation.

Mixture	pH drop	As reduction (%)	Se change (%)	Mo reduction (%)
FA100r3.5	2.68	50.56	5.11	60.57
FA85SD15r3.5	2.65	49.48	2.55	58.23
FA70SD30r3.5	2.61	32.05	-15.10	23.43
FA50SD50r5	2.71	22.51	-22.03	16.58

Selenium behaved differently. At 0 and 15% sediment, selenium decreased only marginally after carbonation (5.1 and 2.6%, respectively), while at 30 and 50% sediment it increased relative to the mean demolition-state concentration. Molybdenum also improved after carbonation, but the benefit declined as sediment content increased. These results indicate that carbonation should not be treated as a universal remedy for all oxyanion-sensitive species. Rather, it is best understood as a selective pH-mediated recovery pathway whose effectiveness depends on both species chemistry and binder composition.

Service-state monoliths remain comfortably compliant

The service-state picture is fundamentally different. All 64-day monolith releases remained below the Dutch Soil Quality Decree limits reported by Mahfoud et al. (2023). Figure 3 and Table 5 show that normalized cumulative releases were well below unity for all reported analytes. Arsenic, despite its demolition-state vulnerability, reached only 0.193–0.240 of the Dutch limit. Molybdenum reached 0.097–0.122. Sulfates, although more responsive to sediment incorporation, remained at only 0.045–0.249 of the applicable limit. Among the displayed analytes, nickel showed the smallest regulatory headroom, but still remained below the threshold at 0.470–0.677 of the allowable release.

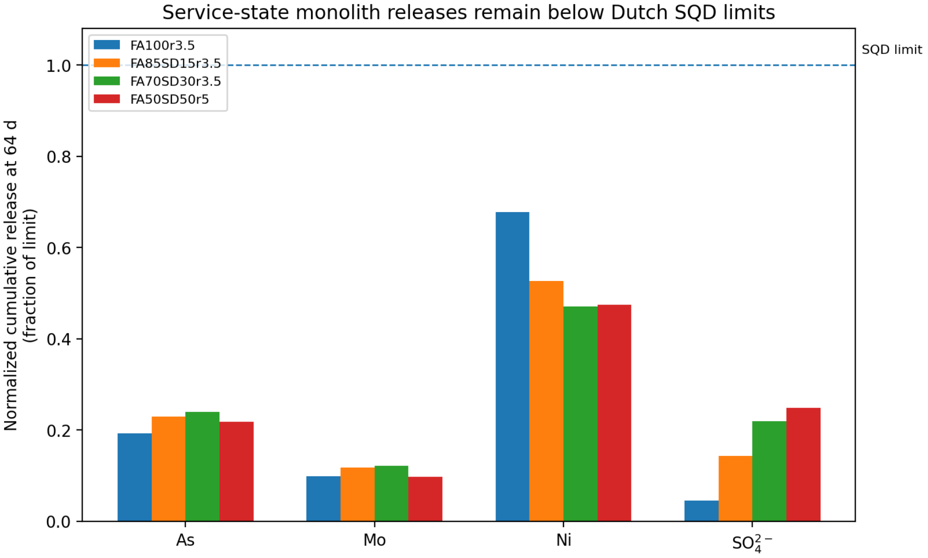

Figure 3: Normalized 64-day cumulative monolith releases as fractions of the Dutch Soil Quality Decree limits.

Table 5: Service-state normalized release ratios at 64 days, expressed as fractions of the Dutch Soil Quality Decree limits for monolithic materials.

Mixture	**As**	**Mo**	**Ni**	**SO_4^{2-}**	**Cl^-**
FA100r3.5	0.193	0.099	0.677	0.045	0.010
FA85SD15r3.5	0.229	0.118	0.527	0.143	0.010
FA70SD30r3.5	0.240	0.122	0.470	0.219	0.010
FA50SD50r5	0.218	0.097	0.474	0.249	0.013

The contrast between Tables 3 and 5 is the central result of the study. The same binder family that exceeds the crushed-state non-hazardous-waste thresholds for arsenic and selenium remains comfortably below the monolithic service-state thresholds. This is not a contradiction. It reflects the coexistence of two retention mechanisms already implied by the source study: chemical stabilization for several cationic species and physical trapping for at least part of the oxyanion inventory (Álvarez-Ayuso et al., 2008; Mahfoud et al., 2023). Once the material is intact, fine porosity and diffusion resistance become dominant; once it is crushed, pore solution accessibility and alkalinity-driven remobilization govern the environmental picture. The convergence of these two independently reported test domains strengthens the lifecycle interpretation even though the contribution remains a secondary analysis.

DISCUSSION

A state-dependent view of environmental performance

The main conceptual contribution of this manuscript is that environmental compliance in sediment-based geopolymers should be interpreted as *state-dependent*. The benchmark dataset does not support the simplistic claim that the binder is either environmentally safe or environmentally problematic in the abstract. Instead, it supports a more discriminating conclusion: the material is service-state compliant as a monolith, but it exhibits a demolition-state oxyanion vulnerability once fragmentation removes the diffusion barrier and exposes alkaline pore solution.

This reframing matters for both research and practice. From a research perspective, it explains why crushed-state and monolith-state leaching studies may appear inconsistent even when they are both correct. From a practical perspective, it means that qualifying such a material for use in blocks, pavers, or non-structural precast elements does not automatically qualify the same material for all end-of-life reuse pathways. A circular-economy strategy must therefore distinguish between direct service use, crushed-material reuse, and pre-conditioned reuse after carbonation. The value added here is not experimental novelty, but a decision-oriented synthesis that makes those distinctions explicit.

Implications for binder design

The results also clarify what kind of design problem this binder family presents. Sediment addition improves mechanical performance through finer particle packing, greater calcium availability, and mixed N–A–S–H/C–A–S–H formation (Mahfoud et al., 2023; Yip et al., 2005). Yet the environmental response is not monotonic. At higher sediment contents, arsenic recovery after carbonation weakens and selenium behavior worsens. This implies that optimal formulation cannot be defined by compressive strength alone. A genuinely robust design should combine mechanical adequacy with state-specific environmental qualification, especially for oxyanion-forming trace species.

Although the present manuscript does not compute a full multi-objective optimum, the results suggest three practical rules. First, monolith performance should be evaluated independently from crushed-state performance. Second, end-of-life management plans should explicitly consider whether fragmentation is likely. Third, carbonation can be used as a targeted end-of-life conditioning step, but its effectiveness should be verified species by species rather than assumed from pH decline alone.

Methodological implications

A further implication concerns testing strategy. Many papers still emphasize one leaching protocol as if it were sufficient to characterize environmental behavior. The present synthesis shows why a single protocol is often inadequate. Batch leaching is indispensable for identifying demolition-state risk; monolith leaching is indispensable for identifying service-state compliance. Carbonation-conditioned testing adds a third dimension by indicating whether an end-of-life recovery pathway exists. For sediment-based geopolymers, these three states should be treated as complementary rather than redundant.

From a methodological standpoint, the study also illustrates the value and limits of secondary quantitative reanalysis. Recalculating derived indicators from an existing benchmark dataset can sharpen the regulatory interpretation, reveal cross-state trade-offs, and improve internal consistency of reporting. At the same time, such reanalysis cannot substitute for new replication, raw pore-solution measurements, aqueous speciation, or exposure modelling. Future work should therefore combine lifecycle-state interpretation with new experimental campaigns designed explicitly around service, demolition, and post-conditioning scenarios.

LIMITATIONS

This study has several limitations. First, it relies on a single, well-characterized benchmark dataset and therefore cannot establish universal thresholds for all sediments or all activator chemistries. Second, the crushed-state and monolith-state results are expressed in different units and derive from different hydrodynamic conditions; they are therefore comparable only in a regulatory and interpretive sense, not as direct mass-transfer equivalents. Third, the source dataset does not include aqueous speciation, pore-solution extraction, or reactive transport modelling, which would help isolate the exact chemical pathways responsible for selenium persistence and the declining arsenic recovery at higher sediment contents. Fourth, because the manuscript is a secondary analysis of previously published measurements, its scientific contribution lies in transparent synthesis and lifecycle interpretation rather than in new experimental evidence. These limitations do not weaken the central conclusion that the environmental classification of these binders depends strongly on lifecycle state, but they do define the appropriate scope of that conclusion.

CONCLUSIONS

This article developed a lifecycle-state compliance framework for one-part sediment–fly ash geopolymer mortars by integrating precursor, demolition-state, carbonation-conditioned, and service-state leaching data from a complete benchmark experimental program. The main conclusions are as follows.

1. The benchmark binder family is mechanically relevant for construction use: sediment addition improved compressive strength, refined mesoporosity, and increased calcium participation in gel formation.
2. Demolition-state fragmentation revealed a selective oxyanion vulnerability. Mean crushed-state arsenic and selenium exceeded non-hazardous-waste thresholds in all four mixtures, while molybdenum, antimony, and chromium remained well below their limits.
3. Alkali activation strongly remobilized arsenic and selenium relative to precursor powders, but not all trace species responded in the same direction; chromium and molybdenum showed strong suppression after activation.
4. Carbonation lowered pH substantially and reduced arsenic in every mixture, but the recovery effect weakened as sediment content increased and did not extend reliably to selenium.
5. Service-state monolith performance remained compliant for all reported analytes under the Dutch Soil Quality Decree, demonstrating that intact products can remain environmentally acceptable even when crushed-state end-of-life behavior is more restrictive.
6. Environmental qualification of sediment-based geopolymers should therefore be framed as state-dependent. Service-state safety, demolition-state reuse, and post-conditioning recovery should be assessed separately within circular construction workflows.

The most important practical implication is that sediment-bearing one-part geopolymers should not be judged by a single environmental test. Their service-state use may be justified, but end-of-life fragmentation and conditioning pathways require separate scrutiny, particularly for arsenic and selenium. More broadly, the manuscript shows that a carefully verified secondary reanalysis can improve the regulatory interpretation of a benchmark dataset even when no new laboratory work is added.

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