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Analysis of Geomechanical Properties of Mine Waste Using Cementitious and Pozzolanic Agents: A Systematic Review

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Abstract

Managing mine waste remains a formidable global challenge, driven by substandard geomechanical properties and significant contamination risks. Although stabilization binder-based offers a promising remedy, the extant literature remains strikingly fragmented, hindering standardized application. The purpose of this review is to synthesize and critically compare scientific evidence on the effectiveness of Portland Cement versus pozzolanic precursors for mine waste valorization. To that end, a systematic literature review (SLR) was conducted, formulating research questions under the PICO framework and applying the PRISMA protocol, which enabled the selection of 68 studies from the Scopus and Science Direct databases. The results indicate that stabilization performance is governed by the chemical compatibility between the waste and the binder, rather than by a universal formulation. Although Portland Cement serves as a benchmark, achieving compressive strengths of up to 57.5 MPa, pozzolanic precursors can achieve superior performance, exhibiting a broad performance window (0.22 to 92.6 MPa), governed by the chemical compatibility. Likewise, strength development does not scale linearly with binder dosage, as a performance benchmark of 20–60% binder content was identified for maximizing UCS in structural units, whereas lower dosages (5–20%) proved effective for geotechnical backfilling, highlighting that optimization is strictly context-dependent. These findings suggest a paradigm shift from a volumetric approach towards one that treats mine waste as a reactive chemical component, where mineralogical characterization forms the basis of formulation design. The main limitation identified is the reliance on thermal curing (60–90 °C) in laboratory studies, which constitutes the greatest barrier to in-situ application. Thus, future research should focus on the development of high-performance formulations effective at ambient temperature to bridge the gap between experimental feasibility and practical application.

1. INTRODUCTION

While the mining industry remains an essential pillar of the global economy and technological growth, it inevitably generates staggering volumes of waste, primarily in the form of overburden and tailings. These materials, composed of low-grade waste rock, represent one of the largest solid waste streams on the planet, posing a formidable geotechnical and environmental challenge that demands sustainable intervention (Hamid and Alnuaim 2023, Bessa et al. 2024, Farenzena et al. 2024, Hu et al. 2025). Beyond the vast land areas required for their disposal, mismanaged waste poses severe risks, specifically regarding acid mine drainage and the leaching of heavy metals (Simate and Ndlovu 2014).

The primary hurdle to repurposing these materials lies in their substandard geomechanical properties, notably their low shear strength, high compressibility, and erratic particle size distribution which preclude their direct integration into infrastructure works (Mabroum et al. 2020, Verhagen et al. 2021). Geotechnical stabilization has consequently emerged as a cornerstone strategy within the framework of the circular economy (Lehmann et al. 2020). Historically, Portland cement has been the standard binder of choice, valued for its ability to provide high mechanical strength. However, its production is responsible for approximately 8% of global CO_2 emissions (Scrivener et al. 2018), a factor that has catalyzed the search for greener alternatives. In this scenario, alkaline activation or geopolymerization technology, which utilizes aluminosilicate-rich precursors such as metakaolin, has gained significant traction as a low-carbon, high-performance alternative for the stabilization and valorization of mine waste (Salihoglu 2014, Wan et al. 2019, Carrillo Beltrán et al. 2024).

Despite the proliferation of studies addressing both stabilization technologies, this body of knowledge has not yet translated into a clear consensus or standardized guidelines. The scientific literature remains strikingly fragmented and highly heterogeneous, studies vary almost erratically in terms of the type of waste rock considered (Provis 2018) (e.g., copper tailings versus iron waste) to its mineralogical reactivity (Pearce et al. 2021). Furthermore, reported stabilizing agent dosages range from a modest 5% to upwards of 90%, with chemical activators and curing regimes fluctuating between ambient conditions and thermal treatments at 90 °C (Berdoudi et al. 2017, M et al. 2021, Farenzena et al. 2024).

The primary knowledge gap identified is the absence of a systematic review that critically and comparatively evaluates the performance of conventional Portland cement against the most promising pozzolanic alternatives. Therefore, this SLR is justified as a necessary effort to bridge this fragmentation, identify robust patterns, reconcile potential discrepancies among reported results, and establish a clear baseline of the cur-rent state of the art. The outcomes of this review are intended to function as a decision-making framework by clarifying which factors, such as mineralogy, binder dosage, and curing conditions are most influential in the success of stabilization processes. This understanding is vital to optimize formulation design while minimizing environmental impacts. Ultimately, this study seeks to provide the consolidated evidence necessary to facilitate the safe adoption of these innovative technologies, thereby accelerating the transition of the mining industry toward a circular economy model.

2. METHODOLOGY

This study was conducted as a systematic literature review (RSL), and the review was executed through a comprehensive analysis of peer-reviewed literature indexed in specialized academic databases. To safeguard the rigor and reproducibility of the findings, the PICO framework (Population, Intervention, Comparison, Outcome) was employed to tailor the search strategy in strict alignment with the research scope. Furthermore, the identification, screening, and synthesis of sources followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. This approach ensured a methodical and transparent structure throughout the investigative process, from the initial identification to the final consolidation of scientific evidence.

2.1. PICO Framework and Research Questions

In formulating the research questions, the four pillars of the PICO framework: Population/Problem, Intervention, Comparison, and Outcome, were meticulously integrated. This structured approach provided the necessary precision to establish rigorous criteria for the identification and selection of information. Consequently, the study was guided by the following overarching and specific research questions (RQs):

RQ (Main): How does the efficacy of Portland cement compare to that of pozzolanic precursors (e.g., metakaolin, fly ash, and slag) in stabilizing mine waste, and to what extent is this performance dictated by the waste's intrinsic properties and sustainability goals?

RQ1 (Problem): Which mining waste streams have dominated the current literature, and how do their inherent mineralogical profiles determine the feasibility and success of diverse stabilization techniques?

RQ2 (Intervention): How do binder dosage thresholds vary across different mine waste streams to meet specific mechanical requirements, and what evidence exists for a performance 'plateau'?

RQ3 (Comparison): How does the inclusion of pozzolanic agents functioning as both partial cement replacements and primary geopolymeric precursors impact the mechanical integrity of stabilized waste when contrasted with conventional cement-only systems?

RQ4 (Results): Which assessment protocols specifically Unconfined Compressive Strength (UCS) and curing regimes (thermal versus ambient) are most prevalent in the literature? Furthermore, what are the practical implications of a heavy reliance on thermal curing regarding the scalability gap between controlled laboratory performance and large-scale industrial deployment?

2.2 Search strategy and keywords selection

The search strategy was developed by deconstructing the main research question into the PICO components (Population, Intervention, Comparison, and Outcome). The specific keywords used for each component are summarized in Table 1. Based on these terms, database-specific Boolean search equations were constructed to retrieve relevant studies on mine waste stabilization using cementitious and pozzolanic binders.

Table 1. Keywords of the PICO components

Acronym	Components	Scopus Search Keywords
P	Problem/ Population	mine tailings, mining waste, waste rock, mine spoil, mining residue, overburden
I	Intervention	Stabiliz, solidif, geopolymer, ground improvement, cementation, alkali activated, alkali-activated, cement
C	Comparison	comparative, comparison, control sample, dosage, evaluation, performance, versus, influence, effect.
O	Outcomes	compressive strength, durability, unconfined compressive strength , UCS, leaching, immobilization, strength, geotechnical properties, stability

The literature search was conducted using the Scopus and ScienceDirect databases, selected for their broad coverage of engineering and environmental research. The search was limited to peer-reviewed articles published between 2010 and 2025, in English and Spanish. Only research articles were considered, to ensure consistency with the inclusion criteria and to exclude non-peer-reviewed sources. The complete Boolean search equations applied in Scopus and ScienceDirect are presented below. Due to differences in database indexing and search functionalities, the query applied in ScienceDirect was simplified while maintaining conceptual alignment with the Scopus search strategy:

For Scopus, the following search equation was used: ("mine tailings" OR "mining waste" OR "waste rock" OR "mine spoil" OR "mining residue*" OR "overburden") AND (stabiliz* OR solidif* OR "ground improvement" OR cementation OR geopolymer* OR "alkali activated" OR "alkali-activated" OR cement* OR metakaolin OR "fly ash" OR slag OR pozzolan* OR binder*) AND (comparative OR comparison OR "control sample" OR dosage OR versus OR evaluation OR influence OR effect* OR performance) AND ("compressive strength" OR "unconfined compressive strength" OR UCS OR durability OR leaching OR "mechanical properties" OR "geotechnical properties" OR microstructure OR immobilization OR stability)

For ScienceDirect: ("mine tailings" OR "mining waste") AND (geopolymer OR "alkali activated") AND (dosage OR performance) AND (leaching OR immobilization)

2.3 Inclusion and exclusion criteria

To safeguard the technical relevance and comparability of the selected studies, predefined inclusion and exclusion criteria were established prior to the full text assessment. These criteria were defined to align with the variables analyzed in the synthesis and to enable meaningful cross-study comparation:

Inclusion Criteria (IC):

IC1: Primary experimental studies published in peer-reviewed journals.

IC2: Studies focused on the stabilization of mine waste materials, including tailings, waste rock, or overburden.

IC3: Studies evaluating cementitious or pozzolanic binders, such as Portland cement, metakaolin, fly ash, slag, or alkali-activated systems.

IC4: Studies reporting at least one quantitative geomechanical parameter, primarily unconfined compressive strength (UCS), or equivalent indicators of mechanical performance.

IC5: Studies providing sufficient methodological information on mix composition and curing conditions (e.g., temperature, duration, or curing type) to enable comparative analysis.

Exclusion Criteria (EC):

EC1: Review articles, conference proceedings, book chapters, technical reports and other non-peer-reviewed literature.

EC2: Studies focused exclusively on material characterization without stabilization treatment.

EC3: Studies based solely on physical or mechanical approaches or using non-target binders outside the cementitious/pozzolanic scope of this review.

EC4: Studies with insufficient technical information or lack of full-text access, preventing the extraction of key variables such as binder type, dosage, curing conditions, or geomechanical performance.

The study identification and selection process followed the PRISMA 2020 guidelines, as illustrated in Figure 1. A total of 536 records were identified through database searching, including 413 records from Scopus and 123 records from ScienceDirect. No duplicate records were identified after screening titles and metadata across both databases, resulting in 536 unique records entering the initial screening phase. A preliminary screening of titles and abstracts led to the exclusion of 230 records due to lack of relevance to mine waste stabilization and geomechanical performance. The remaining 306 records were sought for full-text retrieval, of which 18 reports could not be accessed and were therefore excluded. Consequently, 288 reports were assessed for eligibility.

During the eligibility phase, 238 records were excluded based on the predefined exclusion criteria (EC1–EC4), including non-peer-reviewed literature, studies focused exclusively on material characterization without stabilization, studies based solely on physical or mechanical stabilization or using non-target binders, and studies with insufficient technical information or lack of full-text access. As a result, 50 studies met the inclusion criteria and were selected for systematic data extraction. Furthermore, 18 studies were identified through citation tracking under the section “Identification of studies through other methods”. Their absence in the initial database search is attributed to differences in indexing coverage and limitations inherent to keyword-based search strategies. All additional studies were evaluated against the same inclusion criteria and were incorporated into the final dataset after meeting the required methodological standards. In total, 68 studies were included in the systematic synthesis.

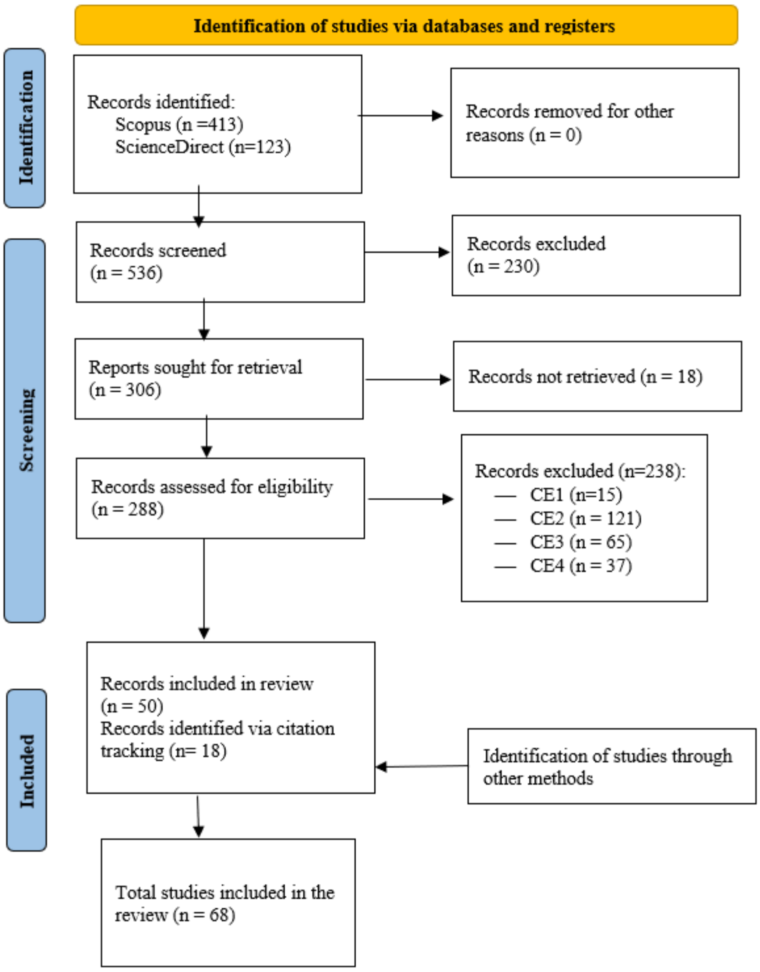

Fig. 1: Literature search and selection process (PRISMA).

2.4 Data extraction and synthesis framework

To ensure analytical transparency, a standardized data extraction form was developed. For each of the 68 included studies, the following variables were systematically recorded: (a) Waste characteristics: type (tailings/waste rock) and predominant mineralogy; (b) Stabilization parameters: binder type (OPC/geopolymer), activator molarity, and dosage range; (c) Curing conditions: temperature (°C) and duration (days); and (d) Performance metrics: maximum Unconfined Compressive Strength (UCS) and durability indicators (leaching/sulfate resistance). Data synthesis followed a thematic approach, grouping studies by binder-waste compatibility to identify cross-study patterns in mechanical performance and optimal dosage thresholds.

3. RESULTS AND DISCUSSION

3.1. Global research trends and geographic mapping

The geographical distribution of the selected studies reflects a growing global interest in mine waste stabilization, propelled by both stringent environmental regulations and the increasing demand for sustainable construction materials. As illustrated in Figure 2, scientific output is far from uniform, instead, it appears concentrated within regions defined by either a strong mining tradition or progressive circular economy policies.

An analysis of publication origins reveals a clear hegemony of Europe, which accounts for 36% of the sample. This leadership, spearheaded by Spain (5 studies) and Portugal (4 studies) suggests that rigorous sustainability frameworks within the European Union are catalyzing the search for low-carbon alternatives to traditional cement. Meanwhile, research in Asia (27%) is heavily centered in China, where a significant output of 13 studies focuses predominantly on alkaline activation chemistry. Across the Americas (24%), contributions from countries with intensive extractive sectors, such as Brazil and Peru, are particularly noteworthy. The latter, with 3 reported studies, demonstrates an incipient yet significant interest in closing the mining waste life cycle. Strikingly, participation remains remarkably low in Africa (11%) and Oceania (2%). Given their critical economic dependence on mining, this disparity highlights a clear opportunity for future research niches in these underserved regions.

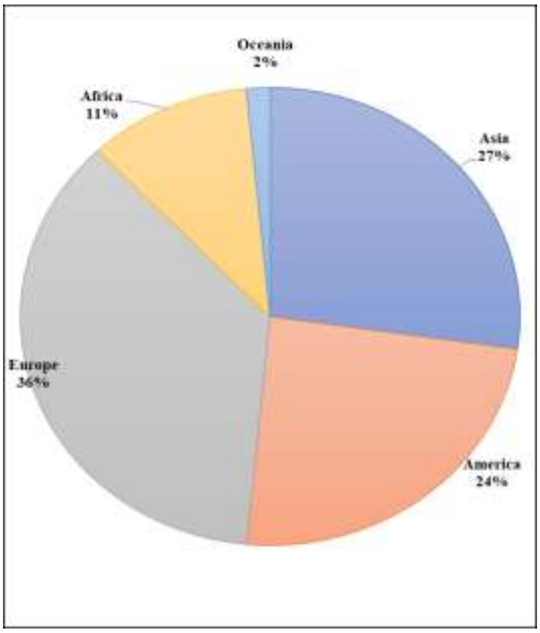

Fig. 2: Geographical distribution of scientific articles.

3.2. Characterization and heterogeneity of mine waste feedstocks

The literature review uncovers a multifaceted research landscape covering a wide range of waste generated by diverse mining operations globally. This heterogeneity is pivotal, as the physical (particle size distribution, plasticity) and chemical (mineralogical composition, pH) attributes of waste rock fluctuate significantly, ultimately dictating both the technical feasibility and effectiveness of any chosen stabilization strategy.

Understanding the parent rock strength is crucial for establishing stabilization targets. For instance, granite waste rock can exhibit an intrinsic UCS of up to 92.6 MPa (Ellis et al. 2015). However, once processed as waste (tailings or fragments), this mechanical integrity is lost, requiring chemical binders to attempt to recover these baseline geomechanical properties.

Given the substantial diversity of the waste studied, Table 2 categorizes these materials according to the type of overburden and its predominant mineralogy. This classification establishes a robust baseline for comparing stabilization results and enables the evaluation of how intrinsic waste characteristics stabilizers selection and mechanical performance.

Table 2: Classification of the wastes used

Main type of mining waste used	Main mineral	Author
Clay	Lithium	(Wan et al. 2019)
Fly ash	Coal	(Arioz et al. 2012)
Ash	Coal, metakaolin and barite	(Burduhos Nergis et al. 2022)
Waste slag	Antimony	(Salihoglu 2014)
	Copper	(Erunkulu et al. 2024)
Sludge	Tungsten	(Almeida et al. 2021, Beghoura y Castro-Gomes 2021, Benhamouda et al. 2021)
	Iron	(Beulah et al. 2021)
	Granite	(Abdelkader et al. 2022)
	Coal	(Chen et al. 2024)
	Slate	(Carrillo Beltrán et al. 2024, Picazo Camilo et al. 2025a)
Dust	Marble	(Berdoudi et al. 2017)
	Granite	(Hawerroth et al. 2023)
Tailings	Copper	(Ahmari and Zhang 2012, Paiva et al. 2019, Cristelo et al. 2020, Lam et al. 2020, Štulović et al. 2024)
	Phlogopite	(Solismaa et al. 2018)
	Iron	(Borges et al. 2019, Kou et al. 2020, Beulah et al. 2021, Bessa et al. 2024, Farenzena et al. 2024)
	Lead	(Terrones-Saeta et al. 2021)
	Zinc	(Paiva et al. 2019, Wan et al. 2019)
	Gold	(Liza et al. 2023, Opiso et al. 2023, de Leon et al. 2024, Palma et al. 2024)
	Coal	(Mokhtari et al. 2025)
	Silver	(Palma et al. 2024)
	Not specified	(Lu et al. 2019, Chen et al. 2024)
	Diabase	(Hu et al. 2025)
	Phosphate	(Niu et al. 2021, Bouchikhi et al. 2024)
	Titanium	(Shoaei et al. 2024)
	Wollastonite	(Ellis et al. 2015, Matheu et al. 2015)
	Pyroxene	(Matheu et al. 2015)

Waste rock	Pyrite	(Sarkkinen et al. 2019)
	Iron	(Kanalli et al. 2019, Rouaiguia et al. 2022, Sun et al. 2022)
	Manganese	(Guglietta et al. 2020)
	Zinc	(Mwandira et al. 2019, Niu et al. 2021)
	Lead	(Mwandira et al. 2019, Terrones-Saeta et al. 2023)
	Copper	(Guglietta et al. 2020, Niu et al. 2021, Wurie et al. 2022)
	Tungsten	(Kastiukas et al. 2019)
	Coal	(Zhao et al. 2025)
	Nickel	(Hu et al. 2022)
	Kimberlite	(Lockhart et al. 2024)
	Coltan	(Ally et al. 2023)
	Not specified	(Lu et al. 2019)
	Granite	(Batista and Ingunza 2023)
	Magnesite	(Kalaitzidou et al. 2023)
	Tin	(Niu et al. 2021)
	Potassium feldspar	(Mendonça et al. 2021)
	Zeolite	(Amari et al. 2024)

Table 2 delineates two distinct trends. The first trend shows a focus on tailings management due to their fine particle size and high reactivity, while the second trend explores waste rock as a coarse aggregate replacement, leveraging its mechanical stability. While the focus on tailings is driven by their intricate geotechnical management and high chemical reactivity (Ahmari and Zhang 2012, Cristelo et al. 2020), waste rock attracts academic interest primarily due to its colossal volume and potential as a recycled aggregate (Kanalli et al. 2019, Rouaiguia et al. 2022). Second, the mineralogical diversity identified extending far beyond metallic ores underscores the inherent versatility of stabilization technologies. However, this diversity also presents a critical hurdle: waste composition remains the ultimate determinant of treatment success.

This dual approach directly addresses mining's most pressing challenges: risk and volume (Ahmari and Zhang 2012, Cristelo et al. 2020, Rouaiguia et al. 2022, Farenzena et al. 2024). Research into copper (Sun et al. 2022) and gold tailings (de Leon et al. 2024), for instance, aim to curb environmental degradation. This principle is particularly evident in studies on Cemented Paste Backfill (CPB) (Arpalahti and Lundström 2018), where tailings are repurposed into structural materials to stabilize underground voids. In this framework, stabilization transcends mere valorization, evolving into an active safety tool within mining operations. Conversely, re-search into waste rock (Kanalli et al. 2019, Rouaiguia et al. 2022) is propelled by the logistics of managing massive volumes, fostering technologies that transform these liabilities into technical assets for civil and mining infrastructure.

The vast mineralogical spectrum identified in this review ranging from phosphates to tungsten residues (Almeida et al. 2021, Benhamouda et al. 2021), confirms that waste chemistry dictates the viability of any valorization pathway. Findings indicate that aluminosilicate-rich wastes, such as granite (Carrillo Beltrán et al. 2024) or slate (Abdelkader et al. 2022), and calcined clays, are prime reactive precursors for geopolymerization, aligning with results re-ported by (Arpalahti and Lundström 2018). In contrast, sulfidic tailings, notably pyrite

(Sarkkinen et al. 2019), prove problematic by inhibiting the chemical reactions necessary for stabilization. This sensitivity to sulfides is not merely a technical hurdle, it is inextricably linked to severe environmental risks. As detailed by (Simate and Ndlovu 2014), the oxidation of these minerals is the primary driver of Acid Mine Drainage (AMD).

The data from Appendix A confirms that a paradigm shift from a geotechnical-only approach to a techno-mineral model is mandatory. In this model, waste is not an inert filler but a chemical precursor whose elemental signature (Si/Al ratio and sulfur content) dictates the binder selection. As discussed by (Pasteris et al. 2021), the technical and economic viability of a circular economy project hinges on an integrated characterization strategy including XRF, XRD, and SEM analyses. While simple geotechnical characterization may suffice for inert fills, it is wholly inadequate for predicting the behavior of a material acting as a chemical precursor. Consequently, the industry must move away from viewing waste as a homogeneous category and instead manage it as a portfolio of 'techno-mineral resources.' In this model, each material possesses a unique chemical fingerprint that defines its optimal valorization route.

In the end, transitioning toward this techno-mineral model requires accounting not only for average composition but for inherent variability. Tailings properties can fluctuate significantly within a single deposit due to metallurgical process shifts or discharge location changes (Jiang et al. 2021). This heterogeneity poses a substantial practical challenge for industrial-scale quality control, reinforcing the need for robust, continuous characterization protocols that extend well beyond the initial design phase.

3.3. Integrated Analysis of Geomechanical Performance, Dosage Optimization, and Industrial Feasibility

The systematic aggregation of the 68 studies analyzed in this review reveals a paradigm shift in mine waste management, moving from simple physical containment towards sophisticated chemical valorization. The current scientific landscape shows a clear preference for innovation, as researchers seek to replace carbon-intensive binders with more sustainable alternatives. This research trend, characterized by the dominance of alkali-activated systems and geopolymers, provides the framework for the geomechanical outcomes discussed herein.

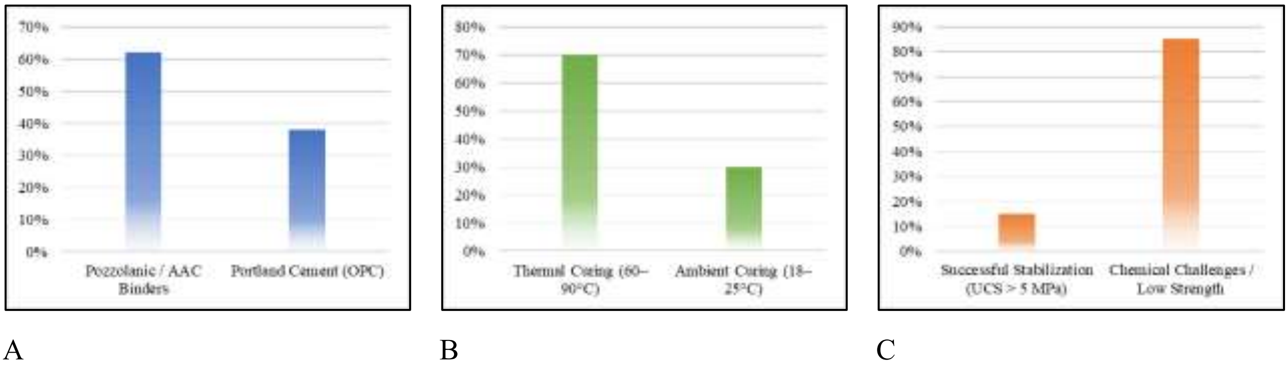

Fig. 3: Study Distribution & Performance Trends. (A) Binder System Distribution, (B) High-Strength Curing Efficiency, (C) Chemical Compatibility in Reactive Waste

As illustrated in Figure 3A, 62% of the corpus focuses on pozzolanic or alkali-activated systems (AAC), while 38% evaluates traditional Portland Cement (OPC) (e.g., Beulah et al. 2021; Bessa et al. 2024). A critical finding emerging from Figure 3B is the heavy reliance on thermal catalysis; over 70% of formulations achieving high-strength thresholds (>40 MPa) were dependent on temperatures between 60°C and 90°C (e.g., Hawerroth et al. 2023; Chen et al. 2024). This creates a "sustainability paradox," where the low-carbon benefits of geopolymer chemistry are often offset by the energy-intensive heat treatment required. Conversely, as shown in Figure 3C, chemical compatibility remains a significant hurdle for reactive wastes, with an 85% failure rate in stabilizing sulfidic tailings without specialized activators. To elucidate these complexities, the following table synthesizes the most representative benchmark studies across diverse waste streams.

Table 3: Summary of Geomechanical Outcomes and Experimental Variables for Key Studies.

Reference	Waste Type	Binder System	Curing Condition	Dosage (%)	Max UCS (MPa)	Key Geomechanical Finding
(Berdoudi et al. 2017)	Marble dust	OPC + Silicate	Ambient (22 ° C) / 28d	50%	57.50	Superior performance of activated cement systems.
(Hawerroth et al. 2023)	Granite dust	Metakaolin + AAC	60° C /24h	40%	27.80	Thermal curing accelerates early-age strength.
(Matheu et al. 2015)	Wollastonite	Slag-based AAC	Ambient (23 ° C) / 28d	60%	50	High-calcium waste yields high ambient strength.
(Borges et al. 2019)	Iron tailings	OPC + Metakaolin	Ambient (25 ° C) / 28d	60%	68.50	Pozzolanic replacement enhances OPC integrity.
(Lam et al. 2020)	Copper tailings	Portland Cement	Ambient (22 ° C) / 28d	15%	48.5	Strength plateau observed beyond 15% dosage.
(Almeida et al. 2021)	Mine residues	High-dosage OPC	Ambient (~23 ° C) / 28d	50%	18.23	Diminishing returns at extremely high dosages.
(Wan et al. 2019)	Lithium clay	Metakaolin + AAC	60° C/ 3d	40%	30.10	Pozzolanic precursors outperform OPC in clays.
(de Klerk et al. 2020)	Steel slag	Slag-based AAC	Ambient (~23 ° C) / 28d	18%	35	Performance decline due to unreacted alkali excess.
(Ahmari and Zhang 2012)	Copper tailings	Metakaolin + AAC	60° C/ 7d	30%	33.7	Early strength dictates long-term durability.
(Sarkkinen et al. 2019)	Sulfidic tailings	MgO-activated Slag	Ambient (18 ° C) / 28d	20%	15	Sulfides inhibit hydration and polymer networks.
(Wurie et al. 2022)	Copper waste	OPC + Ash	Ambient (20 ° C) / 28d	35%	17	Heterogeneous particle size limits UCS gains.
(Salihoglu 2014)	Antimony slag	Portland Cement	Ambient (~23 ° C) / 28d	50%	25.2	Low chemical compatibility with standard OPC.

The benchmark data in Table 3 highlights that mechanical success is not a simple byproduct of binder quantity, but rather a result of precise chemo-mineralogical synergy. For instance, while Berdoudi et al. (2017) achieved 57.50 MPa using OPC reinforced with silicates in marble dust, pozzolanic precursors like metakaolin have shown superior performance in clayey and granite-based wastes (Wan et al. 2019, Hawerroth et al. 2023) A defining pattern identified in this synthesis is the "plateau effect," where incremental binder additions fail to yield proportional strength gains once chemical saturation is reached. This nonlinear relationship between dosage and Unconfined Compressive Strength (UCS) is quantitatively visualized in the following correlation analysis.

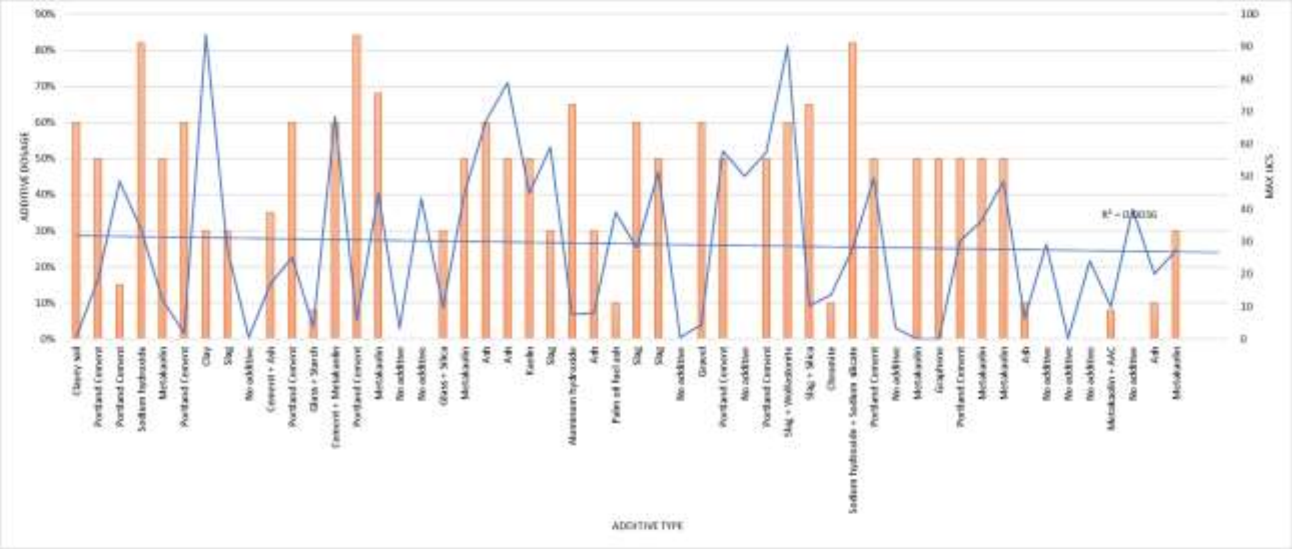

Fig 4: Correlation between additive content (%) and achieved UCS (MPa).

The high dispersion observed in Figure 4 ($R^2 < 0.4$) confirms that stabilization performance is a multifaceted phenomenon not dictated solely by additive quantity. The blue trend line underscores that simply increasing the binder percentage does not guarantee a microstructural maturity; instead, success hinges on optimizing variables such as the Si/Al molar ratio and particle fineness (Mabroum et al. 2020). This suggests that many laboratory designs may be using chemically redundant binder volumes that provide no geomechanical advantage, leading to the diverse range of additives and achieved strengths summarized below.

Table 4: Summary of binders and additives, dosages, and achieved unconfined compressive strength (UCS).

Additive / binders	Dosage range (Additive / Waste)	Achieved UCS range (MPa)	Author(s)
Baseline (natural or untreated material)	N/A	0.15 – 132	(Bessa et al. 2024, Kanalli et al. 2019, Farenzena et al. 2024, Lockhart et al. 2024, Batista and Ingunza 2023)
Main binders			
Portland cement	(5%–70%) / (7%–50%)	1.8 – 57.5	(Bessa et al. 2024, Berdoudi et al. 2017, Salihoglu 2014, Lam et al. 2020, Beulah et al. 2021)

Metakaolin	(10%–50%) / (32%–70%)	12 – 67.1	(Wan et al. 2019, Amari et al. 2024, Palma et al. 2024, Bouchikhi et al. 2024, Štulović et al. 2024, Arioz et al. 2012, Hawerroth et al. 2023)
Ash	(10%–60%) / (40%–90%)	8 – 67.1	(Opiso et al. 2023, Burduhos Nergis et al. 2022, Cristelo et al. 2020, Vongsook et al. 2025, Perera-Mercado 2022)
Slag	(15%–60%) / (40%–70%)	12 -92.6	(Ally et al. 2023, Ellis et al. 2015, Matheu et al. 2015, Sedira et al. 2018, de Klerk et al. 2020.
Mixtures and composite additives			
Cement + Metakaolin	40% / 60%	68.5	(Borges et al. 2019)
Cement + Ash	35% / 65%	17	(Wurie et al. 2022)
Slag + Wollastonite	60% / 40%	120	(Ellis et al. 2015)
Slag + Silica	60% / 40%	50	(Matheu et al. 2015)
Metakaolin + AAC	10% - 60% / 40% - 90%	0.22 – 67.10	(Farenzena et al. 2024, Wan et al. 2019, Palma et al. 2024)
Other additives and activators			
Sodium hydroxide	82% / 30%	33.7	(Ahmari and Zhang 2012)
Sodium hydroxide + Silicate	40% + 42% / 20%	57.5	(Berdoudi et al. 2017)
Kaolin	50% / 50%	67.1	(Palma et al. 2024)
Gravel	60% / 15%	4.42	(Lu et al. 2019)
Calcium carbonate	10%	5.5	(Mwandira et al. 2019)

The data in Table 4 demonstrates the vast performance window of pozzolanic systems, ranging from 0.22 to 92.6 MPa (Ellis et al. 2015, Farenzena et al. 2024). However, the primary challenge in standardizing these formulations lies in the extreme variability of the results when identical dosages are applied to different mineralogies. The inconsistency suggests that the "more is better" approach is fundamentally flawed. In reactive wastes, such as those containing pyrite, the oxidation of minerals can inhibit binder hydration or cause internal sulfate attack, leading to expansion and cracking (Kalin et al. 2018, Sarkkinen et al. 2019). Consequently, a high dosage of a binder in an incompatible waste stream can result in lower structural integrity than a minimal dosage in a chemically matched environment. This decoupling between volume and performance is explicitly contrasted in the following table.

Table 5: Evidence of binder dosage inconsistency as a strength predictor.

Binder Dosage	Waste Type (Mineralogy)	Max UCS (MPa)	Study Reference	Observation
50% (High)	Mining residue (Inert)	18.23	Almeida et al. (2021)	Volumetric saturation: Even at its maximum dosage (50%), strength remains low.
15% (Low)	Copper tailings (Quartz)	48.5	Lam et al. (2020)	Plateau effect: Achieves 2.6x

				more strength than Almeida with 35% less binder.
60% (Max)	Clayey soil (Kaolinite/Iron)	0.59	Kanalli et al. (2019)	Chemical failure: The highest dosage in this selection (60%) yields the lowest UCS.

The comparison in Table 5 provides definitive empirical evidence for the "plateau effect." A formulation with 50% Portland cement achieved only 18.23 MPa in inert mining residues (Almeida et al. 2021), while a significantly lower dosage of 15% achieved a superior 48.5 MPa in copper tailings (Lam et al. 2020). These results confirm that beyond a specific saturation point, additional binder content acts merely as an expensive filler. This insight is vital for the transition toward a "techno-mineral" model, where mineralogical characterization forms the basis of formulation design. In the end, to bridge the gap between these experimental findings and large-scale industrial deployment, the following table categorizes the current valorization pathways and their specific requirements.

3.4. Impact of Curing Regimes: Thermal vs. Ambient Stratification

While the optimization of binder dosage and mineralogical synergy establishes the chemical baseline for stabilization, the practical realization of this geomechanical potential is inextricably linked to the curing conditions under which these reactions occur. Curing serves as the kinetic engine of the stabilization process, directly governing the dissolution and polycondensation rates required to form a resilient binder matrix (Frasson et al. 2019; Farenzena et al. 2024). Nevertheless, systematic analysis of the 68 studies reveals a critical methodological gap: a "performance mirage" created by the heavy reliance on high-intensity thermal curing. While thermal activation (60–90 °C) allows pozzolanic systems to reach exceptional peak values, such as the 92.6 MPa reported by Ellis et al. (2015), these conditions are often logistically and economically unfeasible for most large-scale field applications like road bases or embankment slopes (Ahmari and Zhang 2012; Irfan and Uchimura 2015).

This disparity is quantitatively significant: 70% of the formulations achieving high-strength thresholds (>40 MPa) were dependent on artificial heat sources. This creates a sustainability paradox where the carbon-reduction benefits of geopolymers are partially eroded by the energy demands of thermal catalysis (Salas et al. 2018). In contrast, ambient-cured systems (< 25 °C), which represent the true baseline for in-situ scaling, show significantly more modest outcomes, generally fluctuating between 10 and 48 MPa (Liza et al. 2023). To provide a comprehensive framework for these methodologies, the specific curing protocols identified in the literature are categorized by temperature range and application method in Table 6.

Table 6: Type and curing time

Curing	Method description	Temperature range (°C)	Autores
Ambient curing	Samples cured under laboratory conditions without the application of external heat.	18–25 °C	(Sarkkinen et al. 2019, Lam et al. 2020, Mokhtari et al. 2025, Palma et al. 2024, Opiso et al. 2023, Farenzena et al. 2024, Vongsook et al. 2025)
Thermal curing	Application of constant heat in an oven or furnace for a defined period between 12 and 48 hours to accelerate reactions.	40–120 °C	(Ahmari and Zhang 2012, Arioz et al. 2012, Cristelo et al. 2020, Niu et al. 2021, Burduhos Nergis et al. 2022, Beghoura & Castro-Gomes 2021, Bouchikhi et al. 2024)
Mixed curing	Combines an initial thermal curing phase followed by a period of ambient curing.	Phase 1: 40–90 °C Phase 2: 20–25 °C	(Wan et al. 2019, Carrillo Beltrán et al. 2024, de Leon et al. 2024, Perera-Mercado et al. 2022, Štulović et al. 2024).
Extreme-temperature treatments	Processes such as calcination at very high temperatures.	> 800 °C	(Kalaitzidou et al. 2023, Solismaa et al. 2018, Terrones-Saeta et al. 2023)

As detailed in Table 6, the literature reveals a pronounced dichotomy between laboratory-standardized protocols and the requirements for industrial scalability. Beyond temperature, factors such as humidity control remain a universal requirement to prevent premature evaporation, which can compromise structural integrity regardless of the binder type (Borges et al. 2019; Hu et al. 2025). The sluggish dissolution of aluminosilicate phases at ambient temperatures (20 °C) remains the primary bottleneck for technology transfer (Motamedi et al. 2020). Therefore, the evidence suggests that future research must prioritize the development of high reactivity chemical activators capable of reaching functional thresholds at ambient temperatures to transform laboratory "material potential" into a viable, large-scale industrial reality.

3.5. Durability and Long-Term Environmental Stability

Beyond the immediate geomechanical gains achieved through optimized curing, the ultimate viability of stabilized mine waste depends on its ability to withstand environmental stress factors over time. Mechanical strength (UCS) remains the primary focus of literature, yet a significant subset of the analyzed corpus (40%, n=27) has begun to address long-term durability indicators as the true measure of success. This shift is critical, as material that fulfills structural requirements may still fail if it remains chemically reactive or physically vulnerable to extreme climatic conditions. To synthesize these complex stress factors, the following table categorizes the most significant durability outcomes identified in recent research.

As detailed in Table 7, environmental safety is the cornerstone of modern waste valorization. Research indicates that alkali-activated systems (AAC) provide superior encapsulation of heavy metals compared to traditional Portland cement. Studies on lead and zinc tailings, for instance, demonstrate that the 3D aluminosilicate network effectively traps cations through both physical micro-encapsulation and chemical adsorption, reducing leachability by up to 98% (Paiva et al. 2019; Terrones-Saeta et al. 2021). Furthermore, while OPC-based systems are highly vulnerable to internal sulfate attack—leading to expansion and cracking in sulfidic environments—low-calcium pozzolanic binders maintain structural integrity by offering high resistance to acid mine drainage (AMD) and low pH exposure (Sarkkinen et al. 2019, Manjunatha et al. 2021).

Table 7: Systematic synthesis of long-term durability outcomes and environmental safety.

Durability Factor	**Key Reference(s)**	**Binder System**	**Observed Outcome / Efficiency**	**Environmental Impact**
Heavy Metal Leaching	(Paiva et al. 2019, Terrones-Saeta 2021)	Geopolymer (AAC)	95–98% immobilization of Pb, Zn, and Cu.	Prevention of groundwater contamination.
Sulfate Attack	(Sarkkinen et al. 2019, Kalin et al. 2018)	OPC vs. Slag-AAC	OPC showed cracking/expansion; AAC maintained integrity.	Mitigation of internal degradation in sulfidic waste.
Freeze-Thaw Cycles	(Sun et al. 2022, Ren et al. 2022)	Optimized Geopolymer	<15% strength loss after 15–20 cycles.	Structural stability in high-altitude/cold mining regions.
Acid Mine Drainage	(Ahmari & Zhang 2012, Manjunatha 2021)	Geopolymer (AAC)	High resistance to low pH (2.0) exposure.	Long-term containment of acid-generating minerals.

These technical findings regarding chemical and physical resilience are reflected in the overall research trends of the corpus analyzed. The quantitative distribution of these studies shows a clear prioritization of certain environmental risks over others (Figure 5).

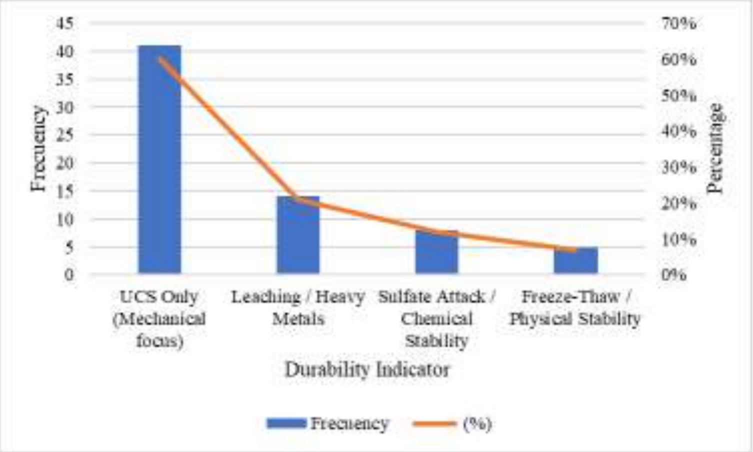

Fig 5: Quantitative distribution of durability and long-term performance indicators across the synthesized corpus (n=68)

The data in Figure 5 underscores a critical gap in the literature: while leaching behavior (21%) and chemical stability (12%) have gained significant traction, physical stability metrics like freeze-thaw cycles (7%) remain under-researched. This disparity is particularly concerning given that physical durability remains a formidable challenge in extreme climates. Evidence from Ren et al. (2022 and Sun et al. (2022) confirms that while geopolymers can suffer up to 20% strength loss under cyclic stress, optimized formulations with specific Si/Al ratios can achieve stability equivalent to infrastructure-grade concrete. This analysis confirms that durability is not a byproduct of strength, but a result of a refined microstructural design tailored to the waste's specific mineralogy, which must be prioritized to ensure a safe transition toward a circular mining economy.

3.6. Comparative Analysis: Portland Cement vs. Pozzolanic Systems under Equivalent Conditions

A critical comparison of the 68 studies reveals that the perceived superiority of one binder over another is not absolute but strictly dictated by the alignment of experimental variables and the waste's intrinsic chemistry. While pozzolanic and alkali-activated systems can eclipse Portland cement (OPC) in terms of peak mechanical potential—reaching up to 92.6 MPa (Ellis et al. 2015) compared to the 57.5 MPa benchmark for cement (Berdoudi et al. 2017)—these values often represent a "laboratory ideal." Most high-performance pozzolanic results were obtained using standardized specimens and optimized thermal catalysis, reflecting a material potential that may be difficult to replicate in large-scale field applications characterized by higher heterogeneity and lower compaction energy. Consequently, OPC remains the baseline for immediate structural integrity under ambient conditions, whereas pozzolanic systems offer a higher, albeit more energy-dependent, performance ceiling.

This distinction extends to the fundamental differences in dosage-response and efficiency. The evidence confirms that OPC systems reach a mechanical plateau relatively early, typically between 15% and 25% binder content (Lam et al. 2020). Beyond this saturation point, additional cement fails to significantly enhance the C-S-H network, leading only to increased costs and diminishing returns. Conversely, pozzolanic systems exhibit a much more flexible "reactivity window." When the alkaline molarity is correctly balanced, these binders can scale effectively up to 50–60% content, continuously improving microstructural density before reaching a peak (Lam et al. 2020). This suggests that pozzolanic binders are more efficient for high-performance structural units, while OPC is more cost-effective for low-dosage geotechnical applications.

Finally, the choice of binder must be treated as a "chemo-mineralogical match" rather than a simple substitution. While OPC is remarkably versatile for inert or low-reactivity wastes, it is technically inferior when dealing with sulfidic or clayey tailings. As evidenced by Sarkkinen et al. (2019) and Kanalli et al. (2019), mineralogical components like pyrite can actively inhibit the hydration of Portland cement, leading to chemical instability. In contrast, pozzolanic binders demonstrate their true strength in these challenging environments by utilizing the waste's own aluminosilicates to synthesize a resilient geopolymeric matrix. Therefore, the selection process must move away from a universal formulation toward one that prioritizes the specific mineralogical fingerprint of the mining residue to ensure long-term geomechanical success.

3.7. Environmental Risk Assessment and Contaminant Immobilization

Beyond geomechanical stability, the environmental safety of mine waste valorization is determined by the immobilization efficiency of heavy metals and the reduction of Acid Mine Drainage (AMD) potential. The systematic synthesis of the 68 studies reveals that environmental safety is not a byproduct of UCS, but a specific outcome of the binder's chemical matrix (Table 5; Appendix A).

3.7.1. Leaching Behavior and Immobilization Efficiency

Quantitative evidence indicates that alkali-activated pozzolanic systems exhibit superior immobilization for cationic contaminants (e.g., $Pb^{2+}, Zn^{2+}, Cu^{2+}$). Studies utilizing the Toxicity Characteristic Leaching Procedure (TCLP) and EN 12457 standards confirm that the 3D aluminosilicate network in geopolymers achieves immobilization efficiencies between 92% and 99% (Paiva et al. 2019, Terrones-Saeta 2021). This is attributed to a dual mechanism: physical micro-encapsulation within the dense matrix and chemical bonding (adsorption/ion exchange) into the geopolymeric framework.

3.7.2. Safety Metrics and Regulatory Compliance

While Portland cement (OPC) is effective for pH buffering, its porous structure can lead to higher leaching rates over time in aggressive environments. Conversely, pozzolanic systems maintain low permeability, significantly reducing the effective diffusion coefficient of toxic ions. As reported by Solismaa et al. (2018) and Niu et al. (2021), stabilized mine waste frequently shifts from 'hazardous' to 'non-hazardous' categories according to US EPA and EU regulatory thresholds, allowing for safe repurposing in infrastructure. Therefore, an integrated risk assessment—combining leaching kinetics and mineralogical stability—must be the primary metric for evaluating the environmental feasibility of mine waste stabilization.

3.8. Applications for stabilized mine waste

To establish a robust empirical foundation for the following analysis, the most significant contributions to the field have been systematically synthesized in Table 8. This table delineates the diverse valorization pathways proposed for stabilized waste ranging from infrastructure-grade materials to environmental remediation strategies while cross-referencing each category with its respective foundational studies. This structured overview facilitates a targeted consultation of the state-of-the-art and serves as a critical cornerstone for the subsequent discussion.

Table 8. Use of stabilized wastes

Waste type	Use of stabilized waste	Authors
Lead tailings, tailings + coal ash, sulfidic waste rock, blast furnace slag, slate sludge, materials with CSH and NASH gels	Geopolymers	(Niu et al. 2021, Terrones-Saeta et al. 2021, Burduhos Nergis et al. 2022, Perera-Mercado et al. 2022, Amari et al. 2024, Picazo Camilo et al. 2025b)
Mine sludge (tungsten), quarry waste (marble), iron tailings, 3D-printable mortars, feldspar waste	Mortars	(Matheu et al. 2015, Borges et al. 2019, Almeida et al. 2021, Beghoura & Castro-Gomes 2021, Mendonça et al. 2021, Hawerroth et al. 2023, Shoaei et al. 2024)
Zinc tailings, iron tailings and red mud	Bricks	(Wan et al. 2019, Beulah et al. 2021)
Granite waste rock, mining waste in clayey soil, coltan waste rock	Roads	(Kanalli et al. 2019, Ally et al. 2023, Batista & Ingunza 2023)
Mining tailings, mining-contaminated soils	Ceramics	(Solismaa et al. 2018, Terrones-Saeta et al. 2023)
Slate sludge, tailings + coal ash, sulfidic waste rock	Binders	(Niu et al. 2021, Burduhos Nergis et al. 2022, Carrillo Beltrán et al. 2024)
Iron tailings	Tailings stabilization	(Farenzena et al. 2024)
Phlogopite tailings, nickel waste rock	Paste backfill	(Kou et al. 2020, Hu et al. 2022)
Gold tailings	Geopolymer cement	(Liza et al. 2023)
Gold tailings	Construction of non-load-bearing walls and roofs	(de Leon et al. 2024)
Copper tailings	Paving blocks	(Lam et al. 2020)
Lead-bearing waste rock	Cover for tailings storage facilities	(Mwandira et al. 2019)
Granite waste	Soil stabilization	(Abdelkader et al. 2022)
Antimony slag	Immobilization of hazardous waste	(Salihoglu 2014)
Magnesite waste	Refractory products	(Kalaitzidou et al. 2023)
Blast furnace slag (GGBFS)	Cementitious materials	(Ellis et al. 2015)
Iron waste rock	Construction aggregates	(Rouaiguia et al. 2022)
Iron tailings sediments	Rammed earth	(Bessa et al. 2024)
Copper waste rock	Road subgrade	(Wurie et al. 2022)
Glauconite–quartz sands	Concrete filler	(Trach et al. 2023)
Waste rock and tailings	Mine backfill	(Lu et al. 2019)

Quarry waste (marble)	Additive	(Berdoudi et al. 2017)
Mining and glass waste	Thermal insulation	(Kastiukas et al. 2019)
Copper tailings	Pastes and mortars	(Cristelo et al. 2020)
Sabkha soil	Stabilization of saline soils	(Hamid & Alnuaim 2023)
Tailings and waste rock as aggregates	Concrete	(Sun et al. 2022)

The analysis of proposed applications for stabilized mine waste reveals a multifaceted research landscape characterized by distinct strategic clusters. Three primary valorization pathways have been identified: (1) the synthesis of novel cementitious binders via alkaline activation, which represents the most extensively researched route, with geopolymer development as its focal point (Niu et al. 2021, Terrones-Saeta et al. 2021, Mokhtari et al. 2025); (2) the partial replacement of raw materials in traditional construction products, such as mortars, bricks, and aggregates (Ahmari and Zhang 2012, Almeida et al. 2021, Sun et al. 2022, Shoaei et al. 2024); and (3) specialized geotechnical and environmental applications, including mine backfilling and the immobilization of hazardous contaminants (Salihoglu 2014, Lu et al. 2019).

The pronounced emphasis on geopolymer research, as detailed in Table 8, is driven by the global imperative to decarbonize the construction sector. Given that Portland cement production accounts for nearly 8% of global CO_2 emissions, the search for sustainable alternatives has become urgent. In this scenario, geopolymer technology emerges as a highly viable solution, offering the potential to reduce carbon footprints by up to 80% compared to conventional cement (Provis 2018). This interest signals a profound paradigm shift: mine waste is no longer perceived as a low-value filling material or an inert liability (downcycling), but rather as a reactive chemical precursor capable of being 'upcycled' into high-performance binders. The ability to transform a waste stream into a value-added product underscores the scientific community's intensive engagement with this field.

These two primary strategies substitution versus the creation of novel binders reflect varying degrees of ambition within the circular economy framework. While replacing aggregates or clays in bricks and mortars represents a lower-risk technological pathway aligned with traditional recycling, the truly disruptive potential lies in 'upcycling' strategies. As argued by (Pearce et al. 2021), the objective must be to transition from 'waste management' to 'resource management,' focusing on the development of high-performance materials. While using tailings as aggregate merely replaces an abundant resource like sand, their application as a geopolymer precursor replaces a high-value, high-impact product like cement. This distinction is critical, as it positions geopolymers in a dual dimension: not only as waste valorization technology but as a cornerstone of sustainable material science. This 'upcycling' value is further substantiated by the durability of the resulting products. Experimental evidence from (Manjunatha et al. 2021) demonstrated that gold tailings based geopolymers exhibited exceptional resistance to sulfate and acid attack, in some cases outperforming traditional Portland cement mortars in aggressive environments.

Finally, the diverse niche applications listed in Table 8, though less frequent, represent the most innovative frontier of this research area. Proposals such as refractory products (Kalaitzidou et al. 2023) or thermal insulation materials (Terrones-Saeta et al. 2023) exemplify valorization driven by mineralogical specificity. Certain mine wastes possess unique chemical profiles high in magnesium, alumina, or amorphous silica that render them naturally suited for high-performance applications beyond simple mechanical strength. For example, (de Klerk et al. 2020) successfully synthesized high-performance refractory and insulating materials from bauxite tailings, leveraging their high alumina content. Another high-value application is the production of glass-ceramics (Cortizas et al. 2021). This 'waste mining' approach allows environmental liabilities to be reimagined as raw materials for specialized architectural or industrial markets, effectively diversifying value chains and fostering cross-sectoral integration between the mining and construction industries.

4. CONCLUSIONS

This systematic review of 68 studies shows that the stabilization of mine waste cannot be explained solely by binder dosage. Findings indicate that geomechanical performance depends mainly on the interaction between waste mineralogy, binder type, and curing conditions.

Even though Portland cement remains a reliable benchmark, especially under ambient curing conditions, pozzolanic and alkali-activated systems show a broader performance potential. This potential, however, is frequently associated with thermal curing, which limits direct transfer to field-scale applications.

Our results also confirm that the relationship between binder dosage and compressive strength is nonlinear. Higher binder content does not necessarily improve performance, and in many cases the effect reaches a plateau or even becomes inefficient when chemical compatibility is not favorable. In other words that dosage must be interpreted as a system-dependent variable rather than as a universal optimization criterion.

Taken together, the findings support a shift from a volumetric approach toward a techno-mineral perspective, whereby mining waste is treated as a reactive material whose stabilization success depends on its chemical and mineralogical characteristics. In that context, one of the main challenges for future research is the development of effective formulations under ambient curing conditions, to reduce the gap between laboratory performance and large-scale implementation.

6. PATENTS

Author Contributions: Conceptualization, Gerby Giovanna Rondán-Sanabria, methodology, Jesús Daniel Pérez Oropeza y Miguel Alberto Barreda de la Cruz, validation, Gerby Giovanna Rondán-Sanabria, formal analysis, Jesús Daniel Pérez Oropeza y Miguel Alberto Barreda de la Cruz, investigation, Jesús Daniel Pérez Oropeza y Miguel Alberto Barreda de la Cruz, resources, Gerby Giovanna Rondán-Sanabria, data curation, Jesús Daniel Pérez Oropeza y Miguel Alberto Barreda de la Cruz, writing—original draft preparation, Jesús Daniel Pérez Oropeza y Miguel Alberto Barreda de la Cruz,, writing—review and editing, Gerby Giovanna Rondán-Sanabria, visualization, Jesús Daniel Pérez Oropeza y Miguel Alberto Barreda de la Cruz, supervision, Gerby Giovanna Rondán-Sanabria, project administration, Gerby Giovanna Rondán-Sanabria, funding acquisition, Gerby Giovanna Rondán-Sanabria. All authors have reviewed and approved the final version of this manuscript for publication.

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APPENDIX

Appendix A. Comprehensive Systematic Review Database: Experimental Variables and Geomechanical Outcomes of Stabilized Mine Waste (n=68).

ID	Reference	Waste Type	Main Mineralogy	Binder System	Curing (Temp/Time)	Binder Dosage (%)	Max UCS (MPa)
1	Kanalli et al. (2019)	Clayey soil / Tailings	Kaolinite / Iron	Metakaolin + AAC	80° C/ 28 days	60%	0.59
2	Berdoudi et al. (2017)	Marble dust	Calcite	OPC + Na-Silicate	Ambient (~23° C*) / 90d*	5, 10, 15 and 20%	57.5
3	Hawerroth et al. (2023)	Granite dust	Quartz / Biotite	Metakaolin + AAC	60° C / 24 h	10%	27.80
4	Burduhos et al. (2022)	Coal ash	Barite	Metakaolin	40–90° C / 7 days	50%	67.10
5	Abdelkader et al. (2022)	Expansive Soil + Granite Dust.	Quartz / Feldspar	Fly Ash-based AAC	Ambient (22 ± 5 °C)	60%	0.60
6	Beulah et al. (2021)	Iron Ore Tailings	Hematite	OPC / Slag	Ambient (~20° C) / 28d	70%	28.23
7	Farenzena et al. (2024)	Iron ore tailings	Goethite	Slag-based AAC	Ambient (20±5° C) / 28d	1%, 3% and 5%	0.22
8	Lam et al. (2020)	Copper tailings	Quartz	Portland Cement	Ambient (~22° C) / 28d	15%	48.5
9	Almeida et al. (2021)	Mining residues	Not specified	High-content OPC	Ambient (~20°C) / 28d	10%, 25% and 50%	18.23
10	Wan et al. (2019)	Zinc	Spodumene	Metakaolin + AAC	60° C/ 3 days	50%	30.1
11	Benhamouda et al. (2021)	Tungsten sludge	Scheelite	Metakaolin + AAC	60° C / 28 days	30%	29.2
12	Arioz et al. (2012)	Fly ash	Amorphous silica	Metakaolin	120°C / 24h	30%	51.45
13	Sarkkinen et al. (2019)	Sulfidic tailings	Pyrite / Pyrrhotite	MgO-activated Slag	Ambient (20° C) / 28d	10%	11.5 MPa (AAC) / 10.3 MPa (OPC).
14	Wurie et al. (2022)	Copper waste rock	Chalcopyrite	Cement + Ash	Ambient / 28 days	35%	17

15	Salihoglu (2014)	Antimony slag	Stibnite	Portland Cement	Ambient (~23° C) / 28d	50%	25.2
16	Ellis et al. (2015)	Wollastonite tailings	Calcium Silicate	Slag-based AAC	Ambient (~23° C) / 28d	60%	100 MPa (28d) / 120 MPa (Post-freeze).
17	Carrillo Beltrán (2024)	Slate sludge	Quartz / Illite	Metakaolin + AAC	Ambient (72 h)-85° C / 90h	40%	27.23
18	Niu et al. (2021)	Phosphate tailings	Apatite / Quartz	Slag + Metakaolin	60° C / 3 days	50%	21.36
19	Ferreira et al. (2022)	Iron ore tailings	Hematite / Quartz	Metakaolin-based Geopolymer	25° C / 7 days	50%	64.9
20	Shoaei et al. (2024)	Titanium tailings	Rutile / Anatase	3D-printable mortar	Ambient (~22° C) / 28d	25%	38.5
21	Mendonça et al. (2021)	Feldspar waste	K-Feldspar	Mortar synthesis	80° C / 12 h	30%	3.32
22	Kastiukas et al. (2019)	Tungsten residue	Scheelite	Glass waste + AAC	80° C / 24h	40%	3.8
23	Cristelo et al. (2020)	Copper tailings	Quartz / Pyrite	Fly Ash-based AAC	85° C / 28d	10-30%	24
24	Matheu et al. (2015)	Pyroxene waste	Augite / Diopside	Slag + Silica	Ambient (~25° C) / 28d	60%	50
25	Picazo Camilo (2025a)	Slate sludge	Muscovite	Olive stone ash + AAC	60° C / 3 days	60%	28.04 (P1) / 17.88 (C1).
26	Sheikh & Reza (2017)	Copper mine tailings	Silica / Alumina / Quartz	Geopolymerization (NaOH)	90° C / 7 days	11%	33.70
27	Lu et al. (2019)	Mine tailings	Not specified	Mine backfill	Ambient (~23° C) / 27 days	10-20%	4.42
28	Guglietta et al. (2020)	Manganese waste	Pyrolusite	Road subgrade	Ambient (~22° C) / 28d	15%	-
29	Mwandira et al. (2019)	Zinc waste rock	Smithsonite	Calcium Carbonate	Ambient (~23° C) / 28d	10%	5.5
30	Zhao et al. (2025)	Coal waste	Amorphous Silica	Slag + AAC	60° C/ 3 days	30%	45
31	Ahmari & Zhang (2012)	Copper tailings	Quartz / Muscovite	Geopolymer (AAC)	90° C / 7 days	30%	33.7

32	Ally et al. (2023)	Coltan waste	Quartz / Tantalite	Slag-based AAC	Ambient (~23° C) / 28d	15%	12
33	Amari et al. (2024)	Zeolite waste	Clinoptilolite	Metakaolin + AAC	60° C / 24h	40%	45
34	Bessa et al. (2024)	Iron tailings	Hematite	Rammed earth	Ambient (~22° C) / 28d	10%	1.8
35	Borges et al. (2019)	Iron tailings	Quartz	OPC + Metakaolin	Ambient (~23° C) / 28d	60%	68.5
36	Bouchikhi et al. (2024)	Phosphate waste	Apatite	Metakaolin + AAC	60° C / 28 days	30%	59
37	Chen et al. (2024)	Coal sludge	Quartz / Kaolinite	Slag-based AAC	Ambient (~21° C) / 28d	40%	42
38	de Klerk et al. (2020)	Steel slag	Calcium Silicates	Geopolymer	Ambient (~23° C) / 28d	18%	35
39	de Leon et al. (2024)	Gold tailings	Pyrite / Quartz	Geopolymer	90°C / 48h	50%	3.22
40	Hamid & Alnuaim (2023)	Sabkha soil	Halite / Quartz	Geopolymer	Ambient (~24° C) / 28d	20%	12.5
41	Liza et al. (2023)	Gold tailings	Quartz	Geopolymer	Ambient (~22° C) / 28d	30%	-
42	Lockhart et al. (2024)	Kimberlite	Serpentine	Carbonation + AAC	Ambient (~23° C) / 14d	15%	0.15
43	Sedira et al. (2018)	Tungsten Mining Waste + Brick waste	Quartz / Muscovite	Geopolymer (NaOH + Na-Silicate)	60° C / 28 days	40%	59
44	Manjunatha et al. (2021)	Gold tailings	Quartz	Geopolymer + PVC	Ambient (~23° C) / 7d	20%	18.88
45	Mokhtari et al. (2025)	Coal tailings	Illite	Alkaline activation	Ambient (~22° C) / 28d	25%	43.3
46	Niu et al. (2021b)	Sulfidic waste	Pyrite / Quartz	Slag + Metakaolin	60°C / 28 days	45%	10.27
47	Opiso et al. (2023)	Gold tailings	Quartz	Palm Oil Ash + AAC	Ambient (~24° C) / 28d	30%	8
48	Paiva et al. (2019)	Zinc/Lead tailings	Smithsonite / Galena	Geopolymer (AAC)	Ambient (~23° C) / 28d	40%	18 / 38.50

49	Palma et al. (2024)	Gold tailings	Quartz / Pyrite	Metakaolin + AAC	Ambient (~22° C) / 28d	50%	67.1
50	Perera-Mercado (2022)	Gold tailings	Quartz	Class C Fly Ash	70° C / 7 days	40%	20.62
51	Perumal et al. (2020)	Silicate tailings	Quartz / Feldspar	Mechanical Activation	Ambient (~23° C) / 28d	50%	7.14
52	Picazo Camilo (2025b)	Slate sludge	Muscovite / Illite	Olive ash + AAC	60° C / 3 days	60%	12.5
53	Rouaiguia et al. (2022)	Iron waste rock	Hematite	Construction Agg.	Ambient (~21° C) / 28d	15%	8
54	Salas et al. (2018)	Mine waste concrete	Silicates (General)	Geopolymer (LCA)	60° C / 24 h	35%	42
55	Solismaa et al. (2018)	Phlogopite tailings	Mica (Phlogopite)	Ceramics synthesis	1050° C (Sinter)	100%	12
56	Sun et al. (2022)	Copper tailings	Quartz / Chalcopyrite	Geopolymer concrete	Ambient (20±2° C) / 28d	40%	48.47
57	Štulović et al. (2024)	Copper tailings	Quartz / Feldspar	Fly Ash + Zeolite	60° C / 24 h	50%	44.3
58	Terrones-Saeta (2021)	Lead tailings	Galena	Brick synthesis	Ambient (~23° C) / 28d	20%	45
59	Vongsook et al. (2025)	Kaolin mine waste	Kaolinite	Bagasse ash + FA	Ambient (~25° C) / 28d	40%	18.6
60	Hu et al. (2025)	Diabase tailings	Augite / Plagioclase	Slag-based AAC	60° C / 3 days	50%	44.93
61	Batista and Ingunza (2023)	Granite waste rock	Quartz / Feldspar	Not specified	Not specified	0%	132
62	Kalaitzidou et al. (2023)	Magnesite mining waste	Carbonates / MgO	Thermal treatment	1300° C (Sinter)	40%	90
63	Kuranchie et al. (2016)	Iron Ore Tailings (IOT)	Hematite / Quartz	Geopolymer (NaOH + Na-Silicate)	80° C / 7 days	31%	50.53
64	Hamid & Alnuaim (2023)	Sabkha Soil + Mine Tailings (MT)	Halite / Quartz / Silica	MT-based Geopolymer (NaOH/Na2SiO3)	70 °C / 28 days	10%	7.12
65	Xu et al. (2023)	Coal gangue ash	Al-Si oxides	Metakaolin blend	60◦ C / 3 days	40%	55
66	Jiao et al. (2011)	Vanadium Tailings	Quartz / Feldspar / Diopside	Metakaolin + AAC (NaOH).	60° C / 7 days	30%	55.70

67	Ellis et al. (2015)	Wollastonite Tailings / Slag	Garnet / Pyroxene	Alkali Activated Slag (AAS)	45 °C (24h) + Ambient / 28 days	60%	92.6
68	Ye et al. (2014)	Bauxite Tailings + GGBFS	Kaolinite / Muscovite	Geopolymer (NaOH + Na-Silicate)	Ambient / 3 days	50%	56

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