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An instrument for using mine tailings in construction: what Chile's copper slag decree does not look at

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An instrument for using mine tailings in construction: what Chile's copper slag decree does not look at

Abstract

Reusing mine tailings in construction requires a legal instrument that states what is assessed, by which test, against which threshold, on which analytical basis, and on whose application. Chile issued such an instrument for copper slag in 2026 but not for tailings, although its hazardous waste regulation classifies both by the same list; the 2026 cadastre records 423 tailings deposits in the Coquimbo Region, 195 of them abandoned. We ask what a Chilean instrument for tailings must contain and whether the slag decree is a sufficient template. We compare the decree with the hazardous waste regulation and the concrete standard, and subject seven samples of one deposit, through a reproducible script, to eight decision rules from five jurisdictions and to the Chilean sulfate limit for concrete. The decree adds no leaching threshold and omits mercury, barium and silver. On identical data, the tailings are non-hazardous by list in Chile, non-inert in the European Union because of sulfide sulfur (0.96 to 1.39%), and pending a prescribed test under four rules; the deciding element changes with the regime. Sulfur sets the admissible dose: 51 to 61% of the cementitious material if measured sulfate is counted and 26 to 32% if all sulfur is counted, a choice no standard resolves. Admissibility is therefore a property of the set formed by tailings, product and regime. The decree is a usable base, but it overlooks sulfur, the product, and applicants who are not generators; we derive five amendments and discuss who should pay for characterisation.

Keywords: Mine tailings, Waste classification, End-of-waste, Regulatory design, Circular economy, Chile

1 Introduction

Chile stores its mine tailings in deposits that public policy has so far treated as facilities to be stabilised, monitored and governed (Cacciuttolo and Atencio, 2022; Vinet et al, 2025; Ojeda-Pereira et al, 2025). The 2026 layer of the national cadastre of tailings deposits records 839 facilities; 423 are in the Coquimbo Region, and 195 of these are listed as abandoned (Servicio Nacional de Geología y Minería, 2026). Some lie within

tens of metres of inhabited areas: in Andacollo, five abandoned or inactive deposits are between 30 and 260 m from the urban area (Parodi et al, 2022).

That this material can enter concrete is not a conjecture. Chilean tailings have been tested as aggregate for paving stones (Lam et al, 2020) and, after thermal and mechanical activation, as supplementary cementitious material (Vargas and Lopez, 2018). The economic case is complementary to that of metal recovery: reprocessing Chilean copper tailings for metals is economic for only a small share of them (Drobe et al, 2021) and demands large investments under uncertainty (Araya et al, 2021), so that bulk uses are the only outlet for most of the mass. The literature on circular economy in mining places regulation, and with it unclear ownership of the waste, among the obstacles that persist once the technology responds (Kinnunen and Kaksonen, 2019; Kinnunen et al, 2022; Armistead and Babaahmadi, 2025; Malafeevskiy, 2026; Nuur et al, 2026), and raw materials policy now sets explicit recycling benchmarks (Hool et al, 2024). What is missing is therefore not knowledge of whether tailings can be used, but a rule stating who decides that they can, and how.

Chile gave a partial answer in 2026. Supreme Decree 46/2025 of the Ministry of Health, published on 12 February 2026, authorises the use of copper slag as artificial aggregate (Ministerio de Salud, 2026). Tailings, which the hazardous waste regulation classifies alongside slag and by the same list (Ministerio de Salud, 2004), have no equivalent instrument. The path this asymmetry suggests is transplantation: writing for tailings a decree analogous to the one for slag. A transplant is legitimate, however, only if what the decree assesses in slag is also what decides for tailings.

1.1 Motivation

The question arises from a case. A public project in the Coquimbo Region, funded by the Regional Government, studies the incorporation of tailings in concrete paving slabs for public space. The Chilean concrete standard admits mineral additions, but its committee declares that it did not adopt the concept of cementitious material because "there is no national normative and regulatory framework to characterise and control its use" (Instituto Nacional de Normalización, 2016, Annex A, our translation); the aggregates standard mentions copper tailings in an annex that gives guidance without setting limits (Instituto Nacional de Normalización, 2024, Annex J); and the sanitary decree that authorises prefabricated elements for open spaces reaches slag only (Ministerio de Salud, 2026). The project thus lacks, before the very State that funds it, a route through which to request authorisation of its product.

If this holds for a deposit whose holder exists and cooperates, it holds all the more for the 195 abandoned deposits of the region, where the absence of a rule is compounded by the absence of anyone entitled to apply. An instrument of use is the piece that converts a liability into a resource, and designing it badly, for instance by copying thresholds that do not decide, has a double cost: it admits what should have been tested and excludes what could have been used.

1.2 Research questions and contribution

The general objective is to determine what a Chilean instrument enabling the use of tailings in concrete and prefabricated products must contain, and whether the copper slag decree suffices as its base. Three questions structure the analysis:

1. What does the slag decree reuse, add and omit with respect to the hazardous waste regulation and to the technical standards for concrete and aggregates?
2. Applied to the same seven samples of one tailings deposit, what verdict and what deciding element does each of eight decision rules from five jurisdictions produce?
3. What dose of tailings does the Chilean sulfate limit for concrete admit, and on which analytical basis does that dose depend?

The paper makes three contributions. First, it reads the Chilean decree against its own legal base and shows that its novelty is procedural, not numerical. Second, it replaces the usual side-by-side comparison of regimes with a test: the rules are coded and applied to measured data, so that the comparison yields verdicts and deciding elements instead of descriptions. To our knowledge, no previous study applies the decision rules of several jurisdictions to one measured tailings material. Third, it derives from the concrete standard a closed-form dose ceiling and shows that the ceiling depends on an analytical basis that no Chilean standard fixes. The thesis that follows from the three is that admissibility does not belong to the tailings but to the set formed by the tailings, the product and the regime, and that what the slag decree does not look at (sulfur, the product, and the applicant who is not a generator) is precisely what an instrument for tailings has to state.

The paper is not a characterisation of the deposit, which requires the complete analytical dataset and is reported separately, nor a leaching study: no leachate has been measured, and Sect. 5.6 states what this implies for each result.

2 Background

2.1 Four hazards, each with its own mechanism

Tailings incorporated in a cementitious matrix retain four hazards that share neither mechanism nor, therefore, test. The first is the leaching of metals and metalloids. Binding is not retention: in geopolymer bricks made with copper tailings, the passage from loose tailings to product raised arsenic and molybdenum in the leachate instead of lowering them (Ahmari and Zhang, 2013), and the performance of cement encapsulation of antimony-bearing mine waste depends on the proportion of binder (Álvarez-Ayuso et al, 2022). Release from a monolithic product is, moreover, governed by mass transport and not by equilibrium, so that its proper test is the tank test (Garrabrants et al, 2014; U.S. Environmental Protection Agency, 2013).

The second hazard is sulfides, which may oxidise after the material has passed a leaching test. The third, related to it, is internal expansion: the oxidation of iron sulfides in the aggregate, pyrrhotite in particular, produces sulfates that react with the cement paste, and in Trois-Rivières it damaged house foundations and slabs within a few years of construction (Duchesne and Fournier, 2013; Duchesne et al, 2021). The

fourth is natural radioactivity, which European regulation assesses in the building material through an activity concentration index (Council of the European Union, 2013). An instrument of use cannot therefore rest on a single test: each hazard is verified where it arises, some in the unmixed tailings and others in the piece.

2.2 Three regulatory logics

Regimes that enable mineral waste in works follow three different logics. The first assesses the component before mixing and requires it to pass a gate: this is the logic of the Chilean slag decree, which tests the slag and not the product (Ministerio de Salud, 2026), and of the material values of the German ordinance on substitute building materials (Bundesregierung, 2021). The second grades the requirement by class of work and by its pathway to water or to people: the German installation modes, the Danish categories (Miljø- og Fødevareministeriet, 2016) and, in Chile, the distinction between open and enclosed spaces. The third assesses what the product emits in service, as the Dutch soil quality regulation does with its diffusion test for shaped materials (Minister van Infrastructuur en Waterstaat, 2022). None of the regimes read combines the three.

The European Union adds a piece the others lack: a criterion of inert extractive waste based on sulfide sulfur (European Parliament and Council of the European Union, 2006; European Commission, 2009), within a framework for extractive waste whose best available techniques have been documented at length (Garbarino et al, 2020). Here lies the starting point of this work. If different regimes ask different questions of different objects, one material may receive as many classifications as questions are put to it, and classification ceases to be a datum that the material carries with it.

3 Materials and methods

3.1 Design

The study combines doctrinal legal analysis with a computational test. The legal analysis establishes, for each regime, the rule that decides whether a material may be used. The test applies each rule, coded, to the same laboratory data. The design is that of a single instrumental case: the tailings are not studied for their own sake but to make the rules produce observable outputs. The case does not ground any criterion; it tests the instruments.

3.2 Legal corpus and inclusion criteria

Each rule was read in the official text of its jurisdiction and coded with four attributes: the object it assesses, the magnitude it compares, the threshold, and the party who answers for compliance. The Chilean corpus comprises Supreme Decree 148/2003 (Ministerio de Salud, 2004), Supreme Decree 46/2025 (Ministerio de Salud, 2026) and the standards NCh170:2016 for concrete (Instituto Nacional de Normalización, 2016), NCh163:2024 for aggregates (Instituto Nacional de Normalización, 2024), NCh1444:2010 (Instituto Nacional de Normalización, 2010) and NCh147:2020 (Instituto Nacional de Normalización, 2020). The comparative corpus comprises Directive 2006/21/EC and Decision 2009/359/EC (European Parliament and Council of the

European Union, 2006; European Commission, 2009), Decision 2003/33/EC (Council of the European Union, 2002), the Dutch soil quality regulation (Minister van Infrastructuur en Waterstaat, 2022), the German ordinance (Bundesregierung, 2021) and the Danish order on residues in construction works (Miljø- og Fødevareministeriet, 2016). The Chilean standards, which are not openly available, were read in the official viewer of the Ministry of Housing and Urbanism and are cited by clause. Quotations from Spanish-language texts are our translations; the originals are reproduced in Online Resource 1.

A regime entered the test if its rule has a numerical threshold, or a codifiable scope condition, on magnitudes that were measured or can be bounded from the measurements. The regimes tested are therefore not a sample of those that enable tailings. They are those that could be read in official text and coded, and this limits what the test can claim (Sect. 5.6).

3.3 Coding protocol

Two distinctions were fixed before the results were known. The first separates rules that apply by right to tailings used in a paving slab from rules applied by declared analogy, whose count is always reported apart. A rule applies by analogy when its own text excludes the material or the use: the slag decree, which addresses slag; the landfill acceptance criteria, from which extractive waste is excluded; and the Danish table, whose list of residues does not contain tailings.

The second distinction defines the classes of verdict by legal effect and not by the label each rule uses: decided favourably (the rule qualifies the material without further testing); decided unfavourably; pending the test that the rule prescribes (total content rules out some elements and the test decides the rest); and not applicable (the rule puts no question to the material). With this definition, the number of classes does not depend on how many analogies are included. Where a text admits more than one reading, all readings were computed and are reported.

3.4 Material and data

The material is tailings from the Tambillos mining operation, in the commune of Coquimbo, whose plant is in operation. Seven samples (A, D, E, G, H, I and K) were analysed by AGQ Chile S.A.: metals by four-acid digestion and inductively coupled plasma optical emission spectrometry, with mercury by aqua regia (AGQ Chile S.A., 2026a), and sulfur and carbon speciation, acid-base accounting, pH and conductivity (AGQ Chile S.A., 2026b). Three samples (G, H and I) were also analysed by X-ray fluorescence and X-ray diffraction at Soluciones Analíticas SpA (Soluciones Analíticas SpA, 2026b,a). The transcription of the reports was checked cell by cell against the originals (48 parameters, seven samples, 336 cells, no discrepancies).

Metals carry an expanded uncertainty of ±34.9% (coverage factor 2). The test compares the reported value, as each rule does, and declares every cell in which the interval crosses the threshold. The neutralisation potential ratio is outside the scope of the laboratory's accreditation, and its equivalence with the static test named by

Decision 2009/359/EC is not demonstrated. Table 1 gathers the parameters used in the text; all parameters used by the analysis are in Online Resource 1.

Table 1 Input data: parameters used by the decision rules, by sample. Metals in mg/kg (four-acid digestion; mercury by aqua regia), expanded uncertainty ±34.9%; sulfur, sulfate and carbon in %; neutralisation potential ratio (NPR) dimensionless

Parameter	A	D	E	G	H	I	K
Arsenic	100	127	52.3	118	62.9	63.2	61.4
Lead	222	251	145	326	197	165	154
Cadmium	3.20	4.56	2.69	5.64	4.58	5.81	3.92
Chromium	38.2	34.3	43.8	35.2	30.3	29.9	32.0
Copper	2,430	1,003	874	933	919	974	907
Zinc	1,315	1,502	1,065	2,257	1,789	1,780	1,574
Cobalt	108	145	104	123	126	143	132
Mercury	<10	<10	<10	<10	<10	<10	<10
Total sulfur (%)	1.68	1.72	1.41	1.45	1.81	1.90	1.83
Sulfide sulfur (%)	1.07	1.18	0.96	1.03	1.17	1.39	1.34
Sulfate, as SO_4 (%)	1.83	1.62	1.34	1.27	1.92	1.53	1.46
Inorganic carbon (%)	0.29	0.15	0.21	<0.10	<0.10	<0.10	<0.10
NPR	1.43	0.87	1.18	0.51	0.60	0.36	0.46

Source: laboratory reports (AGQ Chile S.A., 2026a,b). X-ray fluorescence gives, for G, H and I, sulfur trioxide of 2.69, 2.70 and 3.05% and chromium of 170, 190 and 220 mg/kg (Soluciones Analíticas SpA, 2026b)

3.5 Derived indicators

Where a regime requires a magnitude that was not measured, we compute indicators that belong to no regime and are labelled as our own inference. The total-extraction bound limits from above the leachate of a test run at a liquid-to-solid ratio of 20 L/kg: if w is the total content in mg/kg, the concentration cannot exceed

$$c_{\max} = \frac{w}{20}\ \text{mg/L}, \tag{1}$$

so that an element whose bound does not reach the threshold cannot decide even if tested. The critical fraction is the ratio between the limit L of a regime and the inventory of the element,

$$\varphi = \frac{L}{w}, \tag{2}$$

that is, the fraction of the inventory which, if released, exhausts the limit; the element with the lowest φ governs by inventory. In a shaped product the inventory is referred to surface area, but the dose of tailings, the density and the reference face multiply the inventory of all elements by the same factor: the ranking that results from Eq. (2) does not depend on those assumptions, and the ranking is all that is reported here. Neither indicator predicts release. They identify which element can decide, not which will.

The sulfur balance checks speciation against the total,

$$S_{\mathrm{total}} = S_{\mathrm{sulfide}} + \frac{32.06}{96.06}\,[\mathrm{SO_4}], \tag{3}$$

and the sulfide sulfur that zinc and copper cannot host, assuming both entirely in sphalerite and chalcopyrite, is obtained by subtracting $0.490\,w_{\mathrm{Zn}}$ and $1.009\,w_{\mathrm{Cu}}$, with contents in the same unit as sulfur (mass ratios S/Zn in ZnS and S/Cu in $\mathrm{CuFeS_2}$). The assumption is deliberately generous to the known phases, so that the unassigned remainder is a lower bound. The dose admitted by the Chilean sulfate limit is derived in Sect. 4.4.

3.6 Reproducibility and use of language models

Every derived figure is produced by a script without randomness or external dependencies, from the transcription of the reports and a table of limits with their sources (Online Resources 1 and 2). The manuscript cites the figure the script delivers.

A large language model (Claude, Anthropic) assisted in drafting and translating the manuscript and in writing the calculation script. The authors verified the legal readings, the data and every figure against the sources, and take full responsibility for the content.

4 Results

4.1 What the slag decree reuses, adds and omits

The hazardous waste regulation settles the classification of bulk mining waste by list. Its article 23 provides that, as long as final disposal is not carried out together with household waste, "the following bulk mining wastes [...] shall not be considered hazardous: (a) waste rock, (b) low-grade ore, (c) residues of ore treated by leaching, (d) tailings and (e) slag". It reserves to the Health Authority the power to require their characterisation "in qualified cases", and provides that the toxicity test of article 14 is then replaced by the synthetic precipitation leaching procedure (Ministerio de Salud, 2004; U.S. Environmental Protection Agency, 1994), with the maximum permissible concentrations of that article: arsenic 5, chromium 5, mercury 0.2, lead 5, selenium 1, barium 100, cadmium 1 and silver 5 mg/L. Classification is therefore strictly symmetrical between slag and tailings, and characterisation is a latent power of the authority, not an operating condition.

Supreme Decree 46/2025 builds on that base. It sets "the sanitary and safety requirements for the use of copper slag as artificial aggregate for the construction of roads, highways and motorways, as well as in other infrastructure works and in the manufacture of prefabricated, ornamental or functional elements intended for open spaces" (article 1). Authorisation is granted by the Regional Ministerial Secretariat of Health "exclusively for the uses specified in the application" (article 3); use in enclosed spaces is prohibited (article 7); and slag which, "after a synthetic precipitation leaching test, does not comply with the Maximum Permissible Concentrations [...] shall be considered hazardous waste and may not be used" (article 9) (Ministerio de Salud,

2026). Its Table 1 sets arsenic, lead and chromium at 5 mg/L, cadmium and selenium at 1 mg/L, and an activity index not greater than 1.

The comparison, which Table 2 sets out, yields three results. The decree adds no leaching threshold: it reuses as a condition of use five of the eight concentrations of article 14, with the same test that article 23 already provides. It omits mercury, barium and silver, so that a literal transplant to tailings would relax three elements that a characterisation under the regulation in force includes. What it does add is of another nature: the test becomes mandatory, where article 23 leaves it to discretion; a radiological threshold appears that the regulation does not contain; and a procedure is created. Two absences complete the picture. The object assessed is the slag before use, never the product; and the applicant is, by definition, the "holder of a copper smelter who applies for sanitary authorisation for the use, by itself or by third parties, of its copper slag" (article 2(e)): the architecture presupposes an identified and living generator.

Table 2 What the slag decree reuses, adds and omits with respect to the hazardous waste regulation, and what follows for tailings. Concentrations in mg/L in the synthetic precipitation leachate

Item	Supreme Decree 148/2003 (arts. 14 and 23)	Supreme Decree 46/2025 (slag)	Consequence for tailings
Test	Optional, "in qualified cases"	Mandatory (art. 9)	The obligation is added, not the test
As, Pb, Cr	5	5	No change
Cd, Se	1	1	No change
Hg, Ba, Ag	0.2; 100; 5	Not listed	A literal transplant would relax them
Cu, Zn	No limit	No limit	They govern the inventory under rules R5 and R6
Sulfur	Not addressed	Not addressed	Decides rule R4 and the dose (Sect. 4.4)
Activity index	None	$I \leq 1$, once per slag heap	New threshold, measured on the component
Object	The waste	The slag before use	The product is not tested
Applicant	The generator	The smelter holder (art. 2(e))	Without a generator, no one can apply
Uses	Not regulated	Open spaces allowed, enclosed prohibited (arts. 1 and 7)	Transferable: it prohibits by exposure

Source: authors' elaboration from Ministerio de Salud (2004) and Ministerio de Salud (2026). Rules R4, R5 and R6 are those of Table 3

At the level of technical standards, the asymmetry is one of rank. NCh163:2024 sets specific requirements for copper slag aggregate, among them a maximum total sulfur of 2.0% and a maximum sulfur trioxide of 0.5% (subclause 7.6.2.1 and Table 8). Tailings fall under the remaining artificial aggregates, whose use requires a characterisation study by an authorised laboratory and recognition in a specification or a standard (subclause 7.7), and have only an informative annex that asks for attention to total sulfur and sulfur trioxide without setting limits (Annex J) (Instituto Nacional de

Normalización, 2024). Sulfur, which the standard limits for slag and names for tailings, thus appears in neither of the two sanitary instruments.

4.2 One tailings material, eight rules

Table 3 gives the verdict of each rule. Under every rule the seven samples receive the same class; what changes between samples is the deciding element and the figure.

Table 3 Eight decision rules applied to the seven samples: object, magnitude, verdict with its deciding figure, and form of application. MPC: maximum permissible concentration; L/S: liquid-to-solid ratio; NPR: neutralisation potential ratio

No.	Regime and source	Object	Magnitude	Verdict and deciding figure	Application
R1	Chile, Supreme Decree 148/2003, art. 23	Waste	Membership of the list of bulk mining wastes	Favourable: non-hazardous by list. It looks at no data	By right
R2	Chile, Supreme Decree 148/2003, art. 20	Waste	Total content against 20 × MPC	Pending: lead open in all seven (145 to 326 mg/kg against 100); arsenic in A, D and G (100, 127 and 118 against 100); mercury inconclusive	By right
R3	Chile, Supreme Decree 46/2025, art. 9 and Table 1	Slag before use	Leachate (mg/L) and activity index	Pending: neither measured. The total-extraction bound reaches the MPC for lead (1.45 to 3.26 times) and for arsenic in A, D and G; copper and zinc have no limit	By analogy
R4	European Union, Decision 2009/359/EC, art. 1(1)(b)	Extractive waste	Sulfide sulfur and NPR	Unfavourable: not inert. Sulfide sulfur of 0.96 to 1.39% (9.6 to 13.9 times 0.1%); NPR of 0.36 to 1.43, never above 3	By right
R5	European Union, Decision 2003/33/EC, inert	Waste accepted at landfill	Leachate at L/S 10 (mg/kg)	Pending: not measured. Lowest critical fraction: copper in five samples (0.08 to 0.23%), lead in D and G (0.20 and 0.15%)	By analogy
R6	Netherlands, Regeling bodemkwaliteit 2022, Annex A	Shaped product in service	Emission by diffusion at 64 days (mg/m^2)	Pending: not measured. Copper governs the inventory in all seven; the second quantified element lies at 3.4 to 13.8 times	By right
R7	Germany, Ersatzbaustoffverordnung, § 1(2) and § 2	Unbound material in technical works	Scope	Not applicable: no class for tailings; hydraulically bound mixtures excluded, save three installation modes	By right
R8	Denmark, BEK 1672/2016, § 2, § 5 and Annexes 1 and 8	Residue of Annex 1 used in works	(a) total content against category 1; (b) scope	(b) Not applicable: tailings are not a residue of Annex 1. (a) Unfavourable: arsenic, lead, cadmium, copper and zinc exceed the free-use category by 1.7 to 11.6 times	(b) by right; (a) by analogy

By right, out of six rules, one decides favourably (R1), one unfavourably (R4), two leave the material pending the test they prescribe (R2 and R6), and two put no question to it (R7 and R8 in its scope reading, which are one closed-list structure in two instances). By analogy, out of three, two remain pending (R3 and R5) and one

decides unfavourably (R8 in its table reading). One tailings material, on one dataset, thus receives all four classes of verdict.

Nor is the deciding element the same. In Chile it is lead and arsenic, which the rule of twenty leaves open and which the bound of Eq. (1) shows capable of reaching the maximum permissible concentration: with 326 mg/kg of lead in sample G, $c_{\max} = 326/20 = 16.3$ mg/L, that is, 3.26 times the threshold of 5. Chromium, cadmium and selenium cannot decide even if tested, because their bounds do not exceed 0.44, 0.29 and 0.50 of the threshold. In the European Union the deciding element is sulfide sulfur, without any new test. In the only regime that assesses the product it is copper. Take a slab of 40 × 40 × 5 cm, of 18.4 kg at 2,300 kg/m^3, with 10% of tailings from sample A; its copper inventory referred to the upper face is $2{,}430 \times 1.84/0.16 = 27{,}945$ mg/m^2, and the Dutch limit of 98 mg/m^2 is exhausted if 0.35% of that inventory diffuses, whereas the arsenic limit (260 mg/m^2 against 1,461 in sample D) tolerates 17.8%. The absolute figures depend on the assumed slab; the ranking does not. In Denmark the largest exceedance is that of cadmium (11.6 times in sample I).

Mercury shows a further effect. Its contracted limit of quantification (10 mg/kg) exceeds the threshold of the rule of twenty (4 mg/kg) and that of the Danish category (1 mg/kg), so that the regime decides, by fixing the threshold, whether the datum exists. And "pending" does not mean "hazardous": it means that total content does not suffice to rule the element out and that only the prescribed test decides.

4.3 Sulfur: what the European rule sees and the Chilean one does not

The sulfur of the tailings closes. With Eq. (3), in sample A, $1.07 + 0.334 \times 1.83 = 1.681\%$ against 1.68% of total sulfur, and the difference does not exceed 0.004 points in any of the seven samples. The speciation is therefore internally consistent, and two consequences follow.

The first is that the tailings are not inert as extractive waste, and that this verdict does not depend on the method that remains to be demonstrated. Sulfide sulfur exceeds 0.1% in every sample; six exceed 1%, and the only one that does not, E with 0.96%, has a neutralisation potential ratio of 1.18. Factors of 2.1 (sample A) to 8.3 (sample I) would be needed to reach the ratio of 3 that the decision requires. Inorganic carbon confirms that such factors are out of reach: each 0.10% of inorganic carbon is equivalent to at most 8.3 kg of $CaCO_3$ per tonne, so that the carbonate ceiling of the neutralisation potential is 24.2 kg/t in sample A against an acid potential of 33.3 (a ratio of 0.73), and falls below 0.26 in the four samples whose inorganic carbon does not reach the limit of quantification.

The second is that most of the sulfide has no identified host phase. Diffraction recognises a single sulfide, sphalerite (Soluciones Analíticas SpA, 2026a), and chemistry prevents it from explaining the sulfur measured: in sample I, zinc (1,780 mg/kg) hosts at most 0.087% of sulfur and copper (974 mg/kg), assumed entirely in chalcopyrite, another 0.098%, so that $1.39 - 0.087 - 0.098 = 1.20\%$ remains unassigned. Across the set, between 0.76 and 1.20% of sulfur, from 71 to 87% of the sulfide, has no host; it would be equivalent to between 1.9 and 3.0% of pyrrhotite or between 1.4

and 2.3% of pyrite. The distinction decides the rule applicable to the aggregate: the European standard admits 1% of total sulfur and reduces it to 0.1% when pyrrhotite is present (European Committee for Standardization, 2008). By mass balance, the first limit would admit up to 53 to 71% of tailings in the combined aggregate, and the second, between 5.3 and 7.1%. Identifying the sulfide, for which thermomagnetic and automated mineralogy methods exist (Oberhardt et al, 2025; Wang et al, 2025), moves the dose by an order of magnitude.

Sulfur is therefore the difference that the Chilean sanitary regime does not look at. Slag and tailings receive the same classification under it, which proves only that they are equal for that regime; the European rule, which asks about sulfide, would separate them.

4.4 The dose: the limit falls on the concrete and depends on a basis no standard fixes

The Chilean concrete standard sets no compositional limit for an addition incorporated at the mixer: it requires that additions "shall be evaluated by means of trial concretes" (subclause 7.6). The limit that reaches it is that of the concrete as a whole: the content of sulfates, "expressed as SO_4, shall be less than or equal to 2% of the cement mass and corresponds to the total contribution of the concrete constituents, excluding cement" (subclause 6.3.1) (Instituto Nacional de Normalización, 2016, our translation). The question thus ceases to be whether the tailings comply and becomes how much tailings fits.

Let B be the mass of cementitious material per cubic metre, r the fraction of B that the tailings replace, s the sulfate of the tailings as a mass fraction of SO_4, and A and s_A the mass and the sulfate of the aggregate. Since an addition incorporated at the mixer is not cement, its sulfate enters the numerator and its mass does not enter the denominator. The cement is $(1-r)B$, and subclause 6.3.1 requires

$$s\,r\,B + s_A\,A \;\le\; 0.02\,(1-r)\,B. \tag{4}$$

From Eq. (4) it follows that

$$r \;\le\; \frac{0.02\,B - s_A\,A}{(s+0.02)\,B}, \tag{5}$$

and, with a sulfate-free aggregate,

$$r_{\max} = \frac{0.02}{s+0.02}, \tag{6}$$

which does not depend on B. Replacement acts twice: it raises the sulfate contributed and reduces the mass against which it is compared.

The standard limits sulfates, however, and does not say by which method they are measured in an addition. For aggregates the method is that of water-soluble sulfates (Instituto Nacional de Normalización, 2010); for cement, the gravimetry of acid-soluble

sulfate, with X-ray fluorescence as an alternative only when validated and never in case of dispute (Instituto Nacional de Normalización, 2020). A sulfide is not a sulfate at mixing, but it may become one in the hardened piece. Two readings of s are therefore possible: the literal one, which counts the sulfate present (1.27 to 1.92% of SO_4), and the prudent one, which counts all sulfur as potential sulfate (4.22 to 5.69% by combustion; 3.23 to 3.66% by fluorescence in three samples). Equation (6) then gives, for sample G in the literal reading, $0.02/(0.0127 + 0.02) = 0.612$, and for sample I in the prudent reading, $0.02/(0.0569 + 0.02) = 0.260$. Table 4 and Fig. 1 give the full set.

Table 4 Dose of tailings admitted by the sulfate limit of NCh170:2016 (subclause 6.3.1), by analytical basis of the tailings sulfate and by role of the tailings in the mix. Authors' inference

Analytical basis of s	s (% of SO_4)	As addition: maximum replacement of cementitious material	Same, with aggregate at 0.05% SO_4	As 60 to 70% of solids: times the margin is exceeded
Measured sulfate (literal)	1.27 to 1.92	51.0 to 61.2%	44.5 to 53.3%	2.2 to 4.1
Total sulfur by combustion (prudent)	4.22 to 5.69	26.0 to 32.1%	22.7 to 28.0%	7.3 to 12.2
Total sulfur by fluorescence (prudent; G, H and I)	3.23 to 3.66	35.3 to 38.3%	30.8 to 33.3%	5.6 to 7.9

Third and fourth columns: Eqs. (6) and (5), with B = 350 kg/m^3 and A = 1,800 kg/m^3. Fifth column: tailings equal to 60 to 70% of 2,150 kg/m^3 of solids, with 350 to 375 kg/m^3 of cement and the remaining aggregate free of sulfate. Conversions: $SO_4 = S \times 2.996$; $SO_4 = SO_3 \times 1.200$

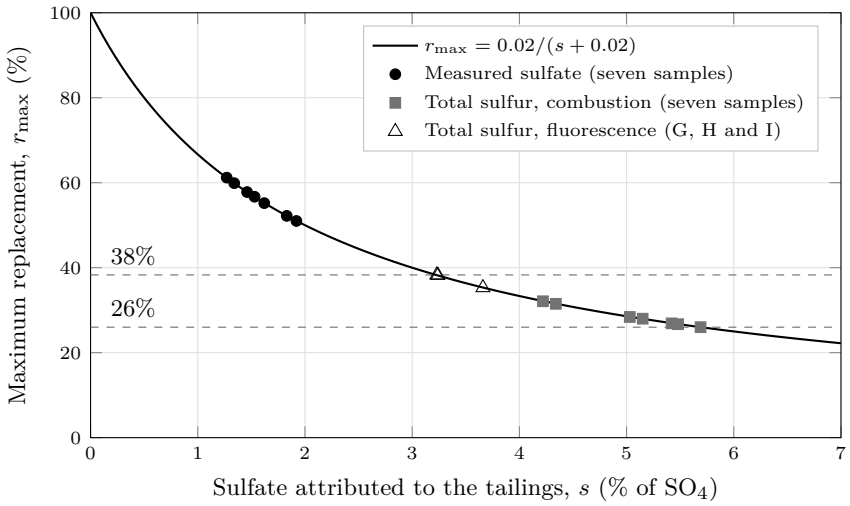


Fig. 1 Maximum replacement of cementitious material by tailings admitted by subclause 6.3.1 of NCh170:2016, with a sulfate-free aggregate, as a function of the sulfate attributed to the tailings. Between the dashed lines, the window in which the decision depends on the technique used to measure total sulfur

Three consequences follow. The analytical basis moves the admissible dose by a factor close to two: from 51 to 61% in the literal reading and from 26 to 32% in the prudent reading by combustion. The discrepancy between techniques, by contrast, decides only within the prudent reading and only in a window: a replacement of up to 26% complies with both and one above 38% complies with neither. What moves the decision most is therefore not a finer measurement of total sulfur but knowing what the sulfide is, because that chooses between the two readings.

The rule has a counterexample that delimits its scope: it is not a property of the tailings but of the mix. The sulfate of the aggregate consumes the same margin, and with an aggregate at the maximum that the aggregates standard tolerates (0.3% of soluble sulfates) and the proportions of Table 4, Eq. (5) leaves between 6 and 14% of replacement, depending on the reading and the sample. And if the tailings cease to replace cement and take the place of the aggregate, as 60 to 70% of the solids, their contribution exceeds the margin by 2.2 to 12.2 times on any analytical basis: with $0.0192 \times 1{,}505 = 28.9$ kg of SO_4 against $0.02 \times 350 = 7.0$, sample H exceeds it 4.1 times even counting only the sulfate present. To fit in that role, the sulfate of the tailings would have to fall to between 0.47 and 0.58%. One tailings material, under one clause, fits or does not fit according to the role assigned to it, the aggregate that accompanies it and the basis on which it is measured.

The ceiling is necessary, not sufficient. Subclause 7.6 requires the addition to be demonstrated in trial concretes, and mechanical performance, which this paper does not assess, may bind before the sulfate limit does.

4.5 Who applies

The slag decree settles standing by definition: the smelter holder applies. For tailings in operation, as in the case, a direct transplant would have a natural equivalent. For abandoned deposits it has none. Of the 195 in the Coquimbo Region, 125 record no tax identification of the holder; of these, 110 record a name and 15 state "unknown" (Servicio Nacional de Geología y Minería, 2026). Absence of a tax number is not absence of an owner: the Mining Code treats tailings as accessory to the beneficiation establishment from which they come and, once the establishment is abandoned, allows a mining concession to be constituted over the concessible substances they contain (article 6) (Ministerio de Minería, 1983); and the mine closure law, which binds mining companies in operation since 2012, does not reach deposits abandoned earlier (Ministerio de Minería, 2011).

Comparative law shows the two ways out. South Africa replicates the Chilean architecture: its waste exclusion regulations give standing to the generator of the waste, and a deposit without a holder is left without an applicant (Department of Environmental Affairs, 2018). Peru inverts it: its law on mining environmental liabilities provides that "the State shall progressively assume the abandoned environmental liabilities of unidentified holders" (article 5, our translation) (Congreso de la República del Perú, 2004), and its regulation opens voluntary remediation, with reuse among its modalities, to parties who do not hold the concession (Ministerio de Energía y Minas del Perú, 2005). Neither enables tailings as a construction product; both show that the question of the applicant precedes the question of the threshold.

4.6 Robustness

Table 5 lists the checks applied to each result. No check changes the class of a verdict. Two change what the pending tests may find, and are flagged as such: chromium, whose two analytical determinations disagree, and mercury, whose limit of quantification exceeds two thresholds.

Table 5 Robustness checks and their effect on the results

Check	Finding	Effect
Laboratory uncertainty on metals (±34.9%)	In R2, arsenic in A equals the threshold and arsenic in D and G and lead in E fall within the interval (65 to 135; 83 to 171; 77 to 159; 94 to 196 mg/kg). In R8(a) the lowest ratio, copper in E (569 to 1,179 mg/kg against 500), does not cross	No class changes: lead in the other six samples keeps R2 open
Alternative reading of the sulfide parameter (as sulfide mineral, factor 0.33)	Sulfide sulfur of 0.32 to 0.46%, still above 0.1% with NPR below 3	R4 unchanged
NPR not measured by the static test named in the decision	Carbonate ceiling of neutralisation potential at most 0.73 of the acid potential	R4 unchanged unless sulfide sulfur were 0.1% or less
Chromium by fluorescence (170 to 220 mg/kg) instead of digestion (29.9 to 43.8 mg/kg)	Chromium would be open in R2 for G, H and I, and its bound in R3 would reach the threshold (8.5 to 11.0 mg/L against 5)	Classes unchanged (already pending); the list of elements the test must decide grows
Mercury below a limit of quantification of 10 mg/kg	Limit above the thresholds of R2 (4 mg/kg) and R8(a) (1 mg/kg)	Cell inconclusive; classes unchanged
Assumed slab in R6 (dose, density, reference face)	All elements scale by the same factor	Ranking by inventory invariant
Relative error of ±10% in s	$r_{\max}$ moves by about ±2 to 2.5 points	Small against the factor of 1.8 to 2.2 between readings
Sulfate of the aggregate from 0 to 0.3%	$r_{\max}$ falls to between 6 and 14%	The ceiling is a property of the mix

5 Discussion

5.1 Admissibility as a property of the set

The results of Sects. 4.2 and 4.4 say the same thing at two scales. If classification belonged to the material, eight rules applied to the same data would not produce four classes of verdict and four different deciding elements; and if the dose belonged to the material, one clause would not admit from 6 to 61% according to the analytical basis and the accompanying aggregate. Neither “hazardous”, nor “inert”, nor “admissible” is a predicate of the tailings: each is a predicate of the set formed by the tailings, the object the regime assesses (the waste, the component, the concrete or the piece) and the test with which it assesses it.

The consequence for design is immediate. One instrument does not inherit the classification of another: that tailings are non-hazardous by list says nothing about their suitability for a public square, because the list looks at no data, and that they

pass a leaching test of the component says nothing about what the piece emits, because the governing element changes from lead to copper when the object changes. An instrument of use must therefore declare five things expressly, not the usual three: the object, the test, the threshold, the analytical basis and the applicant.

5.2 Five amendments to the slag decree

The slag decree serves as a base because of its architecture: authorisation by use, restriction by exposure, mandatory testing and a radiological threshold. It does not suffice, because what it omits is what decides for tailings. Table 6 sets out the five amendments that the results support and distinguishes, for each, whether it is founded on a Chilean rule in force, transferred from another rule on analogous grounds, or reserved to the authority, which is the one that must set the figure. The distinction matters for adoption: founded items need no new evidence, transferred items need a reasoned adaptation, and reserved items mark where the State, not the applicant, must act first.

Table 6 Five amendments to the slag decree for an instrument on tailings. F: founded on a Chilean rule in force; T: transferred from another rule, on analogous grounds; R: reserved to the authority

Item	Slag decree	Instrument for tailings	Ground and grade
1. Leaching list	Five elements: As, Pb, Cr, Cd and Se	The eight of article 14: also mercury, barium and silver, with a limit of quantification below the threshold	F: article 23 of Supreme Decree 148/2003 already provides them for tailings
2. Copper and zinc	No limit	Emission limit of the product for both	R, with T as reference: they govern the inventory under R5 and R6; Dutch values of 98 and 800 mg/m^2 as a starting point
3. Sulfur	Not addressed	Sulfide gate on the unmixed tailings; maximum dose from the sulfate limit of concrete, with the analytical basis declared	Gate: R, with T as reference (Decision 2009/359/EC). Dose: F (NCh170:2016, 6.3.1); analytical basis: R
4. Object assessed	The slag before use	In addition, the piece: tank test, durable shape and activity index of the product	T: the Dutch regulation assesses the shaped product; Directive 2013/59/Euratom applies the index to the building material
5. Applicant	The smelter holder	Whoever proves title over the tailings when the generator is not on record	R: standing over deposits without a holder requires a decision of the authority

The third amendment is the one that most separates tailings from slag, and the only one that no sanitary instrument read contains. It admits an operational formulation in two steps. On the unmixed tailings, a sulfide gate decides whether the material enters: the European criterion (sulfide sulfur up to 0.1%, or up to 1% with a neutralisation potential ratio above 3) is an available reference, under which the tailings of the case would not pass without prior desulfurisation. In the mix, the sulfate limit of concrete becomes a maximum dose through Eq. (5), provided the instrument states by

which method the sulfate of the addition is counted and whether sulfide is counted as potential sulfate. As long as the sulfide phase is not identified, the prudent reading is the only one that does not presuppose what remains to be known.

5.3 The order: mixing does not rehabilitate

The three logics of Sect. 2 cease to compete if they are ordered in series: first the gate, on the unmixed tailings; then the class of work; finally the emission of the product. The order matters for a reason the results make visible. If the gate were tested on the mix, a low dose would pass it by dilution: with 10% of tailings, the lead of sample G would contribute 32.6 mg/kg to the whole and the rule of twenty would rule it out without a test. Dilution is not retention, and both the German ordinance and the Dutch regulation prevent mixing from rehabilitating a component that does not comply (Bundesregierung, 2021; Minister van Infrastructuur en Waterstaat, 2022). This ordering, which contains no figure, is what another jurisdiction can adopt from the analysis without transplanting thresholds; a procedure built on it has been presented elsewhere (reference withheld for anonymous review).

5.4 Economic and policy implications

Three implications concern the allocation of costs and risks, which the legal analysis alone does not show.

The first is that regulatory silence has a price that the instrument can remove at no testing cost. The factor of about two between the literal and the prudent dose is not a property of the material but of an undeclared convention. A producer facing that ambiguity must either design to the prudent reading, and forgo half of the admissible substitution, or design to the literal one and bear the risk that an authority later counts the sulfide. Declaring the analytical basis is a decision of the regulator that requires no new measurement and converts a risk into a parameter.

The second concerns who should pay for characterisation. The decree places the whole burden on the applicant and measures radionuclides once per slag heap, which acknowledges that part of the information is specific to the deposit and not to the batch. Deposit-level information (the sulfide phase, the radionuclides, the representativeness of sampling) is a fixed cost whose result is non-rival: once known, it serves every subsequent user of the deposit. Where a holder exists, the decree's allocation internalises that cost. Where none is on record, as in 125 deposits of the region, no private party can appropriate the benefit of producing the information, and it will not be produced unless the State does so or vests standing, and with it the incentive, in a titled third party. The Peruvian rule, which lets the State assume liabilities of unidentified holders and opens reuse to third parties, is one way of assigning that role; the fifth amendment leaves the choice to the authority but makes the need explicit.

The third is a matter of scale, and it tempers expectations. At 350 kg of cementitious material per cubic metre, the sulfate ceiling admits between 91 and 112 kg of tailings per cubic metre of concrete in the prudent reading, and between 179 and 214 kg in the literal one; a paving slab of $40 \times 40 \times 5$ cm would carry between 0.7 and 1.7 kg. One tonne of tailings therefore requires between 4.7 and 11.0 m^3 of concrete. Use as an

addition is a route for cement substitution and for demonstrating a regulated pathway, not for emptying deposits; the bulk roles that would absorb mass (aggregate, 60 to 70% of solids) are precisely those the sulfate limit closes without desulfurisation. An instrument should be judged, and its compliance costs sized, against that realistic volume.

5.5 An alternative hypothesis

That the Chilean asymmetry is one of instrument does not prove that it lacks a technical component. The test did not subject a copper slag to the eight rules, and until it does it cannot be claimed that slag would pass where tailings do not. There is, moreover, evidence against a purely procedural explanation: the German ordinance lists copper slag and no tailings, in a regime where the Chilean procedure played no part. Either the explanation is incomplete, or there are reasons of material, sulfur among them, that operate in several regimes at once. The results of Sect. 4.3 make the second more plausible.

5.6 Limitations

The test has five limits. No leachate was measured: the four pending verdicts are pending because the test each rule prescribes has not been run, and the inventory indicators say which element can decide, not which will. It is one tailings material from one deposit, and its figures do not extend to others; what extends is the structure of the result, which requires only that regimes assess different objects with different tests. The foreign numerical regimes are all European, and two of them share a structure; no numerical regime in which tailings are in scope as a construction material entered the test. The reading of each rule is ours: where a text admits more than one reading both were computed, but an authority may read otherwise. And three data points condition specific readings without altering any class (Sect. 4.6): the chromium discrepancy, the method of the neutralisation potential ratio, and the fact that the sulfate reported is not a determination under the Chilean methods for aggregates or cement.

6 Conclusions

Chile's copper slag decree serves as a base for an instrument on tailings, but it does not suffice. It adds no leaching threshold to the hazardous waste regulation, omits three of its eight elements, tests the component and not the product, and presupposes an identified generator; what it does contribute (mandatory testing, a radiological threshold, restriction by exposure and a procedure) is transferable.

Subjected to eight decision rules from five jurisdictions, one tailings material receives all four possible classes of verdict: non-hazardous by list in Chile, non-inert in the European Union because of a sulfide sulfur of 0.96 to 1.39%, pending a test under four rules and outside the scope of two. The deciding element changes with the regime and with the object: lead and arsenic in the waste, sulfur in the extractive waste, copper in the piece.

The dose is set by sulfur. Under the sulfate limit of the Chilean concrete standard, the tailings are admissible as an addition at between 51 and 61% of the cementitious material if measured sulfate is counted and at between 26 and 32% if all their sulfur is counted; as the major fraction of the solids they do not fit on any basis. The standard does not say which basis governs, and between 71 and 87% of the sulfide has no identified host phase: identifying it is worth more, for the decision, than any analytical refinement of total sulfur.

An instrument for tailings therefore needs five amendments to the slag decree: the complete leaching list, copper and zinc, sulfur with its analytical basis, a test of the product, and an applicant with title when the generator is not on record. Two of them cost the regulator nothing but a declaration, and one, the applicant, decides whether the information on abandoned deposits will be produced at all. Admissibility is not a property of the tailings but of the set formed by the tailings, the product and the regime that assesses them; an instrument that does not declare that set transplants thresholds, not decisions.

Supplementary information

Online Resource 1 contains the coded decision rules with their thresholds and sources, the input data used in the analysis, the reading of each rule sample by sample, and the original Spanish wording of the provisions quoted. Online Resource 2 contains the calculation script and its output.

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