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Engineering a practical chemical pathway from mine waste to high-value materials

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Abstract

Tailings are typically generated in vast volumes, often millions of tonnes, and consist of finely ground mineral particles forming a complex assemblage of oxides, sulphides, hydroxides, silicates, carbonates and other phases. Rather than discrete mineral streams, tailings occur as composite streams in which mineral species are intimately mixed. This complexity underpins the long-term environmental and engineering challenges associated with tailings storage facilities, often persisting well beyond mine closure. Through a different lens, this large mineral mass represents a near-ready secondary raw material. Increasingly, tailings are being considered as a potential resource capable of supporting post-closure value creation, particularly where volumes, mineralogy and proximity to markets align. The author has participated in multiple studies aimed at analysing, separating and repurposing tailings into high-value, high-volume products, including in remote mining contexts. This paper presents a structured early-stage screening methodology to assess the transformation potential of tailings. The approach integrates X-ray diffraction (XRD), X-ray fluorescence (XRF) and quantitative electron microscopy data to define dominant composite mineral streams within a tailings deposit. These streams are used to identify plausible product pathways and associated separation or processing options. Particular attention is given to construction materials such as ceramics, low-carbon concrete and alkali-activated binders (including geopolymers), which may be produced through thermal treatment, acid or alkaline activation, and blending with other industrial byproducts such as fly ash, slag, red mud or delithiated beta spodumene. To reduce reliance on costly and lengthy laboratory testing, the method incorporates a pre-screening step based on stoichiometric and oxide level molecular analysis, accounting for mineral reactivity and atomic bonding affinity. The proposed framework supports early decision-making in tailings repurposing studies by identifying feasible transformation pathways and prioritising testing programs, with the broader aim of reframing tailings from a long-term liability into a potential feedstock for high-volume construction materials and more sustainable post-closure outcomes.

Keywords: *near-zero mine waste, tailings, re-use, repurposing, post-closure, mine life*

1 Introduction: the challenge

One hundred billion tonnes per annum: this is roughly the amount of material extracted globally each year to produce metals for industry (Vuillier 2025a). With continued growth in metal extraction, a corresponding increase in mine waste is expected. This extracted mass consists of a wide range of minerals; sulphides and oxides are typically targeted for metals such as Cu, Fe, Mg, Zn and Ni, while potash and carbonates serve other applications.

These materials are mostly extracted from rock, which is a combination of minerals forming a solid, cemented matrix. Sulphides are part of the host rock, often mixed with silicates and other phases. Crushing and grinding are required to remove the non-target rock fraction and progressively narrow down the targeted metals. In the case of Cu and Au, which are among the largest generators of mine waste, most of the processed material is ultimately considered waste. This differs from iron ore operations, where iron oxides (FeOx) or

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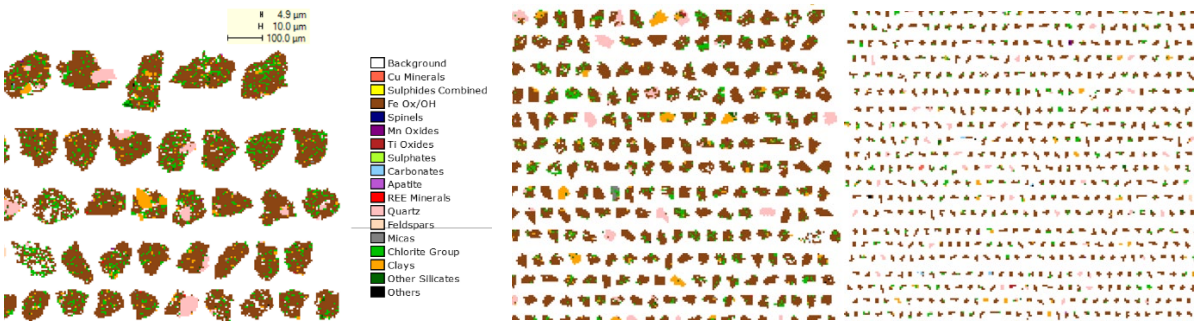
hydroxides (FeOHx) are in a much higher concentration; thereby making the waste fraction smaller, although still significant. Coal operations again present a different profile.

Another important point is that, once crushed and ground, the tailings are generally fine, with a P80 typically less than 100 microns. The particles are angular and multigrained, which is a key characteristic. They can be either liberated, binary (2 grains), ternary (3 grains) or multiphase (more than 3 grains), with oxides, silicates and carbonates intimately cemented together. This structure is strongly influenced by the host rock, the degree of cementation between grains and the relative resistance of each mineral to comminution. This complexity ultimately governs how these materials can be processed and transitioned to higher-value products.

2 Composite versus discrete

As discussed, particles are arranged as composite grains. At the simplest level, a particle may be a single grain (fully liberated) or composed of multiple grains: binary, ternary or multiphase. Geochemical analysis typically reports multiple mineral types, reflecting this composite nature. Each grain forming a particle is generally a mineral, and these small agglomerates form populations of similar particles.

Following grinding, tailings are distributed across different size fractions. As a general trend, smaller particles tend to contain fewer grains, with a higher degree of liberation. Fully liberated particles are therefore more common in finer fractions (e.g. < 10 µm) as shown in Figure 1c.



(a) (b) (c)

Figure 1 QEMSCAN images: (a) Coarse fraction; (b) Medium fraction; (c) Fine fraction

Based on geochemical data (XRF, XRD, QEMSCAN), results typically provide mineral abundance but can also be extended to describe mineral associations (binary, ternary, multiphase), grain proportions and their distribution across particle size fractions.

From this, trends in composition become evident. It becomes possible to divide the material into categories based on dominant mineral associations, with these associations evolving as particle size decreases. For example, quartz may commonly be associated with phyllosilicates and sulphides such as arsenopyrite, clearly visible in electron microscopy images through their distinct X-ray signatures. A typical composite particle may include quartz + kaolinite (phyllosilicate) + iron oxide (FeO), with grains either present as larger domains or as multiple fine grains distributed throughout the particle.

Scanning electron microscopy is therefore a key tool in identifying recurring patterns and defining multiple composite streams based on particle type. This represents an important first step. A truly discrete (single-mineral) stream is rare and would typically correspond to a high-value product due to its high concentration.

In some cases, strong binary associations can be observed, such as iron oxide (FeO) with chlorite (Mg, Fe, $Al)_6(Si,Al)_{10}(OH)_8$ in ultrafine tailings. This type of composite makes direct re-use (e.g. as iron ore) difficult due to the presence of chlorite, although alternative uses may still be possible, as discussed later. Even within a binary system, the ratio between components (e.g. FeO/chlorite) can vary significantly across size fractions. As a result, a single binary composite can be further subdivided into multiple streams (e.g. ratios > 2, > 5, > 10), each with different potential applications in construction.

3 Current thinking

At present, most mining operations focus on specific minerals that contain the targeted metals, particularly where the locked fraction is limited and a concentrate can be readily produced. The emphasis is therefore on particles with the highest metal content and the highest degree of liberation.

The remaining mineral fraction is largely overlooked, unless the operation is producing polymetallic concentrates. In some cases, tailings are reused for backfilling, particularly as more mines move underground. Other operations re-use the predominantly non-metallic fraction for site-related construction purposes. Offsite applications remain relatively rare.

However, even the so-called non-metallic fraction typically contains trace metals at concentrations too high to be classified as clean or inert fill under Environmental Protection Authority (EPA) guidelines. Elements such as antimony (Sb), arsenic (As) and barium (Ba), as well as chloride- and sulphur-bearing phases, are key considerations from both environmental and construction perspectives.

More fundamentally, a full qualitative assessment of all minerals within the process feed is rarely undertaken. In many cases, detailed analysis is performed on the relatively small fraction of metal-bearing minerals (sulphides and oxides), including size-by-size distribution, liberation and mineral associations. In contrast, the non-metallic fraction, which can represent more than 80% of the feed, is often grouped under the generic term ‘gangue’ and receives limited attention, despite being produced at a large scale (multiple Mtpa) and ultimately stored in tailings facilities.

4 New approach

Recent projects required the identification of tailings removal and re-use pathways. Our approach was to treat tailings as a composite value aggregate rather than a single waste stream. Geochemical characterisation included all minerals, not only the metal-bearing phases. This required characterising silicates, carbonates, sulphates, chlorite and phosphate fractions with the same level of detail typically applied to sulphide minerals, including size-by-size fractionation.

Mineral associations such as silicate-carbonate or silicate-clay systems became as important as sulphide associations. In this framework, the full material – effectively 100% of the ore – was characterised. This also allowed the impact of metal removal to be assessed on both the remaining metallic and non-metallic fractions. The approach extended to evaluating sequential processing stages, from the initial tailings composition after the primary process through downstream steps, and how second, third or further processing stages modified the composition and generated products and byproducts.

The removal of the metallic fraction, whether as a bulk or more discrete separation, resulted in progressive decontamination of the non-metallic fraction. This resulted in an increase in its potential value, as well as a redistribution and local concentration of remaining elements within specific subfractions.

This approach treated tailings as the primary feed material, either before or after discharge into the tailings storage facility (TSF). The material was then treated as a sequence of composite streams, generating multiple products while reducing the residual fraction to a minimal low-value remainder.

5 Some basic reminders: chemical framework

The approach was grounded in a small set of chemical principles that directly supported the transformation of tailings into engineered products (Vuillier 2025b). These are not presented as theoretical background, but as practical tools we used to interpret composite mineral streams and predict their behaviour during processing.

At the most fundamental level, the periodic table defines how elements interact. Elements combine based on their valence electrons, seeking stable configurations. This governs which elements are likely to associate in minerals and how they will behave during transformation. Molar mass provides the link between mineral composition and quantitative chemical balance, which is essential for stoichiometric calculations.

Ionic bonds and covalent bonds control the stability and reactivity of minerals. For example, silicate structures dominated by strong Si-O bonds are generally more stable and less reactive, while other phases, particularly those with weaker bonding or structural disorder, are more amenable to chemical transformation. This distinction is critical when assessing which mineral fractions can actively participate in processes such as geopolymerisation on thermal phase formation processes.

Stoichiometry provides the quantitative framework to translate mineral composition into chemical systems. Each mineral can be expressed in terms of its molar composition, allowing direct comparison between feed material and target products. For example, in our project material, simple compounds such as calcium carbonate ($CaCO_3$) or ferric oxide (Fe_2O_3) were extended to more complex minerals such as chlorite mineral groups, where multiple elements are combined within a single structure. In composite particles, these minerals coexist but were simplified into equivalent chemical systems for transformation analysis. This allowed the definition of target products in comparable terms, such as aluminosilicate systems for geopolymer applications.

We identified oxide decomposition as a key step in this simplification. Mineral formulas can be expressed as equivalent oxide components (e.g. SiO_2, Al_2O_3, CaO), which provides a consistent basis for assessing suitability for construction materials. This representation aligns directly with established compositional frameworks used in ceramics and cementitious systems. For example, kaolinite $Al_2Si_2O_5(OH)_4$ can be expressed as $Al_2O_3.2SiO_2.2H_2O$ and, after thermal treatment (dehydroxylation), transformed into a reactive $Al_2O_3.2SiO_2$ system (metakaolin), which is highly suitable for geopolymer applications. A similar approach can be applied to more complex minerals such as chlorite, enabling comparison across composite streams.

It is important to note that oxide composition defines chemical potential but not reactivity. Reactivity is also controlled by mineral structure, crystallinity, bonding strength, and particle size. These aspects are addressed later in the process through a simplified reactivity correction.

Chemical and mineralogical testing provided the data required to apply this framework. The objective was to characterise the full composition of the tailings, not only the metal-bearing fraction. Key tools included particle size distribution (PSD), specific gravity (SG), XRF, XRD and QEMSCAN (or equivalent). PSD and SG defined the physical framework of the material, while XRF and XRD provided elemental and mineralogical composition. QEMSCAN added a critical layer by quantifying mineral associations, degree of liberation, and particle-scale composition through imaging and automated classification.

Together, these methods provided a detailed identification of composite streams, including how minerals were associated within particles and how these associations varied with size. This formed the basis for defining multiple streams and linking them to potential processing and product pathways.

In practice, the approach began with a representative head sample. Initial testing was used to define the most relevant level of analysis, including size-by-size fractionation and, where appropriate, density-based separation. This staged approach allowed the complexity of the material to be reduced progressively while retaining the key chemical relationships required for transformation.

6 Viewing tailings storage facilities differently

A relatively small, representative sample of tailings was sufficient to initiate this approach. Laboratory testing, typically completed within a few weeks, provided the basis for defining the material as a set of composite streams rather than a single bulk waste. It was important that the sample captured the variability of the deposit, including spatial differences across the TSF (e.g. coarse beach zones, finer central areas and potential vertical variations due to deposition history or geochemical evolution). In this framework, the TSF was effectively treated as an orebody.

For demonstration purposes, a simplified polymetallic tailings assemblage was considered, comprising quartz, feldspar, kaolinite, calcium carbonate, chalcopyrite, arsenopyrite and cobaltite. This combination reflected a typical silicate-dominated host rock with sulphide mineralisation, representative of many hydrothermal or porphyry-related systems, potentially modified by alteration or metamorphic overprinting.

The resulting material exhibited complex mineral associations, which persisted through processing and were expressed in the tailings as composite particles.

The material had a P80 of approximately 100 µm, with a distribution across coarse (> 100 µm), medium (30–100 µm) and fine (< 30 µm) fractions. These size fractions provided a practical basis for defining composite streams, reflecting the relationship between particle size, degree of liberation and mineral association.

Within each size fraction, particles were further grouped into dominant composite streams based on mineral associations. These streams were not pure mineral phases but particle populations defined by a dominant grain type and associated secondary minerals. Quartz-, feldspar-, kaolinite- and sulphide-dominant, and cobalt-rich, streams were identified, each representing a distinct chemical and mineralogical system.

The degree of complexity within these particles varied systematically with size. Coarser fractions tended to contain more multiphase particles, with dominant minerals typically representing 50–75% of the particle composition. Medium fractions commonly exhibited binary or ternary associations, with dominant minerals in the range of 60–80%. Finer fractions generally contained fewer grains per particle and higher degrees of liberation, with dominant minerals often exceeding 70–90%.

This structured breakdown allowed the original tailings to be reinterpreted as a set of chemically and physically distinct streams. Each stream could then be evaluated independently in terms of metal recovery potential, contamination and suitability for transformation into construction materials.

Crucially, this approach shifted the perspective from a single waste stream to a multiproduct system. Rather than treating tailings as a residual material, the composite streams were considered as intermediate feedstocks that could be progressively separated, transformed and recombined, depending on the targeted application. The result was a framework in which multiple value pathways could be identified and assessed in parallel, forming the basis for integrated reprocessing and repurposing strategies (Vuillier 2025c).

This defines the ‘new approach’: tailings are no longer a residue but a set of valuable feedstocks.

7 Simplified case study

To demonstrate the proposed framework described in Section 6, a simplified case study based on our project was developed.

The bulk mineral composition was defined as quartz 38%, feldspar 27%, kaolinite 20%, calcium carbonate 5%, arsenopyrite 5%, chalcopyrite 3%, cobaltite 2%.

This simplified assemblage is consistent with a silicate-dominated host rock containing sulphide mineralisation.

The material was then subdivided into 5 dominant composite streams (A to E) across 3 size fractions (coarse, medium, fine), resulting in a structured representation of the tailings as 15 composite streams.

A simplified set of rules was applied to define the internal composition of these streams, as shown in Figure 1:

- particle size influences grain complexity
- coarse particles (> 100 µm) – predominantly multiphase, dominant mineral ~50–75%
- medium particles (30–100 µm) – binary/ternary associations, dominant mineral ~60–80%
- fine particles (< 30 µm) – fewer grains per particle, dominant mineral ~70–90%

The resulting Tables 1,2 and 3 define the distribution of minerals within each composite stream for each size fraction. Each stream represented a population of particles characterised by a dominant mineral and associated secondary phases.

Table 1 Coarse fraction: more than 100 microns (20%)

Stream	Description	Wt%	Quartz	Felds	Kaol	Calc	APy	Ccp	Cobalt
A	Quartz-dominant	55.0%	80%	15%	3%	2%			
B	Feldspar-dominant	35.0%	20%	75%	3%	2%			
C	Kaolinite-dominant	3.0%	10%	10%	65%	5%	5%	3%	2%
D	Sulphides-dominant	5.0%	5%	5%	5%	0%	30%	45%	10%
E	Cobalt-dominant	2.0%	5%	5%	5%	0%	10%	5%	70%

Table 2 Medium fraction: more than 30 to 100 microns (45%)

Stream	Description	Wt %	Quartz	Felds	Kaol	Calc	APy	Ccp	Cobalt
A	Quartz-dominant	60.0%	75%	10%	10%	5%			
B	Feldspar-dominant	24.0%	10%	70%	15%	5%			
C	Kaolinite-dominant	12.0%			90%	10%			
D	Sulphides-dominant	2.0%	10%	5%	5%		40%	40%	
E	Cobalt-dominant	2.0%		10%			10%	10%	70%

Table 3 Fine fraction: less than 30 microns (35%)

Stream	Description	Wt %	Quartz	Felds	Kaol	Calc	APy	Ccp	Cobalt
A	Quartz-dominant	17%	85%	10%	5%				
B	Feldspar-dominant	30%	10%	80%	5%	5%			
C	Kaolinite-dominant	30%	5%	5%	75%	15%			
D	Sulphides-dominant	20%	5%	5%	5%		55%	30%	
E	Cobalt-dominant	3%		5%			10%	10%	75%

These 3 tables provide a simplified but structured representation of the tailings as a set of composite streams rather than a single bulk material. Each stream reflects both mineral composition and particle-scale association, capturing the combined effects of comminution, mineral hardness and liberation behaviour.

This representation formed the basis for subsequent analysis. By defining the material in terms of composite streams, it became possible to:

- track the distribution of metals and non-metallic components across fractions
- assess separation potential using simple physical processes (e.g. gravity)
- evaluate chemical suitability for downstream applications
- link each stream to specific product pathways.

In this framework, the head feed was no longer treated as a homogeneous tailings mass but as a structured system that can be progressively separated, transformed and recombined.

7.1 Presenting tailings as composite multi-streams for multiple product creation

Based on the dataset defined above the material could be fractionated into 3 size ranges and further subdivided into dominant composite streams based on mineral associations, dominant species and likely physical behaviour (e.g. density).

In this simplified case, quartz-, feldspar-, kaolinite-, sulphide- and cobalt-dominant streams were identified. This classification was informed by practical experience, particularly with respect to potential re-use in construction materials. At this stage it is important to combine metallurgical and material expertise as both recovery and end use requirements influence stream definition.

It is important to note that a quartz-dominant stream does not imply pure quartz. Each stream remains a composite, and a certain level of impurity or 'defect' is both expected and, in many cases, acceptable. From a re-use perspective, particularly to minimise additional processing and energy consumption, it is often preferable to retain minor secondary phases within acceptable limits defined by construction standards.

For each size fraction, composite streams were defined based on the dominant grain type within each particle population. The relative proportions of associated minerals within each stream reflect the degree of liberation and mineral locking. In this simplified framework, coarse particles are assumed to contain a higher proportion of multiphase associations, medium particles a mix of binary and ternary associations, and finer particles fewer grains per particle, with generally higher liberation but still variable inclusion of fine sulphides.

Following this fractionation, and for early-stage product screening, the tailings assemblage was decomposed into dominant mineral substreams. This provided a clearer basis for assessing metal recovery potential, construction material suitability and likely contaminant thresholds. Within each substream, the presence of binary, ternary and multiphase particles is retained to reflect the composite nature of real tailings and the imperfect separation between metallic and non-metallic fractions.

7.2 Reactivity screening approach

Not all silica is reactive. Quartz was generally assumed to be inert under standard processing conditions or to require significant thermal activation, whereas reactive silica and alumina are primarily sourced from minerals such as kaolinite (included in this example) and, to a lesser extent, feldspar phases. This distinction was important as it implies that quartz-rich streams are more likely to be suitable for use as fillers rather than as reactive precursors.

Oxide composition provides a useful first assessment of the theoretical chemical potential of composite mineral streams, particularly in terms of silicon dioxide (SiO_2) and aluminium oxide (Al_2O_3) availability for ceramic or alkali-activated systems. However, oxide composition alone does not reflect the actual capacity of a material to participate in chemical reactions. Minerals with similar oxide compositions can exhibit different reactivity due to differences in crystal structure, degree of disorder and bonding environment.

For example, metakaolin, produced by dehydroxylation of kaolinite, is highly reactive due to its disordered structure, whereas feldspar and quartz, despite being rich in Si and Al, remain relatively inert under similar conditions due to their stable crystalline frameworks. Accordingly, a simplified reactivity factor was introduced.

This factor represents the proportion of the oxide inventory that is likely to become chemically available under the selected processing conditions. It was based on 3 primary parameters:

- mineral structure and crystallinity (amorphous versus crystalline)
- thermal activation state
- particle size and associated surface accessibility.

The resulting effective reactive oxide provides a more realistic basis for early-stage assessment of geopolymerisation potential and other transformation pathways.

This approach was not intended to predict reaction kinetics or final product performance but it provides a practical and scientifically grounded screening tool to compare different tailings compositions and prioritise subsequent testing.

7.3 Identifying and listing potential value pathways

The simplified system was chemically dominated by silicate minerals (quartz, feldspar and kaolinite), which defined the primary potential for construction material applications. In contrast, sulphide minerals, although present in smaller proportions, disproportionately control metal recovery potential and environmental risk.

Based on the composite stream definition, oxide composition and simplified reactivity assessment, an initial value screening was established as follows:

- quartz-dominant streams – high-volume material, primarily suited as a filler or aggregate component
- feldspar-dominant streams – suitable for ceramic applications due to combined SiO_2–Al_2O_3–alkali composition
- kaolinite-dominant streams – high potential for geopolymer and alkali-activated systems following thermal activation
- sulphide-dominant streams – recovered first to maximise metal value and decontaminate the remaining material for re-use.

As introduced earlier, oxide composition provides a first assessment of chemical potential. However, effective utilisation depends on reactivity, which is controlled by mineral structure and physical accessibility. In this framework, kaolinite is considered a high-potential precursor only after dehydroxylation to metakaolin, while feldspar and quartz exhibit lower effective reactivity despite favourable oxide composition.

Reactivity is generally governed by a combination of bond environment, crystallinity, defect density, surface area and dissolution behaviour. This distinction is essential for linking composite streams to viable processing pathways and end use applications.

7.4 Chemical check

Based on the simplified mineral assemblage defined previously, each mineral is expressed using its representative chemical formula: quartz SiO_2, feldspar $KAlSi_3O_8$, kaolinite $Al_2Si_2O_5(OH)_4$, calcium carbonate $CaCO_3$, arsenopyrite FeAsS, chalcopyrite $CuFeS_2$, cobaltite – CoAsS.

These formulas provided the basis for converting the mineralogical composition of each composite stream into a quantitative chemical system.

The first step consisted of defining the molar mass of each mineral in Table 4, which allowed the relative contribution of each element to be calculated on a consistent basis. This was required to:

- quantify elemental distribution across composite streams
- assess key ratios such as Si/Al for downstream applications
- evaluate contamination against EPA guidelines and construction standards.

Table 4 Mineral formula and molar mass

Mineral type	Chemical formula	Molar mass	Mineral type	Chemical formula	Molar mass
Quartz	SiO2	60.08	Arsenopyrite	FeAsS	162.83
Feldspar	$KAlSi_3O_8$	278.33	Chalcopyrite	$CuFeS_2$	183.51
Kaolinite	$Al_2Si_2O_5(OH)_4$	258.16	Cobaltite	CoAsS	165.92
Calcium carbonate	$CaCO_3$	100.09			

Atomic masses, indicated in Table 5, were used to convert mineral compositions into elemental contributions.

Table 5 Atomic mass elements

	Si	Al	Fe	K	Ca	C	As	Cu	S	Co	O	H
Atomic mass	28.08	26.98	55.84	39.09	40.07	12.01	74.92	63.54	32.06	58.93	15.99	1.01

Using these relationships, the composite streams defined earlier were translated into an elemental composition for each size of fraction (coarse, medium, fine) and for the total material, as shown in Table 6. Hydrogen was excluded for simplification, while oxygen is retained as it represents a significant proportion of the system.

Table 6 Elemental composition by fraction in %

Minerals		Si	Al	Fe	K	Ca	C	As	Cu	S	Co	O
Coarse fractions		7.17	0.89	0.28	0.99	0.16	0.05	0.35	0.17	0.32	0.14	9.48
Medium fractions		15.17	2.94	0.29	1.46	0.97	0.29	0.49	0.16	0.37	0.22	22.50
Fine fractions		8.24	2.85	2.03	1.39	0.84	0.25	2.18	0.76	1.70	0.28	14.34
All size fractions	TOTAL	30.58	6.68	2.6	3.84	1.97	0.59	3.02	1.09	2.39	0.64	46.32

The resulting chemical distribution reflected both the mineralogy and the composite nature of the particles. All elements are present across all size fractions, with these clear trends emerging:

- an increase in metal concentration (Fe, Cu, Co, As) in the finer fractions, reflecting progressive liberation and higher SG
- a relative enrichment of silicate components in the medium and coarse fractions
- persistence of minor contaminants across all fractions due to multiphase particle associations.

For clarity, concentrations are expressed as percentages for values greater than 1%, with ppm values retained for lower concentrations.

This chemical representation provides a first-order validation of the composite stream model. It confirms:

- The system is chemically consistent with the initial mineral assemblage.
- Elemental distribution follows expected comminution and liberation trends.
- No fraction can be considered purely metallic or non-metallic.

This dataset formed the basis for the next step of the analysis, where the material can be separated into metallic and non-metallic fractions (Section 7.6). The impact of this separation, based on a simplified gravity approach without additional grinding, can be assessed to evaluate both metal recovery potential and the suitability of the remaining material for construction applications.

7.5 Oxide approach for construction materials

The next step focuses on construction material potential. The composition of each composite stream is more effectively expressed on an oxide basis rather than as individual mineral formulas.

The main oxides identified in the system are SiO_2, Al_2O_3, K_2O, CaO, Fe_2O_3, As_2O_3, CuO, SO_2 and CoO. This representation provides a consistent framework to assess transformation pathways across multiple end uses, including geopolymers, cementitious systems and ceramics.

Oxide notation reflects the fundamental chemical building blocks controlling these processes. While original minerals differ in structure and reactivity, their behaviour during thermal treatment, alkali activation or

hydration is primarily governed by the availability and interaction of key oxides. Expressing compositions in oxide form therefore allows direct comparison with established material design domains.

This approach also simplifies mass balance calculations and enables the use of standard compositional frameworks such as:

- SiO_2–Al_2O_3– flux systems for ceramics
- CaO–SiO_2–Al_2O_3 systems for cementitious materials.

However, oxide composition alone does not fully capture reactivity, which is also controlled by mineral structure, crystallinity and particle size. For this reason, oxide-based screening is complemented by a separate reactivity assessment.

Table 7 presents the oxide composition of each mineral, forming the basis for evaluating the potential of each composite stream.

Table 7 Decomposed oxide composition by unit of each mineral (stoichiometric basis)

Mineral type	Chemical formula	SiO_2	Al_2O_3	K_2O	CaO	CO_2	Fe_2O_3	As_2O_3	CuO	SO_2	CoO
Quartz	SiO2	1.0									
Feldspar	$KAlSi_3O_8$	3.0	0.5	0.5							
Kaolinite	$Al_2Si_2O_5(OH)_4$	2.0	1.0								
Calcium carbonate	$CaCO_3$				1.0	1.0					
Sulphides	FeAsS, $CuFeS_2$, CoAsS						1.0	1.0	1.0	4.0	1.0

To support early-stage screening for construction applications, an effective reactive oxide concept is introduced for silicate systems.

Reactive silicate/aluminosilicate oxides (SiO_2, Al_2O_3) were estimated from the oxide contribution (Xi), a structural reactivity factor (fs,i) such as lattice type, and a particle accessibility factor (fp,i) reflecting size, surface exposure and degree of liberation.

This provides a simplified indicator of the fraction of oxides likely to participate in chemical reactions under selected processing conditions.

Reactivity is also influenced by bond characteristics. Although Al–O shows higher ionic character than Si–O based on electronegativity differences, the shorter Si–O bond distance introduces a partial covalent character, making it more stable overall.

This approximate bond strength ranking: Si–O > Al–O > Fe–O > Ca–O has direct implications for reactivity:

- quartz (Si–O dominated) → largely inert
- feldspar → moderately reactive
- kaolinite (after calcination – metakaolin) → highly reactive.

Table 8 summarises the indicative reactivity potential of each stream. The lower bound reflects coarser, multiphase particles; the upper bound reflects finer, more liberated particles.

Table 8 Indicative reactivity potential (non-metallic fraction)

Stream	Description	Raw react	Calc react	Interpretation
A	Quartz-dominant	0.03–0.04	0.04–0.08	Generally inert
B	Feldspar-dominant	0.09–0.16	0.11–0.20	Moderate reactivity
C	Kaolinite-dominant	0.05– 0.09	0.36–0.69	Strong after calcination

7.6 Metallic – non-metallic fraction

This step is central to our overall strategy. It provides a practical way to assess the value of the entire tailings stream by separating it into 2 functional components:

- a metallic fraction, dominated by sulphides and oxides, targeting metal recovery
- a non-metallic fraction, composed primarily of silicates, carbonates and other gangue minerals, targeting construction material applications.

This separation is not absolute. Due to the composite and multiphase nature of particles, both fractions retain some degree of cross-contamination. However, even a partial separation is sufficient to significantly improve both value recovery and re-use potential.

At this stage the approach deliberately assumes minimal processing, relying primarily on physical separation (e.g. gravity). Additional grinding may improve separation efficiency but would materially impact project economics and is therefore not considered in this first-pass assessment.

For a simplified separation basis using the dominant composite streams defined earlier, a basic density-based separation was assumed as follows: quartz dominant ~2.6, feldspar dominant ~2.6, kaolinite dominant ~2.8, sulphide dominant ~4.6, cobalt dominant ~5.5.

This allowed a first-order separation between low-density non-metallic and high-density metallic streams, resulting in these initial conceptual fractions:

- a metallic-rich fraction (~10–15%) enriched in Fe, Cu, Co, S and As
- a non-metallic-rich fraction (~85–90%) dominated by Si, Al, K and Ca.

These values were consistent with the initial mineral assemblage and confirm that most of the mass remains in the non-metallic fraction and most of the economic metal value is concentrated in a relatively small stream.

7.6.1 Metallic fraction – interpretation

The metallic fraction formed a polymetallic concentrate, combining sulphide-rich streams (arsenopyrite, chalcopyrite, cobaltite) resulting in enrichment in Fe, Cu, Co and S, with As primarily associated with arsenopyrite and cobaltite. Residual silicates remained due to incomplete liberation. This stream presented clear potential for metal recovery (Cu, Co, Fe) and played a key decontamination role by removing deleterious elements, notably As from the bulk non-metallic fraction. The internal separation of this fraction is not developed further at this stage, but its underlying value is clearly established.

7.6.2 Non-metallic fraction – interpretation

The non-metallic fraction represented the primary volume stream and was significantly decontaminated relative to the original feed.

It became dominated by SiO_2, Al_2O_3, K_2O and CaO, with some residual metals reduced to low levels (generally < 1% total, excluding Al). Arsenic was significantly reduced to trace levels but remained locally present, depending on the fraction. The removal of most of the metallic fraction moved the material closer to EPA compliance thresholds and applicable industry standards. It became suitable for construction material pathways (ceramics, geopolymers, precast concrete with waste rock), subject to further verification.

A key insight was that metal concentration increases in finer fractions while silicate-rich material dominates medium fractions.

This suggested potential fast-track pathways, such as ceramics or geopolymer feed for the medium and fine fraction, and precast concrete for the coarse fraction when combined with the fine fraction of waste rock. Some minor cleaning may still be required but the benefit of using already crushed material is significant.

7.6.3 Strategic implication

This separation step demonstrated that value was created through not only through metal recovery but through the progressive decontamination of the bulk material. By removing a relatively small metallic fraction, the remaining mass became more suitable for re-use, enabling multiple downstream product pathways, reducing tailings long-term storage and supporting post-mine closure opportunities.

Value was therefore maximised not through a single process but through sequential separation and transformation of composite streams. This approach established the non-metallic fraction as a valuable material system rather than a residual waste.

7.7 Construction products and chemical pathways

The non-metallic fraction represented approximately 85–90% of the total tailings mass (depending on whether the feed is considered upstream or downstream of processing). This fraction therefore controlled both the volume opportunity and the long-term value creation potential.

The most immediate and scalable application is in construction materials, particularly precast concrete (CCAA 2008). This is relevant even for remote sites. Where tailings and waste rock volumes reach millions of tonnes, a localised manufacturing operation becomes viable, especially when integrated across a cluster of mines. Precast elements (pipes, panels, segments) can be transported over long distances and exported to regions where natural aggregates are constrained, including parts of Southeast Asia.

A key advantage is that tailings and waste rock are already partially processed. Crushing and grinding are among the most energy-intensive steps in conventional aggregate production. Their re-use therefore contributes directly to lower embodied energy, not only through alternative binders but also through reduced comminution requirements.

Beyond concrete, 2 major transformation pathways emerge:

- ceramics, driven by bulk oxide composition (SiO_2–Al_2O_3–flux systems)
- geopolymers/alkali-activated materials, driven by reactive aluminosilicate chemistry.

A critical point is that the non-metallic fraction is not constrained to a single product. Multiple product streams can be developed in parallel, reducing market risk and enabling distributed manufacturing around mine sites at different stages of operation or closure.

Where compositional gaps exist, particularly in Si/Al balance or flux content, these can be adjusted using locally available materials such as fly ash, slag or red mud. This is not a limitation but part of a broader industrial symbiosis approach.

7.7.1 Oxide framework for product mapping

To establish a direct link between mineralogy and engineering application, the system is expressed in oxide form. This provides a common basis for comparing different product pathways as follows:

- geopolymers
  - N-A-S-H: $Na_2O{\cdot}Al_2O_3{\cdot}xSiO_2{\cdot}yH_2O$
  - C-(N)-A-S-H: $Na_2O{\cdot}CaO{\cdot}Al_2O_3{\cdot}xSiO_2{\cdot}yH_2O$
  - K-A-S-H: $K_2O{\cdot}CaO{\cdot}Al_2O_3{\cdot}xSiO_2{\cdot}yH_2O$
- ceramics – SiO_2 + Al_2O_3 + (K_2O, Na_2O, CaO)

- concrete – $CaO + SiO_2 + Al_2O_3 + Fe_2O_3 + H_2O$
- soils/technosols: $SiO_2 + Al_2O_3 + Fe_2O_3 + CaO + H_2O$ + organics + trace elements.

This oxide-based representation maps mineral assemblages to known material systems.

7.7.2 From minerals to oxides (stoichiometric link)

Each mineral is decomposed into its equivalent oxide components based on stoichiometry, and these contributions are weighted by their mass fraction in these composite streams:

quartz → SiO_2; feldspar ($KAlSi_3O_8$) → $3SiO_2 + 0.5Al_2O_3 + 0.5K_2O$; kaolinite → $Al_2O_3 + SiO_2$ (after dehydroxylation) and $CaCO_3$ → $CaO + CO_2$

This produces a bulk oxide inventory, which forms the chemical basis for all downstream pathways. SiO_2 ≈ dominant (~75%), Al_2O_3 ≈ moderate (~15%) and $K_2O + CaO$ ≈ minor but critical (fluxing role)

7.7.3 Ceramic pathway (bulk chemistry controlled)

In ceramic processing, behaviour is governed by the bulk oxide balance, not reactivity, as follows:

- Al_2O_3 → controls mullite formation (strength phase)
- SiO_2 → forms glassy matrix (structure)
- K_2O/CaO → fluxes (reduce melting temperature, enable densification).

From the mass balance:

- alumina is the limiting component → controls mullite formation
- excess silica → contributes to glass phase
- fluxes → sufficient for vitrification without major additives.

This is a chemically coherent ceramic system.

7.7.4 Reactive pathway (geopolymer – chemistry + structure controlled)

Unlike ceramics, geopolymerisation depends on reactive fraction, not total composition, as follows:

- quartz → largely inert
- feldspar → partially reactive
- kaolinite → highly reactive after calcination (metakaolin).

This transforms the system to:

• state	reactive SiO_2	reactive Al_2O_3
• raw	high Si, low Al	Al-limited
• calcined	balanced	suitable for gel formation.

This shift moves the system into the compositional range required for N-A-S-H gel formation.

The approach combines mineralogical decomposition, oxide normalisation and reactivity correction to define practical transformation pathways from tailings to engineered products as demonstrated in construction-focused applications of mine waste aggregates (Vuillier 2025a).

8 Conclusion

This study and related projects demonstrate that mine tailings can be approached not as a single waste material but as a set of composite streams that can be translated into an oxide inventory and directed towards specific product pathways.

By integrating chemical, mineralogical decomposition, oxide normalisation and oxide reactivity correction, a clear early, fast-track chemical pathway can be established from tailings to high-value products. This approach, tested on multiple projects, showed that an identical bulk oxide composition may be directly suitable for ceramic applications where overall chemistry governs phase formation. For alkali activation, however, performance depends only on the reactive fraction of that bulk composition and therefore it required prior thermal activation.

This distinction is critical. Quartz-rich streams remain largely inert in geopolymer systems but contribute to ceramic frameworks, while calcined kaolinite-rich streams become the dominant precursor for alkali activation. Feldspar plays an intermediate role, contributing both to fluxing in ceramics and partially to geopolymerisation. Where reactive components are insufficient, the system can be adjusted through the controlled addition of complementary aluminosilicate sources (e.g. fly ash), consistent with the oxide-bases framework.

This approach provides a practical tool for early-stage assessment, allowing tailings to be screened, adjusted and directed towards appropriate transformation routes and progressively removed from the mine site. This supports the development of integrated processing strategies where metal recovery and multiple high-value construction products can be combined, reducing waste volumes while generating multiple value streams.

Ultimately, this approach reframes tailings as an engineered feedstock, where chemical pathways are selected and controlled to match the requirements of the target product.

Rather than adapting products to waste, this approach adapts waste to products through controlled chemical pathways.

This shift opens the way for near-zero mine waste strategies, where the majority of tailings can be progressively converted into usable materials with only a residual fraction requiring long-term storage; aligning with broader industry efforts to transition mine waste into usable resources (Vuillier & Ingwersen 2022). This is particularly relevant for remote operations, where the production of higher-value products can offset transport costs while leveraging already processed materials.

Future work should focus on validating these pathways through targeted testing and scaling the approach into integrated, site-specific processing flow sheets.

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