

Review

Embankments for Transportation Infrastructure as a Pathway for Valorisation of Incineration Bottom Ash and Mine Tailings

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Abstract

The growing demand for granular materials in transportation infrastructure increases the extraction of natural aggregates and the environmental impacts of the construction sector. At the same time, large volumes of municipal solid waste incineration bottom ash (IBA) and mine tailings (MTs) are generated and stored, posing environmental and geotechnical challenges. This review critically evaluates the potential of these waste streams as alternative materials for transportation infrastructure embankments, including zoned embankment approaches, that may enhance sustainability. The analysis integrates evidence on physical, geotechnical, and environmental performance, including compaction, compressibility, shear strength, permeability, bearing capacity, chemical composition, leaching, and ecotoxicity. IBA generally exhibits favourable engineering properties, although its performance depends on ageing and pre-treatment. MTs show greater variability, with behaviour largely controlled by mineralogy, particle-size distribution, and contaminant mobilisation potential. Environmental assessment should consider total chemical composition alongside leaching behaviour, ecotoxicity, and exposure conditions. Overall, the safe use of IBA and MTs requires an integrated evaluation of geotechnical and environmental performance, enabling their selective placement within functional embankment zones. Such approaches can support circular resource use and more sustainable transportation infrastructure without compromising technical performance.

Keywords: Incineration bottom ash; mine tailings; zoned embankments; transportation infrastructure; circular economy; waste valorisation



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1. Introduction

Transportation infrastructure plays a central role in economic, territorial, and social development, but its expansion and maintenance incur a very high consumption of construction materials [1,2] due to the massive use of mineral aggregates and granular materials in earthworks [3,4]. The global consumption of sand and gravel is estimated at about 40 to 50 billion tonnes per year and is expected to increase further due to population growth, urbanization, and infrastructure expansion [5]. Additionally, according to Segui et al. [6], the consumption of crushed stone may reach approximately 30 thousand tonnes per kilometre of road. The continued use of soils, sand, crushed rock, and gravel intensifies

resource scarcity and environmental damage [7]. As non-renewable materials, the extensive consumption of natural aggregates accelerates resource depletion [8], while their extraction and processing increase carbon emissions and habitat degradation [2].

In parallel, large volumes of inorganic waste from urban, industrial, and mining activities continue to be generated, stored, and disposed of [9,10], frequently resulting in long-term environmental and geotechnical risks linked to land occupation, dust emissions, leaching of potentially toxic elements, acid mine drainage (AMD), instability of storage facilities, and loss of potentially valuable mineral resources [10,11].

The growing demand for construction materials and the need for more sustainable waste management require reducing the use of primary aggregates in transportation infrastructure while promoting safe, high-volume valorisation pathways for waste streams. The circular economy addresses these challenges by promoting the use of waste as a substitute for primary materials and prioritising its recovery over disposal [12]. Global waste generation is increasing rapidly and may rise by 70% by 2050 [13], reaching an estimated 3.4 billion tonnes worldwide and presenting a pressing environmental challenge [14]. Thus, the valorisation of inorganic waste as secondary construction materials represents a promising strategy for concurrently reducing waste disposal and the consumption of primary materials. This approach is closely aligned with circular economy principles, provided that its technical performance and environmental safety are verified under relevant service conditions.

Among inorganic waste streams with potential for geotechnical valorisation, municipal solid waste incineration bottom ash (IBA) and mine tailings (MTs) are particularly relevant due to their high availability and their predominantly mineral composition [15]. However, both materials are still largely managed through disposal practices that demand long-term monitoring and control, while generating significant environmental problems. IBA are the main solid waste generated by municipal solid waste incineration, generally accounting for 80–90% of the solid residues from the process [16] and approximately 20–25% of the mass of the incinerated waste [9]. Their mineral fraction, commonly rich in SiO_2 , CaO , Al_2O_3 , and Fe_2O_3 [17], and broad particle size distribution [18] support their potential use as secondary aggregate in road embankments, bases, sub-bases, and subgrades [9]. However, this potential is strongly conditioned by source-dependent heterogeneity, ageing state, alkalinity [17], soluble salts, and potentially toxic metal release [9], requiring careful technical and environmental assessment before application [18].

MTs are defined as the solid residues remaining after physicochemical treatments applied to ore for the recovery of valuable minerals [15], typically consisting of finely ground rock particles mixed with water and residual processing reagents [10]. MTs may represent more than 90% of the material handled during mining operations [15], with the global mine tailings production being estimated at 5 to 7 billion tonnes per year [10]. This highlights the scale of the challenge associated with mineral extraction and processing [11]. The conventional storage of MTs in containment dams involves environmental risks, including the oxidation of residual sulphide minerals and the generation of AMD, the leaching of potentially toxic metals, and the risk of tailings dam failures [10]. These issues highlight the importance of developing sustainable approaches for tailings recycling and valorisation.

Transportation infrastructure embankments are a promising application for the valorisation of IBA and MTs because they require large material volumes and may be designed as zoned systems. In a zoned embankment, the foundation, core, shoulders, transition layers, and capping layer have different mechanical, hydraulic, and environmental requirements. The suitability of IBA and MTs should therefore be assessed according to the compatibility between material properties and the functional requirements and exposure conditions of each zone. Structurally demanding or more exposed zones require materials

with higher mechanical stability, lower deformability, adequate drainage capacity, and lower environmental uncertainty. More protected internal zones, such as the core, may accommodate materials with poorer geotechnical performance and higher environmental uncertainty, provided that compaction, drainage, leaching control, and water exposure are properly managed.

Previous reviews (e.g., [6,16,17]) have addressed IBA and MTs in construction or road-related applications. However, to the knowledge of the authors, these reviews tend to be material specific, construction-product oriented, broad in terms of road applications and/or focusing on single perspectives of performance. They do not systematically relate IBA and MTs to the functional requirements of transportation infrastructure embankment zones and do not usually include different perspectives of behaviour, including technical and environmental behaviour. In particular, there is limited guidance for their use in transportation embankments, particularly in zoned embankments where materials with different engineering properties and environmental risk profiles can be assigned to specific functional zones. Thus, this article critically reviews the potential use of IBA and MTs in embankments for transportation infrastructure. The contribution of the present review is to integrate geotechnical and environmental evidence on IBA and MTs within a zoned embankment perspective. This approach relates physical properties, compaction behaviour, compressibility, shear strength, permeability, bearing capacity, chemical composition, leaching behaviour, and ecotoxicological response to the functional requirements of embankment zones, identifying the potential applications, limitations, and conditions required for safer valorisation in transportation infrastructure. By relating material characterisation to embankment zoning, this review goes beyond a generic perspective of waste as aggregate and frames the valorisation of inorganic waste as a design problem in transportation geotechnics. This approach allows the properties and risks of each material to be fitted against the requirements of different embankment zones, supporting a safer, more durable, and sustainable use of inorganic waste in transportation infrastructure.

2. Review Methodology

The selection of the literature was guided by the objective of the manuscript, namely, to critically assess the geotechnical and environmental suitability of IBA and MTs for use in transportation infrastructure embankments.

Relevant literature was identified through systematic searches of Scopus, Web of Science, ScienceDirect, and Google Scholar, complemented by backward citation tracking of pertinent publications. The search focused mainly on publications from 2000 onwards, because most studies on waste valorisation in transportation infrastructure and environmental assessment of secondary aggregates were published during this period. Earlier publications were included when they provided fundamental concepts, testing procedures, regulatory background, or widely accepted geotechnical, chemical or environmental principles.

The search was organized according to the main themes of the manuscript: valorisation of inorganic residues and the circular economy; embankments for transportation infrastructure and requirements for zoned embankments; geotechnical properties of municipal solid waste incineration bottom ash (IBA) and mine tailings (MTs); and environmental characterisation, including chemical properties, leaching behaviour and ecotoxicity assessment. The search keywords included combinations of 'municipal solid waste incineration bottom ash,' 'MSWI bottom ash,' 'incineration bottom ash,' 'IBA,' 'MIBA,' 'mine tailings,' 'iron tailings,' 'copper tailings,' 'tungsten tailings,' 'gold tailings,' 'road embankment,' 'transportation embankment,' 'zoned embankment,' 'road construction,' 'railway embankment,' 'waste valorisation,' 'secondary aggregate,' 'geotechnical properties,' 'particle-size distribution,' 'compaction,' 'Proctor test,' 'compressibility,' 'shear strength,' 'permeability,' 'California

Bearing Ratio,' 'CBR,' 'leaching,' 'ecotoxicity,' 'ecotoxicological,' 'heavy metals,' 'pH,' and 'acid mine drainage.'

References were included when they supported the scope of the review, justified the focus on IBA and MTs, or addressed the functional requirements of embankments, the geotechnical and environmental assessment of IBA and MTs, or comparable waste-derived materials. Studies were excluded when they were not relevant to embankment applications, transport infrastructure, geotechnical behaviour, hydraulic performance, leaching, ecotoxicity, environmental risk, or related geotechnical applications.

The selected literature consisted primarily of peer-reviewed scientific journal articles, complemented by review papers, conference proceedings from specialized and renowned international conferences and/or written by prominent experts in their fields, books, technical reports, regulatory or institutional documents, and theses or dissertations. The synthesis was qualitative and comparative, and the reported values were interpreted as ranges and trends rather than universal design values, owing to the heterogeneity of the materials studied and variations in waste origin, treatment conditions, particle-size fractions, testing procedures, leaching protocols, and ecotoxicological methods.

Overall, 113 references were selected and critically analysed in this review, comprising 33 studies primarily addressing IBA, 32 focusing on MTs, and 1 study covering both materials, complemented by references on embankment engineering, geotechnical testing, environmental assessment, regulations, and related topics. The selected literature is recent, with 86 references (76%) published from 2016 onwards, ensuring that the review reflects current knowledge.

The quality and usefulness of the selected publications were assessed qualitatively. Studies that clearly reported material origin, ageing or treatment condition, particle-size fraction, test methods, compaction energy, moisture or saturation condition, and measured geotechnical parameters were preferred. For environmental assessment, studies reporting chemical composition, leaching method, liquid-to-solid ratio, pH conditions, contaminant concentrations, ecotoxicological endpoints, or regulatory interpretation were preferred. The synthesis was qualitative and comparative. Reported values were interpreted as ranges and trends rather than universal design values. Direct comparison among studies was made cautiously, especially when testing procedures, particle-size fractions, compaction energies, saturation states, or leaching protocols differed.

3. Embankments for Transportation Infrastructure

Transportation infrastructure, including roads, motorways, airports, and railways, requires large quantities of materials during construction and maintenance [19]. In this context, transportation infrastructure embankments are designed to support road pavements or railway systems [20] and must ensure stability and deformation control under expected loading conditions, and adequate environmental performance [21]. Their mechanical behaviour depends essentially on the foundation, fill materials, geometry, drainage, and loads imposed by the supported infrastructure [22]. The construction of embankments involves sequential operations of excavation, transport, spreading, and compaction, usually using heavy mechanical equipment. These activities may represent 30 to 50% of the cost and duration of infrastructure projects, which makes the optimisation of materials and construction procedures a relevant technical and economic issue [19]. Therefore, sustainability should be integrated from the earliest planning and design stages, traditionally maximising the reuse of on-site geomaterials, for example [19,21].

As indicated in Figure 1, embankments may be organised into different functional zones, including foundation, core, shoulders, transition layers, capping layer, and superstructure, which may correspond to the road pavement or railway track. In this case,

material applied in each zone should be selected according to the foundation conditions, environmental conditions (rain, drying, wind, temperature variations, etc.), applied loads, and acceptance limits associated with construction, stability, and deformation. Zoning is particularly relevant when materials of limited quality or excavation surplus are available, allowing poorer-quality materials to be placed in less critical zones, mixed with higher-quality materials, or applied in stratified sandwich-type configurations [21,23].

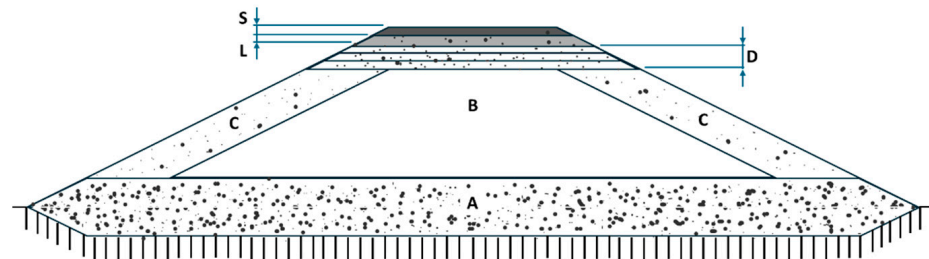


Figure 1. Conceptual scheme of a zoned embankment for transport infrastructure. A—foundation (natural ground); B—core; C—shoulders; D—transition layer; L—capping layer; S—superstructure. Adapted from [21].

Based on this zone-based functional logic, the zoning of transportation embankments implies, from a geotechnical perspective, that material selection should be guided by the geotechnical function and requirements of each layer. The foundation (A) must provide adequate bearing capacity and settlement control [24]. The core (B) constitutes the main volume of the embankment and should be constructed with compactable materials capable of ensuring global stability and acceptable long-term deformations. The shoulders (C) contribute to the lateral integrity of the embankment and should be properly compacted, particularly near the slopes, in accordance with the stability and deformation requirements of the project [21]. Transition layers (D) are among the most critical zones, as they must reduce stiffness discontinuities and differential settlements between the embankment or backfill and rigid structures. Consequently, they require selected granular materials or, where appropriate, cement-treated granular mixtures, which provide higher stiffness and lower susceptibility to plastic deformation [25]. The capping layer (L) should consist of well-graded, low-plasticity, strong, and free-draining granular materials capable of distributing traffic-induced stresses and protecting the underlying subgrade [26]. Thus, higher-quality materials should be prioritized in the transition and capping layers, whereas lower quality materials may be considered in less critical internal zones, provided that the requirements for stability, compactability, and deformation performance are satisfied [21]. Although the mechanical performance of the zoned embankment is critical for ensuring the satisfactory performance of the superstructure (S), the environmental safety of a waste-based embankment solution also depends on the chemical and ecotoxicological characteristics of the waste materials used in each embankment zone. In this regard, the accessibility of water to a given zone is one of the most important factors, and materials with a higher potential environmental impact should preferably be located within the core of the embankment to mitigate environmental risks.

4. Potential of Inorganic Waste for Embankment Construction

4.1. Geotechnical Characterisation

This section considers the geotechnical performance of IBA and MTs for use in transportation infrastructure embankments, focussing on the properties that control the shear and the deformation behaviour of the compacted materials. The relevant parameters in-

clude physical properties, such as particle-size distribution and index properties, as well as compaction, compressibility under different conditions, permeability and shear strength.

4.1.1. Physical Properties

Regarding physical properties, the analysis considers the particle-size distribution of both IBA and MTs, the plasticity based on consistency limits and plasticity index, the classification according to the Unified Soil Classification System (USCS) and the specific gravity of solid particles.

Particle-size distribution defines the percentage of particles of different sizes within a given material, being represented by particle-size distribution curves [27]. In granular materials, particle sizes may span a wide range, from 0.001 mm to 10 mm or more, reflecting variability in grain size composition [28]. The shape of the particle-size distribution curve provides important insight into the engineering behaviour of a material, as a well-graded or continuous distribution generally implies more efficient compaction, enhanced particle interlocking, and improved structural stability [29]. Figure 2 shows grain-size distribution curves reported for the analysed materials. The IBA [30] is predominantly composed of particles ranging from 0.075 to 2.36 mm (Figure 2), whereas the tungsten mine tailings (TMTs) [31] exhibit a finer particle-size distribution, with most particles falling between 0.005 and 1 mm (Figure 2). The iron mine tailings (IMTs) [32] also exhibit a fine particle-size distribution ranging from 0.004 to 0.25 mm (Figure 2). The analysed materials fall within the granulometric range typically associated with granular materials.

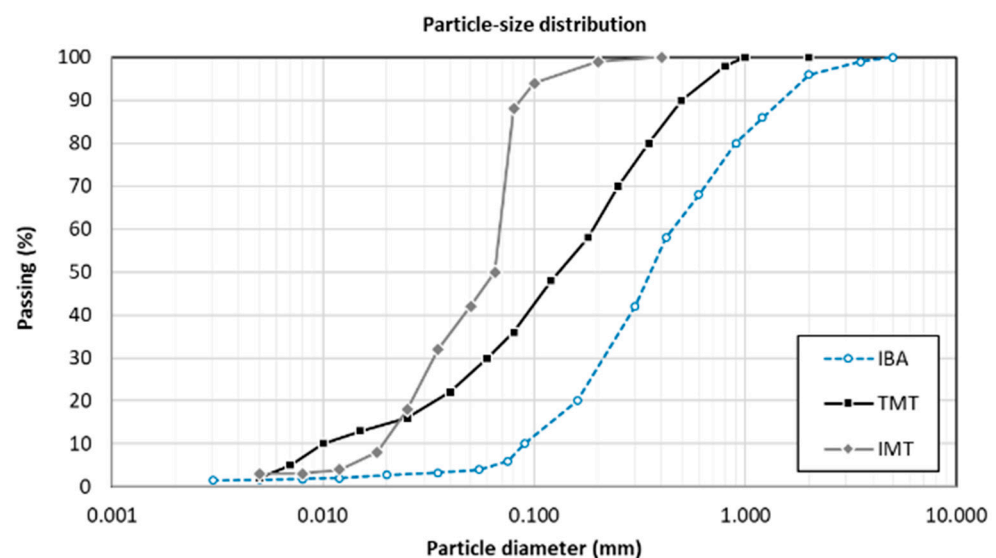


Figure 2. Particle-size distribution of IBA (adapted from [30]), TMTs (adapted from [31]) and IMTs (adapted from [32]).

Particle-size distribution curves can also be used to assess the coefficients of curvature (C_c) and uniformity (C_u). According to Kalore and Babu [30], a soil is considered well graded when the coefficient of uniformity is $C_u > 4$ for gravels and $C_u > 6$ for sands, while the coefficient of curvature should fall within the range $1 \leq C_c \leq 3$. If either C_u or C_c falls outside these limits, the soil is poorly graded.

Table 1 presents C_u and C_c values reported for IBA and for MTs, showing that IBA frequently exhibits higher C_u values than MTs. For IBA, the reported C_u values range from 7 to 162.5, usually above 40 [15]. In contrast, most MTs exhibit C_u values below 15, indicating more uniform particle-size distributions. Some MTs [33] show higher C_u values, ranging from 15.9 to 26.7, although these remain below the highest values reported for IBA. This suggests that IBA generally has wider particle-size distributions. Although C_c

values of the two materials partially overlap, IBA exhibits a wider range [34]. Overall, the C_U values indicate that IBA more frequently satisfies the uniformity requirements for well-graded materials, although it does not always meet the corresponding C_C criteria. Conversely, MTs tend to exhibit more uniform particle-size distributions and are more commonly classified as poorly graded, despite the significant variability observed among tailings from different mining operations.

Table 1. C_C and C_U values reported for IBA and MTs in the literature.

Ref.	Material and Origin	Material Condition	Particle-Size Fraction	C_U	C_C
[14]	IBA, Europe	3 months weathered	<9.5 mm	54.73	5.11
		12 months weathered	<9.5 mm	42.18	1.70
[18]	IBA, China	N.R.	Mostly <10 mm	10	1.11
[30]	IBA, India	Air and oven-dried	N.R.	7	1.47
[15]	IBA, Europe	1 year weathered	<9.5 mm	42.18	1.70
[35]	IBA, China	N.R.	0–9.5 mm	20.19	1.05
[34]	IBA, Japan	0–365 days aged	N.R.	66.9–162.5	0.4–10.5
[36]	Iron tailings, Portugal	air-dried	<0.3 mm	2.9	1.8
[37]	Iron tailings, China	N.R.	Coarse and fine	3.11–8.82	0.59–1.05
	Copper tailings, Mexico	N.R.	Coarse and fine	2.15–14.80	0.89–2.12
[38]	Iron tailings, Iran	N.R.	<2.36 mm	0.64	0.66
[15]	Tungsten tailings, Portugal	Air-dried	N.R.	7.99	1.17
	Iron tailings, Portugal	Air-dried	N.R.	2.91	1.84
[39]	Iron tailings, Brazil	N.R.	N.R.	6.67	1.16
[33]	Copper tailings, Brazil	N.R.	N.R.	15.9–26.7	1.7–5.1
[40]	Iron tailings, India	Oven-dried	N.R.	12.5–14.8	0.41–1.08
[31]	Tungsten tailings, Portugal	N.R.	0.005–1 mm	13.7	1.75

Note: C_U : Coefficient of uniformity; C_C : Coefficient of curvature; IBA: Municipal solid waste incineration bottom ash; MTs: Mine tailings; N.R.: Not reported.

Consistency limits indicate how mechanical behaviour varies with water content [27]. The plasticity index (PI), obtained as the difference between the liquid limit (LL) and the plastic limit (PL), reflects the degree of plasticity of the material [41], higher PI values indicating greater plasticity and more clay-like behaviour [27]. Table 2 presents the consistency limit values reported for IBA and MT samples, suggesting that IBA tends to be less plastic than MTs. For IBA, LL values range from 40% to 46%, with PI values below 11%. Conversely, MTs show LL values between 18% and 32% and PI values under 15%.

The Unified Soil Classification System (USCS) provides a useful framework for the preliminary assessment of geotechnical behaviour by grouping materials according to their particle-size distribution and plasticity characteristics. Granular materials, classified as GW (well graded gravel), GP (poorly graded gravel), SW (well graded sand), and SP (poorly graded sand), generally exhibit favourable engineering properties, including high permeability, low compressibility, and good load-bearing capacity. In contrast, fine-grained or plastic materials, such as ML (silt), CL (low plasticity clay), MH (elastic silt), and CH (high plasticity clay), are typically associated with higher compressibility, lower drainage capacity, and, in some cases, swelling behaviour [42], and lower resistance. Table 3 summarises the USCS classifications reported for IBA and MTs in the reviewed studies.

Based on the literature data presented in Table 3, IBA are predominantly classified as coarse-grained granular materials according to the USCS. Most reported classifications fall within sandy soil groups, although one study classified IBA as GP (poorly graded gravel). Overall, these classifications indicate that IBA generally exhibits favourable drainage characteristics and relatively low compressibility when compacted, supporting its potential use in geotechnical applications. In contrast, mine tailings show a broader range of USCS clas-

sifications, both as granular (GW-GC, SM, SC, and SM-SC) or fine-grained or transitional materials (CL and CL-ML). This variability reflects the strong influence of ore mineralogy, particle-size distribution, beneficiation processes, material handling, and sample preparation procedures. Therefore, while IBA display a more consistent granular behaviour, MTs exhibit less predictable geotechnical characteristics and require case-specific assessment before being considered for engineering applications.

Table 2. Consistency limits of IBA and MTs.

Ref.	Material and Origin	Ageing Condition	Particle-Size Fraction	LL (%)	PL (%)	PI (%)
[14]	IBA, Europe	3 months weathered	<0.425 mm	46.2	42.5	3.7
		1 year weathered	<0.425 mm	40.2	35.9	4.3
[15]	IBA, Europe	1 year weathered	<0.425 mm	40.2	35.9	4.2
[35]	IBA, China	N.R.	0–2.36 mm	42.8	31.9	10.9
[37]	Iron ore tailings, China	N.R.	Fine tailings	28	19	9
	Copper ore tailings, Mexico	N.R.	Fine tailings	28	13	15
[15]	Tungsten tailings, Portugal	Air-dried	N.R.	17.7	12.1	5.7
	Iron ore tailings, Portugal	Air-dried	N.R.	17.6	11.1	6.5
[32]	Iron ore tailings, Portugal	N.R.	N.R.	20	15	5
[43]	Copper mine tailings, Philippines	N.R.	N.R.	32.1	25.8	6.2
[31]	Tungsten tailings, Portugal	N.R.	0.005–1 mm	23	15	8

Note: IBA: Municipal solid waste incineration bottom ash; MTs: Mine tailings; LL: Liquid limit; PL: Plastic limit; PI: Plasticity index; N.R.: Not reported.

The specific gravity of solid particles, or solid particle density (G_s) is a fundamental index property in granular materials, as it supports the calculation of weight-volume relationships, such as void ratio, porosity, and degree of saturation [44]. For natural mineral materials, such as sands, silts, and inorganic clays, typical values range from 2.65 to 2.80. Higher values, close to 2.75–3.00, may indicate the presence of denser minerals, although geotechnical suitability should not be assessed on the basis of G_s alone. Conversely, values below approximately 2.60 may suggest the presence of organic matter or less dense constituents, requiring complementary assessment before structural applications [27]. Table 4 compiles G_s values reported for IBA and MTs, including details on material origin.

Table 3. USCS classification of IBA and MTs reported in the literature.

Ref.	Material and Origin	Material Condition	Particle-Size Fraction	USCS
[14]	IBA, Europe	3 months weathered	<9.5 mm	SP-SM
		12 months weathered	<9.5 mm	SW-SM
[18]	IBA, China	N.R.	Mostly <10 mm	SW
[45]	IBA, India	Air and oven-dried	N.R.	SP-SM
[15]	IBA, Europe	1 year weathered	<9.5 mm	SW-SM
[46]	IBA, USA	N.R.	<50 mm	GP
[34]	IBA, Japan	0–365 days aged	N.R.	SM
[47]	IBA, Europe	Outdoor weathered >3 months	<2 mm	SW
[37]	Iron ore tailings, China	N.R.	Fine	CL
	Copper ore tailings, Mexico	N.R.	Fine	CL
[15]	Tungsten tailings, Portugal	Air-dried	<9.5 mm	SM-SC
	Iron ore tailings, Portugal	Air-dried	<9.5 mm	CL-ML
[39]	Iron ore tailings, Brazil	N.R.	N.R.	SM
[33]	Copper tailings, Brazil	N.R.	N.R.	SM
[31]	Tungsten tailings, Portugal	N.R.	0.005–1 mm	SC

Note: N.R.: Not reported; USCS: Unified Soil Classification System; SW: Well-graded sand; SP: Poorly graded sand; SM: Silty sand; SC: Clayey sand; CL: Low-plasticity clay; GP: Poorly graded gravel; SW-SM: Well-graded sand with silt; SP-SM: Poorly graded sand with silt; SM-SC: Silty sand with clay; CL-ML: Low-plasticity silty clay.

Table 4. Specific gravity of solid particles (G_s) of IBA and MTs.

Ref.	Material and Origin	Material Condition	Particle-Size Fraction	G_s
[14]	IBA, Europe	3 months weathered	<9.5 mm	2.62 ± 0.05
		1 year weathered	<9.5 mm	2.80 ± 0.30
[45]	IBA, India	N.R.	N.R.	2.165
[15]	IBA, Europe	1 year weathered	<9.5 mm	2.80 ± 0.28
[46]	IBA, United States	≥ 1 month aged	N.R.	2.83 ± 0.04
[48]	IBA, India	Air-dried 1 week	<4.75 mm	2.59–2.63
[49]	IBA, China	N.R.	0–20 mm	2.13
[37]	Iron ore tailings, China	N.R.	Coarse and fine	3.08–3.23
	Copper ore tailings, Mexico	N.R.	Coarse and fine	2.76–2.77
[38]	Iron ore tailings, Iran	N.R.	<2.36 mm	3.10
[15]	Tungsten mine tailings, Portugal	Air-dried	N.R.	3.16 ± 0.07
	Iron ore tailings, Portugal	Air-dried	N.R.	4.57 ± 0.01
[39]	Iron ore tailings, Brazil	N.R.	N.R.	2.92
[32]	Iron ore tailings, Portugal	N.R.	N.R.	4.70
[33]	Copper tailings, Brazil	Air-dried	N.R.	2.814–3.149
[40]	Iron ore tailings, India	N.R.	N.R.	3.16–3.20
[43]	Copper mine tailings, Philippines	N.R.	0.075–4.75 mm	2.82
[50]	Gold mine tailings, Philippines	N.R.	silty sand	2.71–2.72
[31]	Tungsten tailings, Portugal	N.R.	0.005–1 mm	3.12

Note: G_s : Specific gravity of solids; IBA: Municipal solid waste incineration bottom ash; MTs: Mine tailings; N.R.: Not reported.

IBA generally exhibits lower G_s values than mine tailings, although the reported range is relatively broad, varying from 2.13 to 2.83. Most weathered or aged IBA samples fall within approximately 2.59–2.83, which is close to the values typically observed for natural soils and suggests behaviour consistent with relatively low-density aggregates. Nevertheless, the lower values reported, ranging between 2.13 and 2.165, indicate greater material heterogeneity and may be associated with the presence of lighter constituents. In contrast, mine tailings exhibit a wider and generally higher range of G_s , from 2.71 to 4.70, reflecting the strong influence of ore type and mineralogical composition. Iron ore tailings are particularly notable for their higher values, occasionally as high as 4, due to the presence of denser mineral particles. Copper, tungsten and gold tailings display intermediate G_s values, generally ranging from 2.71 to 3.16. Overall, G_s should be interpreted on a material-specific basis, considering compositional, mineralogical and geological variability, as well as differences in material condition and particle-size fraction.

Considering the physical properties analysed, both IBA and MTs show potential for use in geotechnical applications, although their behaviour differs significantly. IBA presents a predominantly granular character, with broad particle-size distributions, frequently high C_U values, and USCS classifications mainly associated with sandy or silty sandy materials, such as SW, SW-SM, SP-SM, and SM. These characteristics indicate favourable drainage capacity, efficient compaction, particle interlocking, and relatively low compressibility when compacted, supporting possible use in embankments, pavement layers, and filling works. Their G_s values are also generally close to those of natural granular soils, reinforcing their physical compatibility with conventional construction materials. However, the variability observed in some properties shows that IBA performance depends strongly on origin, ageing, processing, and particle-size fraction.

In contrast, MTs exhibit more heterogeneous physical behaviour, largely controlled by ore type, beneficiation process, and mineralogical composition. Although some MTs are classified as granular materials, others fall within finer or intermediate USCS classes, such as CL, CL-ML, SC, and SM-SC, indicating greater variability in drainage and compressibility

behaviour. Their particle-size distributions are often finer and more uniform than those of IBA, which reduces particle interlocking and increases sensitivity to water content. MTs generally also show low to moderate plasticity, their suitability in geotechnical works being less predictable. Iron tailings tend to show better performance than other tailings.

IBA generally behave as granular materials, although their properties depend on source, ageing, processing, and particle-size fraction. MTs show greater variability because their behaviour depends strongly on ore type, mineralogy, grinding process, fines content, and saturation condition. Therefore, iron-rich, copper, tungsten, gold, and sulphide-bearing tailings should not be interpreted as a single uniform material group.

4.1.2. Compaction

Compaction is an essential stage in the construction of earthworks, as it increases dry density, reduces void volume, and improves the mechanical behaviour and homogeneity of the material [51] through the application of mechanical energy [27]. The efficiency of compaction depends on water content, applied energy, particle-size distribution, mineralogy, and soil type. The optimum moisture content (w_{opt}) and maximum dry unit weight ($\gamma_{d,max}$), are the main control parameters [52]. The Proctor test allows the relationship between moisture content and dry density to be established, defining the appropriate compaction conditions for field application [27,52]. The compaction curve obtained from the Proctor test and presented in Figure 3 shows that the material has an optimum moisture content of 9.7% and a maximum dry unit weight of 22.1 kN/m³.

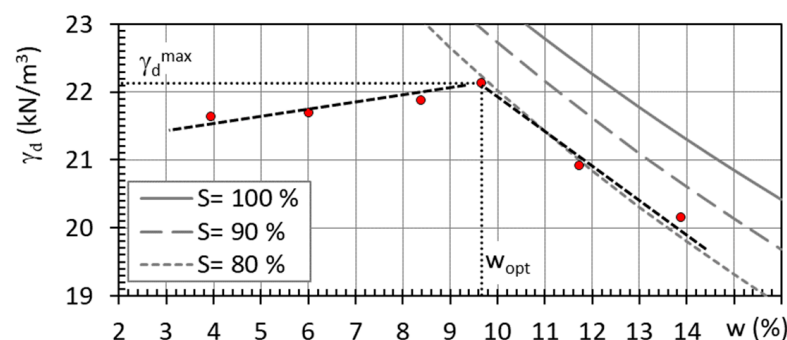


Figure 3. Proctor compaction curve (black dash line, representing the Proctor test results—red dots), indicating the optimum water content (w_{opt}) and maximum dry density ($\gamma_{d,max}$), while S represents the degree of saturation. Adapted from [31].

The compaction parameters reported for IBA and MTs from different locations and tested using different methods are shown in Table 5. The data show considerable variability in the compaction parameters of IBA, with w_{opt} values ranging from 10.8% to 26.0% and $\gamma_{d,max}$ values ranging from 13.3 to 18.34 kN/m³. The lowest $\gamma_{d,max}$ values were obtained in standard Proctor compaction (SPC) tests, namely 13.3 kN/m³ [48] and 13.98 kN/m³ [4], whereas the highest values were generally associated with modified Proctor compaction (MPC) tests, such as 18.34 kN/m³ [53]. For studies in which the same IBA was tested under different compaction energies, increasing the compaction energy led to lower w_{opt} and higher $\gamma_{d,max}$ values [48], as expected. Ageing also appears to affect the compaction behaviour of IBA, as the w_{opt} decreased from 18.2% to 15.4%, while $\gamma_{d,max}$ increased from 16.48 to 17.03 kN/m³ when ageing increased from 3 and 12 months [14]. MTs also exhibit a wide range of compaction parameters, with w_{opt} values ranging from 9% to 19.5% and $\gamma_{d,max}$ values ranging from 15.7 to 29.3 kN/m³. The lowest w_{opt} and highest $\gamma_{d,max}$ were reported for iron ore tailings tested using MPC [32], whereas the highest w_{opt} and lowest $\gamma_{d,max}$ were obtained for copper mine tailings tested using SPC [43]. As expected, the MPC

method resulted in lower w_{opt} and higher $\gamma_{d,max}$ values, indicating greater densification with increasing compaction energy, both iron ore tailings [54] and copper tailings [33].

For comparison, conventional borrow materials have been reported to present w_{opt} values between 12.5% and 23% and $\gamma_{d,max}$ values between 15.01 and 18.93 kN/m³ [55]. IBA results tend to overlap these intervals, particularly those obtained with MPC, for which $\gamma_{d,max}$ values ranged approximately from 16.48 to 18.34 kN/m³. This suggests that, under appropriate compaction conditions, IBA exhibits compaction behaviour comparable to that of conventional embankment materials. Lower $\gamma_{d,max}$ values, such as 13.3 kN/m³ [48] and 13.98 kN/m³ [4], and higher w_{opt} values, such as 26.0% [56], are atypical and may not represent real IBA performance or reflect poor industrial processes involved in the MSW treatments. For MTs, some $\gamma_{d,max}$ values are within the range of conventional borrow materials, whereas others clearly exceed it, particularly iron ore tailings, with values up to 29.3 kN/m³ [32], and tungsten tailings, with a $\gamma_{d,max}$ of 22.1 kN/m³ [31].

Table 5. Compaction parameters of IBA and MTs.

Ref.	Material	Origin	Proctor Test Method	w_{opt} (%)	$\gamma_{d,max}$ (kN/m ³)
[14]	IBA aged 3 months	Europe	MPC	18.2	16.48
	IBA aged 12 months	Europe	MPC	15.4	17.03
[15]	IBA aged 12 months	Europe	MPC	15.4	17.50
[18]	IBA	China	MPC	10.8	17.26
[57]	IBA	China	MPC	16.0	17.26
[58]	IBA	India	MPC	11.0	16.80
[48]	IBA	India	SPC	19.2–23.4	13.3–15.1
			MPC	15.8–18.0	15.1–16.1
[46]	IBA, aged 1 month	USA	MPC	15.8 ± 1.0	17.78 ± 0.24
[53]	IBA, aged 3 months	France	SPC	15.0	17.46
			MPC	12.5	18.34
[49]	IBA, aged 3 months	China	MPC	17.7	18.24
[56]	IBA	India	N.R.	26.0	14.30
[4]	IBA	China	SPC	11.0	13.98
[38]	Iron ore tailings	Iran	SPC	10.8	20.9
[39]	Iron ore tailings	Brazil	SPC	11.6	19.2
[54]	Iron ore tailings	Brazil	SPC	11.4	19.20
			MPC	9.4	20.5
[32]	Iron ore tailings	Portugal	MPC	9.0	29.32
[59]	Gold ore tailings	Brazil	SPC	14.6–18.8	16.46–17.71
[33]	Copper tailings	Brazil	SPC	12.8	18.49
	Copper tailings	Brazil	MPC	10.4	19.44
	Copper tailings	Brazil	SPC	14.4	19.02
	Copper tailings	Brazil	MPC	10.3	21.13
[43]	Copper mine tailings	Philippines	SPC	19.5	15.7
[31]	Tungsten tailings	Portugal	MPC	9.7	22.1

Notes: IBA: Municipal solid waste incineration bottom ash; MTs: Mine tailings; $\gamma_{d,max}$: Maximum dry unit weight; w_{opt} : Optimum water content; SPC: Standard Proctor compaction; MPC: Modified Proctor compaction; N.R.: Not reported.

These values indicate that IBA can generally be compacted within the range expected for granular embankment materials, but the results vary with ageing condition, particle-size fraction, fines content, pre-treatment, and compaction energy. Higher compaction energy tends to reduce w_{opt} and increase $\gamma_{d,max}$, confirming that compaction method must be considered when comparing results from different studies.

Thus, the potential replacement of natural materials is supported, for IBA, by the similarity between several w_{opt} and $\gamma_{d,max}$ values and those of conventional materials and, for MTs, by the high $\gamma_{d,max}$ values observed in some tailings. However, given the variability

of the results and the influence of compaction energy, material origin, and material type, their use in transportation embankments should be assessed on a case-by-case basis, namely in the case of MTs. In fact, the majority of the IBA show great potential for producing well-compacted embankments. In addition, direct comparison of compressibility parameters reported in the literature should be interpreted with caution, as the analysed studies considered different material origins, initial conditions, loading ranges, saturation states, and specimen preparation procedures, all of which may influence the reported values.

4.1.3. Compressibility

One-dimensional compressibility assesses the deformability of a material due to increments of vertical stress under lateral confinement. The oedometer test defined the variation in void ratio with applied vertical stress, producing the so-called e -log σ'_v curve (Figure 4). This curve enables the determination of the main compressibility parameters of the material, namely the compression index (C_c), for the virgin compression branch (red line), and the recompression index (C_r), for the recompression branch (blue line). The swelling or expansion index (C_s), may also be obtained from the unloading branch (green line). For each applied loading stage, the coefficient of consolidation (C_v), can also be determined empirically. Figure 4 illustrates a one-dimensional compressibility curve for compacted tungsten tailings [31].

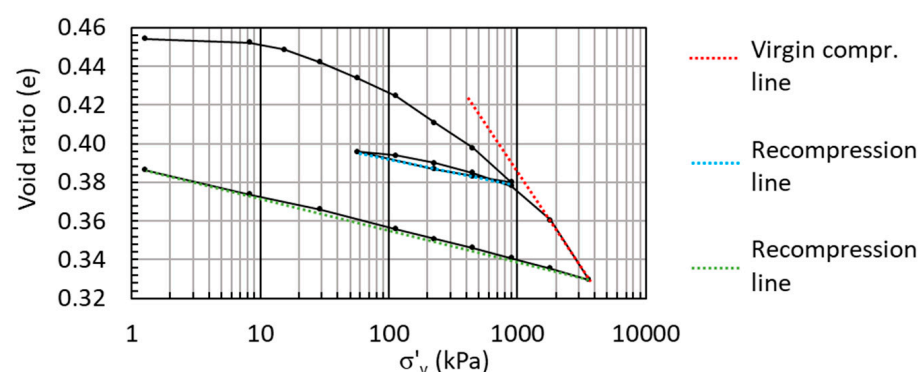


Figure 4. Schematic representation of the determination of compressibility parameters from the e -log σ'_v curve, including the C_c , C_r and C_s . Adapted from [31].

Table 6 presents a summary of the compressibility parameters of IBA and MTs reported in different studies, considering material origin, initial sample condition, applied loading range, and saturation condition adopted during the tests.

The data reveal clear differences in the compressibility behaviour of IBA and MTs. The compressibility of IBA depends on ageing and saturation. Samples aged for 12 months show lower Δe and C_c values than samples aged for 3 months, indicating reduced deformability after ageing. A study [60] indicated that submerged specimens and non-immersed specimens exhibit similar C_c , suggesting comparable compressibility and relative insensitivity to the presence of water [60].

The coefficient of consolidation, C_v , was reported for the IBA samples, with values ranging from 80.1 to 849.7 m^2/d . For MTs, the available data include copper mine tailings and tungsten mine tailings. MTs show variable compressibility and should not be treated as a single material group. Copper mine tailings present the highest compressibility among the reviewed materials, with $C_c = 0.3416$ and C_v values between 0.034 and 0.136 m^2/day . These values indicate greater susceptibility to consolidation settlement, especially under saturated or poorly drained conditions. Copper tailings should therefore be restricted to less critical zones or improved before use. In contrast, the tungsten mine tailings exhibit lower void ratios, with $e_0 \approx 0.45$ and $e_f \approx 0.33$, together with $\Delta e \approx 0.12$, $C_c = 0.101$ and

$C_s = 0.015$, although under a wider loading range of 1–3600 kPa. These results indicate that the compacted tungsten mine tailings show lower compressibility than the compacted copper mine tailings.

Table 6. Compressibility parameters of IBA and MTs.

Ref.	Material and Origin	Initial Condition	e_0	e_f	Δe	Loading Range (kPa)	Saturation Condition	C_v (m ² /d)	C_c	C_r or C_s
[14]	IBA, Europe	Aged 3 m; compacted: Modified Proctor	N.R.	N.R.	0.23 ± 0.02	1.4–4398	Submerged	80.14 ± 29.16	0.182 ± 0.017	0.013 ± 0.001
		Aged 12 m; compacted: Modified Proctor	N.R.	N.R.	0.14 ± 0.06	1.4–4398	Submerged	828.62 ± 572.06	0.155 ± 0.044	0.012 ± 0.001
[15]	IBA, Europe	Aged 12 m; compacted: Modified Proctor	N.R.	N.R.	0.14 ± 0.06	1.4–4398	Submerged	849.72 ± 609.14	0.150 ± 0.040	0.012 ± 0.001
[60]	IBA, France	Aged 3 m; compacted: Modified Proctor	0.428–0.433	0.384–0.386	0.042–0.049	55–6610	No immersed	N.R.	0.0409–0.0420	0.0026
		Aged 3 m; compacted: Modified Proctor	0.431–0.441	0.370–0.371	0.060–0.071	55–6610	Submerged	N.R.	0.0461–0.0465	0.0035–0.0036
[61]	Copper MTs, Philippines	Compacted by moist tamping	0.964–1.441	N.R.	N.R.	5–200	Submerged	0.034–0.136	0.3416	0.0263
[31]	Tungsten MTs, Portugal	Sample compacted using modified Proctor energy	≈ 0.45	≈ 0.33	≈ 0.12	1–3600	Submerged	N.R.	0.101	0.015

Notes: e_0 : Initial void ratio of the material before consolidation testing; e_f : Final void ratio at the end of the test; Δe : Variation in void ratio during the test; C_v : Coefficient of consolidation; C_c : Compression index; C_r : Recompression index; C_s : Swelling index; IBA: Municipal solid waste incineration bottom ash; MTs: Mine tailings; N.R.: Not reported; m: Months.

In relation to conventional materials, compacted IBA exhibits behaviour compatible with granular materials, as its C_c values, ranging from 0.0409 to 0.182 ± 0.017 , fall within the range reported for sands [62], $C_c = 0.002$ –1.0. Its C_r values, ranging from 0.0026 to 0.013 ± 0.001 , are also close to the range reported for sands by Zheng et al. [63], $C_r = 0.0023$ –0.0150. Similarly, the compacted tungsten mine tailings exhibit relatively low compressibility, with $C_c = 0.101$ and $\Delta e \approx 0.12$, which is close to the $\Delta e \approx 0.14$ reported by Uygur and Doven [64] for dense sand. Based on compressibility, compacted IBA and compacted tungsten mine tailings show potential for use in embankment construction. Lower values of C_c , C_r or C_s , and Δe indicate more controllable deformations and behaviour closer to that of granular materials. However, copper tailings should therefore be restricted to less critical zones or improved before use.

4.1.4. Shear Strength

Shear strength represents the ability of a soil or granular material to resist failure under tangential stresses, resulting from friction and interlocking between particles [65]. The parameters commonly used to define shear strength are cohesion (c'), and the internal friction angle (ϕ') [66]. These parameters are influenced by effective stress, drainage conditions, density, particle-size distribution, particle shape and fines content [27]. Shear strength is commonly represented by the Mohr–Coulomb failure criterion, in which failure occurs when the stress state reaches the failure envelope, as expressed by (Equation (1)) [67]:

$$\tau_f = c' + \sigma'_f \times \tan \phi' \quad (1)$$

where τ_f —shear stress, relative to peak or residual conditions; σ'_f —normal effective stress; c' —cohesion; ϕ' —friction angle; and “f” and “'” represent failure and effective stress conditions, respectively.

Figure 5 illustrates the Mohr–Coulomb failure envelope obtained from the direct shear test and the Mohr circle obtained from the triaxial test for IBA aged for one year. Figure 5A represents the peak condition, while Figure 5B represents the residual condition. The dashed lines correspond to the Mohr–Coulomb failure envelopes, whereas the circle represents the stress state obtained from the triaxial test. The slope of the envelope is

associated with the shear resistance ϕ' , while the intercept with the vertical axis is associated with c' . Under peak conditions, the triaxial test indicates a slightly higher shear strength than that obtained from the direct shear test, which was attributed to more effective compaction and the use of larger particles in the triaxial test. Under residual conditions, the results of the two tests were similar. In this formulation, c' corresponds to cohesion in terms of effective stress, while ϕ' corresponds to the friction angle in terms of effective stress, the parameters being obtained by regression of the relationship between normal effective stress and shear stress at failure [15]. Higher values of ϕ' indicate greater frictional resistance, while higher values of c' may indicate some degree of cementation or merely a mathematical effect reflecting the non-linearity of the failure envelope. Direct shear box tests and triaxial tests are the most widely used methods for determining shear strength parameters.

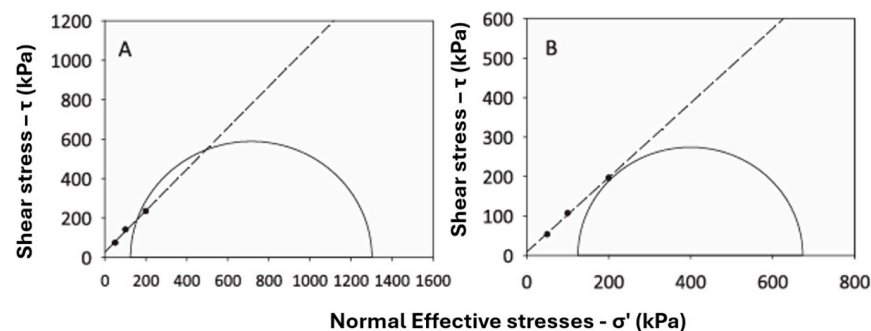


Figure 5. Mohr–Coulomb failure envelope (dash line, obtained from shear box testing - dots) and Mohr circle obtained from triaxial testing for IBA aged for one year under (A) peak and (B) residual conditions. Adapted from [14].

Table 7 summarises the shear strength parameters reported for IBA and MTs, considering different materials, origins, sample preparation procedures, test types, stress levels, and shear states. The results indicate that IBA exhibits higher strength parameters, although some variations exist. Overall, IBA friction angles range from 35.2° to 49.7° , and cohesion values vary between 8.5 and 46.2 kPa. Under residual conditions, friction angles remain relatively high, between 41.6° and 43.4° . Indian IBA also exhibits high peak friction angles, ranging from 40.5° to 46.1° in saturated consolidated drained triaxial tests and from 43.3° to 49.7° in dry direct shear tests, although cohesion was not reported.

For MTs, the available data include gold ore, iron ore, copper, gold mine, and tungsten tailings, with friction angles ranging from 22° to 51° and reported cohesion values between approximately 0 and 42.7 kPa. The lowest values correspond to the residual strengths of copper mine tailings from the Philippines tested under CU and CD triaxial conditions, whereas the highest friction angles, 49 – 51° , were obtained for compacted iron ore tailings from India in direct shear tests. Other MT materials show intermediate behaviour, including Brazilian gold ore tailings with residual friction angles of 31.9 – 35.7° , Philippine gold mine tailings with values of 32.5 – 36.8° , Brazilian copper tailings with residual values of 34.8 – 36.1° , and Portuguese tungsten tailings with a peak friction angle of 37.6° and cohesion of 42.7 kPa. Compared with a conventional gravelly soil, with reported friction angles of 41.2 – 44.1° and cohesion values of 0.2–0.7 kPa [68], several IBA samples show comparable or superior frictional performance, with peak friction angles frequently exceeding 40° and reaching up to 49.7° . In contrast, MT behaviour is more variable: some tailings exhibit lower friction angles than gravelly soil, particularly under residual conditions, whereas compacted iron ore tailings clearly exceed this reference range. The cohesion values reported for IBA and MTs are substantially higher than those of the conventional soil, reaching 46.2 and 42.7 kPa, respectively. However, the relatively high c' values reported for IBA should be interpreted cautiously. In granular waste-derived materials, c' may

reflect apparent cohesion, particle interlocking, partial cementation, ageing effects, or the linearisation of a non-linear failure envelope, rather than true intrinsic cohesion.

Table 7. Shear strength parameters of IBA and MTs.

Ref.	Material and Origin	Material Condition	Test Type	Stress (kPa)	Shear State	ϕ' (°)	c' (kPa)
[14]	IBA, Europe	dp < 2 mm; aged 3 months; compacted; unsaturated; drained	Direct shear box-CD	$\sigma'_n = 50, 100, 200$	Peak	40.1	46.2
					Residual	41.6	18.9
		dp < 2 mm; aged 12 months; compacted; unsaturated; drained	Direct shear box-CD	$\sigma'_n = 50, 100, \text{ and } 200 \text{ kPa}$	Peak	46.4	27.7
					Residual	43.4	8.5
[15]	IBA, Europe	dp < 2 mm; aged 12 months; compacted; unsaturated; drained	Direct shear box-CD	$\sigma'_n = 50, 100, \text{ and } 200 \text{ kPa}$	Peak	46.4	27.7
					Residual	43.4	8.5
[48]	IBA, India	<4.75 mm; Compacted; saturated; drained	Triaxial compression-CD	$\sigma'_3 = 100, 200, \text{ and } 400 \text{ kPa}$	Peak	40.5–46.1	N.R.
					Residual	35.2–38.4	N.R.
		dp < 4.75 mm; oven-dried and compacted; dry; drained	Direct shear box	$\sigma_n = 100, 200, \text{ and } 400 \text{ kPa}$	Peak	43.3–49.7	N.R.
					Residual	36.5–40.3	N.R.
[59]	Gold ore tailings, Brazil	Sandy silt; compacted; saturated; drained and undrained	Triaxial compression-CU and CD	$p'_0 = 100\text{--}1600 \text{ kPa}$	Residual	31.9–35.7	N.R.
[40]	Iron ore tailings, India	Fine-grained; compacted	Direct shear box	N.R.	Peak	49–51	10–10.01
[43]	Copper mine tailings, Philippines	Silty; compacted; saturated; undrained	Triaxial compression-CU	$\sigma'_3 = 50, 100, \text{ and } 200 \text{ kPa}$	Residual	22–27	N.R.
			Triaxial compression-CD	$\sigma'_3 = 50, 100, \text{ and } 200 \text{ kPa}$	Residual	24–28	N.R.
[50]	Gold mine tailings, Philippines	Sand and silty sand; compacted; dry; drained	Direct shear box	13.63–87.50	Residual	36.6–36.8	N.R.
		Sand and silty sand; compacted; saturated; drained	Direct shear box	13.63–54.50	Peak	32.5–33.3	≈ 0
[31]	Tungsten tailings, Portugal	dp = 0.005–1 mm; compacted; unsaturated; drained	Direct shear box	$\sigma'_n \approx 5, 10, 50, 100, \text{ and } 200 \text{ kPa}$	Peak	37.6	42.7
[33]	Copper tailings, Brazil	Silty sand; compacted; saturated; undrained	Monotonic simple shear	$p'_0 = 50, 100, 200, \text{ and } 400 \text{ kPa}$	Residual	34.8–36.1	N.R.

Note: dp: Particle diameter; σ'_n : Effective normal stress; σ_n : Total normal stress; σ_3 : Confining stress; σ'_3 : Effective confining stress; p'_0 : Initial effective stress state; CU: Consolidated undrained; CD: Consolidated drained; ϕ' : Friction angle; c' : Cohesion; N.R.: Not reported.

Overall, compacted IBA and selected MTs, particularly iron ore tailings and tungsten tailings, show shear strength parameters compatible with potential use in transportation infrastructure embankments. However, shear strength results depend on material type, test method, drainage condition, saturation state, density, and stress level, which also affect conventional granular soils used in embankment construction and determine the need for these materials to be assessed by geotechnical experts considering the specific conditions of the embankment.

4.1.5. Permeability

Permeability is a geotechnical parameter that describes the ability of water to flow through the voids of soils or granular materials, being expressed by the coefficient of permeability (k). Roy and Bhalla [27] classify soils as impermeable when k is lower than 10^{-8} m/s and very permeable when k is higher than 10^{-6} m/s. Therefore, higher permeability values indicate greater drainage capacity. Permeability is a relevant parameter for assessing the geotechnical behaviour of materials, particularly in applications where drainage capacity through the material are conditioning factors. Table 8 summarises the values of k reported in the literature for IBA and MTs.

Table 8. Permeability parameters of IBA and MTs.

Ref.	Material and Origin	Material Condition	Determination Method	Permeability, k (m/s)
[14]	IBA, Europe	Compacted: Modified Proctor; Aged 3 m	Oedometer	$5.40 \times 10^{-7} \pm 1.90 \times 10^{-7}$
		Compacted: Modified Proctor; Aged 1 y	Oedometer	$4.68 \times 10^{-6} \pm 3.66 \times 10^{-6}$
			Constant-head triaxial test	0.8×10^{-6}
[15]	IBA, Europe	Compacted: Modified Proctor; Aged 1 y	Oedometer	$4.81 \times 10^{-6} \pm 3.87 \times 10^{-6}$
[48]	IBA, India	Compacted: Standard Proctor	Constant-head permeability test	7×10^{-6} to 8×10^{-5}
[69]	IBA, India	Compacted: Modified Proctor; Aged 3 m	Falling-head permeability test	1.52×10^{-7}
[59]	Gold ore tailings, Brazil	Compacted: Standard Proctor	Falling-head permeability test	5.0×10^{-8} to 1.3×10^{-6}
[40]	Iron ore tailings, India	Compacted: Standard Proctor	Constant-head permeability test	3.70×10^{-5} to 4.10×10^{-5}
[31]	Tungsten tailings, Portugal	Compacted: Modified Proctor	Oedometer	10^{-7} to 10^{-10}

Note: IBA: Municipal solid waste incineration bottom ash; MTs: Mine tailings; m: months; y: year.

The data presented in Table 8 indicate that the permeability of IBA ranges from 1.52×10^{-7} to 8×10^{-5} m/s, covering more than two orders of magnitude. European IBA generally exhibits permeability values on the order of 10^{-7} to 10^{-6} m/s. For IBA aged for 3 months and compacted, the oedometer-based permeability was $5.40 \times 10^{-7} \pm 1.90 \times 10^{-7}$ m/s. For IBA aged for 1 year, the reported values increased to $4.68 \times 10^{-6} \pm 3.66 \times 10^{-6}$ m/s and $4.81 \times 10^{-6} \pm 3.87 \times 10^{-6}$ m/s, also based on oedometer-derived assessments. A constant-head triaxial permeability test conducted on 1-year-aged European IBA reported a value of 0.8×10^{-6} m/s. By contrast, IBA from India displays a wider range of permeability values. Compacted IBA tested under constant-head conditions exhibited the highest values, ranging from 7×10^{-6} to 8×10^{-5} m/s, whereas compacted IBA aged for 3 months and tested using a falling-head permeability method showed a considerably lower value of 1.52×10^{-7} m/s. These findings suggest that, as expected, the permeability of IBA is governed not only by material origin and ageing condition, but also by compaction procedure and testing methodology. With respect to MTs, the data report permeability values for gold ore tailings [59], iron ore tailings [40], and tungsten tailings [31]. The reported values range from 10^{-10} to 4.10×10^{-5} m/s, spanning nearly six orders of magnitude and evidencing substantial differences in the hydraulic behaviour of the analysed tailings. The highest permeability values were observed for compacted iron ore tailings, tested under constant-head conditions, with values in the order of 10^{-5} m/s. Intermediate values were reported for compacted gold ore tailings, evaluated using falling-head permeability testing, in the order of 10^{-8} to 10^{-6} m/s. The lowest values correspond to compacted tungsten tailings, assessed through oedometer-based permeability evaluation, with permeability being as low as 10^{-10} m/s. Overall, these results highlight the pronounced influence of tailings type, origin, compaction conditions, particle size distribution, etc., which can vary significantly. The variability observed indicates that the hydraulic behaviour of IBA

depends on material origin, ageing condition, particle-size fraction, compaction state, and test method employed. Therefore, permeability values reported for IBA should not be compared without considering these conditions. Likewise, MTs exhibits even greater variability and should not be treated as a single material group.

Compared with the conventional gravelly soil [68], described as well graded and predominantly composed of coarse particles, with permeability coefficients in the order of 10^{-4} m/s, the waste-derived materials analysed in Table 8 generally exhibit lower permeability. Even the highest values reported remain below those measured for the conventional gravelly soil. This indicates a more restrictive hydraulic response, which may reduce drainage capacity and promote water retention under specific field conditions. Thus, when IBA and MTs are considered for use in embankments, drainage requirements and spatial placement of these materials within the embankment must be suitably considered.

4.1.6. California Bearing Ratio (CBR)

Infrastructure systems such as embankments must provide adequate load-bearing capacity. For this reason, the California bearing ratio (CBR) is widely used as a geotechnical index to evaluate the bearing capacity of soils and granular materials [70]. CBR tests are generally performed either in the laboratory or in the field, and CBR values higher than 20% are commonly associated with strong geotechnical performance, whereas values below 5% indicate unsuitability for structural applications [71].

Table 9 presents California bearing ratio values reported in the literature for IBA and MTs. The data show considerable variability in the California bearing ratio (CBR) values reported for both IBA and MTs. For IBA, CBR values can be as high as $121 \pm 6\%$, which suggests that when properly compacted its performance as a building material in embankments may be excellent. The lowest values reported may once again reflect poor testing conditions or industrial processes involved in MSW treatment. For MTs, CBR values tend to be smaller, but still fairly good or even very good on some occasions, namely in Au–Cu tailings from Indonesia and zinc tailings from India, and particularly in Portuguese iron tailings. Lower values may reflect unsuitable testing conditions or reflect the large variability that can be found in MTs. Overall, IBA generally presents significantly higher CBR values than MTs, suggesting greater bearing capacity and greater potential for use in road embankments, particularly in zones subjected to higher structural demands. Nevertheless, some variability exists in both materials and some overlap exists between low-performing IBA samples and better performing MT samples, highlighting the need for case-specific assessment. Considering the reference values reported by Mahmud and Nuru [55], several IBA with CBR values above 23% may be comparable to conventional borrow materials used in embankments or other geotechnical applications. In contrast, most MTs exhibit lower CBR values and may therefore require more stringent quality control. Tailings with very low CBR values, such as coltan tailings, should be used with caution or improved before application.

Overall, IBA shows very good overall technical performance for use in transportation embankments, mainly due to their granular nature, generally sandy or silty-sandy gradation, good compactability, high shear strength, and frequently high to very high CBR values. When properly aged and compacted, their behaviour may be comparable to that of conventional granular materials, although their performance remains dependent on origin, processing, particle-size distribution and possibly ageing. By contrast, MTs exhibit more variable behaviour. Sandy or silty-sandy tailings with low plasticity, good compactability, and adequate shear strength may be suitable for embankment construction. However, finer, clayey, or low-permeability tailings tend to show poorer drainage, higher deformability, and lower CBR values, and may therefore require stabilisation, blending with granular

materials, or stricter quality control. Overall, IBA appear to be technically more suitable than MTs, especially for zones subjected to higher structural demands. Nevertheless, the reported CBR values should be interpreted considering differences in material origin, ageing condition, compaction procedure, soaking condition, and testing methodology among the reviewed studies. Therefore, the reported values are more appropriate for identifying general trends than for establishing universal design values.

Table 9. California bearing ratio parameters of IBA and MTs.

Ref.	Material and Origin	Material Condition	Time Before CBR Test (Days)	Test Condition	CBR (%)
[58]	IBA, Chandigarh, India	Compacted: Modified Proctor	0	Unsaturated	15
			4	Saturated	19
			28	Saturated	21
[34]	IBA, Japan	Compacted: Modified Proctor	N.R.	N.R.	43–93
[46]	IBA, USA	Aged ≥ 1 m; Compacted: Field vibratory plate compactor	N.R.	N.R.	121 $\pm$ 6
[72]	IBA, China	Compacted: Modified Proctor	N.R.	N.R.	≥ 72.96
[73]	IBA, India	Compacted: Modified Proctor	N.R.	N.R.	100
[45]	IBA, India	Compacted: Modified Proctor	0, 4, and 28	Unsaturated	16
	IBA, India	Compacted: Modified Proctor	0, 4, and 28	Saturated	20
[74]	IBA, India	Compacted: Modified Proctor	N.R.	Saturated	39.7–48.4
[75]	IBA, India	Compacted	N.R.	N.R.	8–12
[76]	IBA, China	Compacted	4	Saturated	4.2
[77]	Au–Cu MTs, Indonesia	Compacted	N.R.	Immersed	14.75
[78]	Magnesite tailings, India	Compacted	0	Unsoaked	18.25
[79]	Zinc tailings, India	Compacted: Modified Proctor	4	Immersed	11
[80]	Zinc tailings, India	Compacted	4	Immersed	12
[81]	Coltan tailings, RDC	Compacted: Modified Proctor	4	Immersed	0.33–1.33
[82]	Iron tailings, Portugal	Compacted	4	Immersed	73

Notes: IBA: Municipal solid waste incineration bottom ash; MTs: Mine tailings; CBR: California bearing ratio; Au–Cu: Gold–copper; RDC: Democratic Republic of the Congo; N.R.: Not reported.

4.2. Environmental Characterisation

This section highlights the environmental performance of both IBA and MTs, to assess their suitability for use in transportation infrastructure embankments. As waste-derived materials, their application depends not only on geotechnical performance but also on their chemical composition, the release of potentially hazardous substances through leaching, and the associated risks to terrestrial and aquatic ecosystems. Therefore, environmental behaviour is a key consideration for their safe and sustainable valorisation.

4.2.1. Chemical Properties

Chemical characterisation of the solid matrix constitutes a fundamental first step in assessing the suitability of waste-derived materials for transportation infrastructure embankments, as it enables the identification of salts, metals, metalloids, and other constituents that may affect environmental performance. However, the total concentration of these elements alone does not provide a reliable indication of environmental risk, as their mobility and bioavailability depend on site-specific physicochemical conditions [83]. Hence, this section examines the chemical composition of IBA and MTs to identify potentially critical constituents and found a basis for interpreting environmental behaviour before evaluating leaching characteristics and their suitability for embankment applications.

Table 10 presents the chemical characterisation of IBA, considering different material conditions, including fresh, air-dried, aged, washed, unwashed, and different particle-size fractions. The physicochemical parameters include moisture content, organic matter,

loss on ignition, chlorides, and sulphur, as well as concentrations of various metals and metalloids. The reported parameters are compared with the values commonly observed in natural soils [84], thereby providing a reference framework for contextualising the chemical composition of IBA and identifying potential elemental enrichments.

The data show that IBA has a variable chemical composition, influenced by material condition, washing, ageing conditions, and particle-size distribution. Organic matter values are relatively similar among the reported samples, whereas moisture content and, especially, loss on ignition show greater variability. Chloride concentrations exceed the common range reported for soils, and sulphur exceeds this range in the finer fractions. Among metals, Cu, Pb, and Zn stand out due to their elevated concentrations, frequently exceeding soil reference values. Finer fractions tend to concentrate higher contents of salts and metals, whereas washing clearly reduces the concentrations of several elements, in particular the ones associated to soluble salts. Overall, IBA shows higher concentrations of salts and metals, particularly Cl, Cu, Pb, Zn, Cd, and Hg, but elements such as Cr, Ni, As, and Mn remain within the common ranges reported for soils.

Table 11 presents the chemical characterisation of different MTs in the solid matrix, including materials from tungsten–tin–copper, iron, and sulphidic gold mines and it reveals marked chemical differences among MTs, reflecting the distinct origins of the materials. Tungsten mine tailings [15] stand out due to their very high concentrations of Cu, Zn, and Cd, all of which exceed the common ranges reported for soils, indicating a composition strongly enriched in these elements. In contrast, iron mine tailings [15] show generally low concentrations, with several elements below the limits of quantification and Zn and Mn values within the common ranges reported for soils. Iron tailings [85] also show moderate concentrations, with most reported elements falling within the common soil ranges. Sulphidic gold mine tailings are distinguished mainly by their high S and As contents, both of which exceed the ranges commonly reported for soils, while Cu concentration is slightly above the reference range.

Table 10. Chemical characterisation of IBA solid matrix.

Parameter	[15]	[14]	[14]	[86]	[87]	[87]	[87]	[88]	[88]	[89]	[89]	Soil Range [84]
Material condition	Air-dried	Aged for 3 months	Aged for 12 months	Fresh	Medium	Fine	<1.18 mm	Unwashed	Washed	Fresh	Weathered	—
MC (%)	17.5 ± 1.3	21 ± 2	17 ± 1	13.7 ± 0.30	N.R.	N.R.	N.R.	N.R.	N.R.	N.R.	N.R.	—
OM (%)	3.4 ± 0.9	3.6 ± 0.5	3.4 ± 0.9	3.38 ± 0.09	N.R.	N.R.	N.R.	N.R.	N.R.	N.R.	N.R.	—
LOI (%)	N.R.	N.R.	N.R.	N.R.	6.2	13.3	22.18	8.8–14.25	4.14–5.25	N.R.	N.R.	—
Cl (mg/kg)	N.R.	N.R.	N.R.	N.R.	4290	8890	17,100	N.R.	N.R.	N.R.	N.R.	20–900
S (mg/kg)	N.R.	N.R.	N.R.	N.R.	6070	10,900	16,400	N.R.	N.R.	N.R.	N.R.	20–10,000
Cu (mg/kg)	1323 ± 27	1245 ± 14	1308 ± 47	824 ± 21	1420	3220	3550	114–850	42–112	652–5430	2820–10,600	2–100
Pb (mg/kg)	1107 ± 14	2443 ± 96	1095 ± 32	120 ± 8	416	774	1100	93–683	29–94	1340–1430	870–4970	2–200
Zn (mg/kg)	2877 ± 153	1625 ± 8	2843 ± 106	1624 ± 23	5250	6970	7600	433–1173	84–145	3420–4920	5630–13,600	10–300
Cr (mg/kg)	41 ± 2	25 ± 13	40 ± 2	59.5 ± 14.5	618	853	863	80–169	4.4–70	132–165	125–278	1–1000
Cd (mg/kg)	<0.18	2.9 ± 0.46	7.7 ± 0.46	<3.6	N.R.	N.R.	N.R.	0.4–3	<0.3–0.6	3.13–14.1	4.15–48.9	0.01–0.7
Ni (mg/kg)	45 ± 0.8	35 ± 3	45.0 ± 0.1	22.3 ± 2.9	93	159	218	23–35	16–47	N.R.	N.R.	5–500
Sb (mg/kg)	<2.1	42 ± 8.50	61 ± 7.29	N.R.	N.R.	N.R.	N.R.	1.3–7.6	<0.3–1.4	N.R.	N.R.	—
As (mg/kg)	N.R.	14 ± 1.93	17 ± 3.19	N.R.	N.R.	N.R.	N.R.	1.3–3.4	<0.3–10	3.81–6.32	4.61–16.6	1–50
Hg (mg/kg)	N.R.	8 ± 1.31	9 ± 0.28	N.R.	N.R.	N.R.	N.R.	<QL	<QL	0.2–9.47	<0.2	0.01–0.03
Mn (mg/kg)	646 ± 1	750 ± 0.03	1300 ± 0.05	326 ± 11	N.R.	N.R.	N.R.	74–357	109–371	N.R.	N.R.	20–3000

Note: IBA: Municipal solid waste incineration bottom ash; MC: Moisture content; OM: Organic matter; LOI: Loss on ignition; N.R.: Not reported; “—”: No reference value indicated; QL: Quantification limit.

Overall, the greatest deviations from common soil values occur with tungsten tailings, due to Cu, Zn, and Cd, and in the sulphidic gold tailings, due to S and As. For IBA, composition is strongly influenced by the ageing conditions, washing processes, and the particle-size fraction considered. The tendency for some chemical elements to be more concentrated in the finer fractions suggests a stronger association of these elements with smaller particles, whereas washing appears effective in partially reducing the metal and salt load.

Table 11. Chemical characterisation of MTs solid matrix.

Parameter	[15]	[15]	[85]	[90]	Range for Soil [84]
Material condition	W-Sn-Cu mine tailings; air-dried	Iron mine tailings; air-dried	Iron mine tailings; <200 mesh	Sulphidic gold mine tailings; slurry dried at 105 °C and used as powder	—
MC (%)	0.5 ± 0.1	0.2 ± 0.2	1.55–2.31	N.R.	—
OM (%)	10.8 ± 0.6	0.6 ± 0.01	1.04–1.26	N.R.	—
Cl (mg/kg)	N.R.	N.R.	N.R.	N.R.	20–900
S (mg/kg)	N.R.	N.R.	N.R.	18,900	20–10,000
Cu (mg/kg)	3307 ± 314	<0.34	20	120	2–100
Pb (mg/kg)	58 ± 32	<1.53	9.5	4.3	2–200
Zn (mg/kg)	15,137 ± 2630	41 ± 5	33	71	10–300
Cr (mg/kg)	<0.56	<0.56	29	74	1–1000
Cd (mg/kg)	185 ± 0.9	<0.18	0.066	<0.3	0.01–0.7
Ni (mg/kg)	31 ± 0.05	<0.85	6	100	5–500
Sb (mg/kg)	<2.1	<2.1	N.R.	32	—
As (mg/kg)	N.R.	N.R.	N.R.	1520	1–50
Hg (mg/kg)	N.R.	N.R.	0.003	N.R.	0.01–0.03
Mn (mg/kg)	658 ± 56	418 ± 141	N.R.	N.R.	20–3000

Note: N.R.: Not reported; MC: Moisture content; OM: Organic matter.

4.2.2. Leaching Behaviour

Leaching is the process by which a liquid comes into contact with a solid matrix (also known as solid–liquid extraction), enabling the identification of which chemical species present in the solid may dissolve into the liquid phase. This process is influenced by several key parameters, including pH, contact time, the testing method employed, and the liquid-to-solid ratio (L/S) [91]. The environmental assessment of reused materials or waste through leaching tests is necessary to determine whether the release of pollutants is compatible with environmental conditions. Water is considered the main vector of pollution from waste [92], as leaching can occur following rainfall in materials placed in or on the ground, potentially leading to the contamination of adjacent soils, groundwater, and surface water [93]. The standard method EN 12457-2 [94] is frequently used for conducting leaching procedures in studies reported in the literature, as shown in Tables 12 and 13. This procedure is performed using L/S equal to 10 L/kg, using distilled water under agitation for 24 h. The resulting eluate is then filtered through a 0.45 µm pore-size membrane. But environmental suitability cannot be assessed solely from total elemental composition but should also consider leaching behaviour, ecotoxicity, exposure conditions, pH-dependent release, and the potential for long-term contaminant mobilisation. In the reviewed studies, leaching tests were commonly performed using batch procedures, especially EN 12457-2 or EN 12457-4 [95], often with a liquid-to-solid ratio, L/S, of 10 L/kg. Other procedures, including SPLP, TCLP, and KSLT, were also reported for specific MTs. As these methods simulate different environmental or regulatory exposure scenarios, they do not provide directly comparable results. Batch leaching tests provide short-term equilibrium-type information, whereas SPLP, TCLP, and KSLT represent different extraction conditions and may mobilise different contaminant fractions. Column leaching tests, although less frequently reported in the reviewed literature, may provide more representative information on long-term contaminant release under percolation conditions than batch tests. Therefore, the leaching results reported in this review should be interpreted as comparative indicators of environmental behaviour rather than as directly interchangeable values. The concentrations of potentially toxic metals and ions in the eluates were compared with the European Union

landfill acceptance criteria for inert, non-hazardous, and hazardous waste, in accordance with Council Decision 2003/33/EC [96], as presented in Tables 12 and 13. These criteria are useful reference thresholds for identifying relative levels of concern regarding leaching. However, they were developed for landfill waste acceptance and do not directly represent real reuse conditions in transportation embankments. Therefore, compliance with landfill criteria should not be interpreted alone as proof of suitability for embankment use. Instead, leaching limit values established for waste valorisation should be considered. These limits should be application-specific and reflect the intended conditions of use. However, such criteria are often unavailable. For IBA, the limit values adopted in many EU countries generally exceed the leaching limit values established for inert landfill disposal [9]. Table 12 presents the leaching behaviour of IBA reported in different studies, including fresh and aged materials analysed using different leaching methods.

Table 12. Leaching behaviour of IBA and comparison with EU waste landfill acceptance criteria.

Parameter	[86]	[15]	[14]	[14]	[97]	[98]	[89]	Inert Landfill ^b	Non-Hazardous Landfill ^b	Hazardous Landfill ^b
Material	Fresh IBA	IBA	IBA aged 3 m	IBA aged 1 y	IBA	Aged IBA	IBA	—	—	—
Leaching standard and method	EN 12457-2; L/S = 10 L/kg	EN 12457-2; L/S = 10 L/kg	EN 12457-2; L/S = 10 L/kg	EN 12457-2; L/S = 10 L/kg	EN 12457-2; L/S = 10 L/kg	NaOH 8M/ICP-MS	DIN 38414-4/S4 [99]; L/S = 10 L/kg	—	—	—
pH	11.1 ± 0.13	9.57 ± 0.52	9.0 ± 0.9	9.3 ± 0.7	N.R.	—	8.7–12.7	—	—	—
EC (mS/cm)	3.52 ± 0.09	0.34 ± 0.09	1.2 ± 0.1	0.32 ± 0.09	—	—	—	—	—	—
As (mg/kg)	—	—	0.036 ± 0.004	0.085 ± 0.004	0.01–0.05	6.06–16.77	—	0.5	2	25
Ba (mg/kg)	—	—	0.13 ± 0.001	0.03 ± 0.002	0.24–0.36	196.98–536.79	—	20	100	300
Cd (mg/kg)	<0.18	<0.18	0.0012 ± 0.0002	<0.001	0.01	—	—	0.04	1	5
Cr total (mg/kg)	<0.56	<0.56	0.057 ± 0.001	0.067 ± 0.001	0.08–0.31	10.31–35.65	0.05–0.80 ^a	0.5	10	70
Cu (mg/kg)	19 ± 0.6	<0.34	8.82 ± 0.15	0.93 ± 0.02	1.02–2.61	13.44–77.63	0.20–5.90 ^a	2	50	100
Hg (mg/kg)	—	—	<0.001	0.0013 ± 0.0001	<0.01	0.05–0.28	—	0.01	0.2	2
Mo (mg/kg)	—	—	0.2 ± 0.004	0.073 ± 0.002	0.19–0.25	14.84–18.60	—	0.5	10	30
Ni (mg/kg)	<0.85	<0.85	0.11 ± 0.002	0.017 ± 0.001	0.06–0.10	6.58–9.13	—	0.4	10	40
Pb (mg/kg)	<1.53	<1.53	0.01 ± 0.0002	0.036 ± 0.001	0.05–0.10	133.30–736.89	<0.05–41.0 ^a	0.5	10	50
Sb (mg/kg)	—	—	0.2 ± 0.002	0.18 ± 0.002	0.13–0.35	—	—	0.06	0.7	5
Se (mg/kg)	—	—	<0.03	<0.03	0.02–0.25	—	—	0.1	0.5	7
Zn (mg/kg)	<0.13	<0.13	0.094 ± 0.002	0.15 ± 0.003	0.04–0.51	325.18–4187.92	<0.20–3.70 ^a	4	50	200
Cl [−] (mg/kg)	7149 ± 700	—	423 ± 6	50 ± 8	—	—	1050–25,600 ^a	800	15,000	25,000
SO ₄ ^{2−} (mg/kg)	3988 ± 26	—	281.2 ± 0.3	254 ± 10	—	—	88–9980 ^a	1000	20,000	50,000

Note: ^a Original values in mg/L, converted to mg/kg; ^b Criteria established by Council Decision 2003/33/EC; EC: Electrical conductivity; N.R.: Not reported; “—”: Not applicable; y: Year; m: Month. Landfill criteria are used here only as comparative reference thresholds and do not directly represent field reuse conditions in embankments.

Table 13. Leaching behaviour of MTs and comparison with EU waste landfill acceptance criteria.

Parameter	[40]	[40]	[40]	[15]	[15]	[100]	[100]	[101]	[101]	Inert Landfill ^d	Non-Hazardous Landfill ^d	Hazardous Landfill ^d
Material	IMTs; A	IMTs; B	IMTs; C	TMTs	IMTs	IMTs: IOTs-1	IMTs: IOTs-2	Mn and Zn MTs	Mn and Zn MTs	—	—	—
Leaching standard and method	EN 12457-4; L/S = 10 L/kg	EN 12457-4; L/S = 10 L/kg	EN 12457-4; L/S = 10 L/kg	EN 12457-2; L/S = 10 L/kg	EN 12457-2; L/S = 10 L/kg	SPLP; L/S = 20:1	SPLP; L/S = 20:1	TCLP; L/S = 20:1	KSLT; L/S = 10:1	—	—	—
pH	7.86	7.98	7.92	4.41 ± 0.10	5.11 ± 0.25	4.20 ± 0.05	4.20 ± 0.05	7.5 ± 0.14	7.5 ± 0.14	—	—	—
TDS (mg/kg)	1195 ^b	1335 ^b	1270 ^b	—	—	—	—	—	—	4000	60,000	100,000
EC (mS/cm)	0.239 ^c	0.267 ^c	0.254 ^c	1.26	0.01	—	—	—	—	—	—	—
As (mg/kg)	0.90 ^b	1.20 ^b	1.00 ^b	—	—	0.0421 ^a	0.0588 ^a	8.6 ^b	2.4 ^b	0.5	2	25
Ba (mg/kg)	—	—	—	—	—	—	—	—	—	20	100	300
Cr total/ Cr(VI) (mg/kg)	0.08 ^b	0.12 ^b	0.11 ^b	<0.56	<0.56	0.0159 ^a	0.0193 ^a	8.4 ^b	3.6 ^d	0.5	10	70
Cu (mg/kg)	1.10 ^b	1.30 ^b	1.20 ^b	2.1 ± 0.1	<0.34	0.368 ^a	0.405 ^a	5.8 ^b	0.8 ^b	2	50	100
Hg (mg/kg)	BDL	BDL	BDL	—	—	—	—	—	—	0.01	0.2	2
Ni (mg/kg)	<0.01 ^b	0.02 ^b	<0.01 ^b	8.4 ± 0.1	<0.85	0.0126 ^a	0.0228 ^a	—	—	0.4	10	40
Pb (mg/kg)	0.21 ^b	0.26 ^b	0.24 ^b	<1.53	<1.53	0.0154 ^a	0.0184 ^a	3.0 ^b	1.0 ^b	0.5	10	50
Zn (mg/kg)	3.90 ^b	4.50 ^b	4.30 ^b	866 ± 312	<0.13	1.089 ^a	1.443 ^a	—	—	4	50	200
Cl [−] (mg/kg)	—	—	—	—	—	—	—	200 ^b	200 ^b	800	15,000	25,000
F [−] (mg/kg)	—	—	—	—	—	—	—	1.1 ^b	1.1 ^b	10	150	500
SO ₄ ^{2−} (mg/kg)	—	—	—	—	—	—	—	2240 ^b	2240 ^b	1000	20,000	50,000

Notes: ^a Values originally expressed in µg/L, converted to mg/kg; ^b values originally expressed in mg/L, converted to mg/kg; ^c values originally expressed in S/m, converted to mS/cm; ^d criteria established by Council Decision 2003/33/EC; BDL: Below detection limit; “—”: Not applicable. Landfill criteria are used here only as comparative reference thresholds and do not directly represent field reuse conditions in embankments.

Based on the literature, IBA generally exhibits alkaline behaviour, with pH values ranging from 8.7 to 12.7. Fresh IBA typically tends to present higher pH and electrical conductivity (EC) reflecting a greater content of soluble salts and readily leachable species. With ageing, both parameters tend to decrease, indicating a lower leaching potential. Ageing contributes to reducing the leaching of several parameters, including Cu, Ba, Mo, Ni, Cl[−], and SO₄^{2−}. In the study of Bandarra et al. [14], Cu decreased from 8.82 ± 0.15 mg/kg after 3 months to 0.93 ± 0.02 mg/kg after 1 year, thereby meeting the inert landfill limit. Cl[−] and SO₄^{2−} values also decreased after ageing. Some parameters still remain above the inert landfill limit, but below the non-hazardous landfill limit (e.g., Sb). In fresh IBA, Cu, Cl[−], and SO₄^{2−} are the main parameters exceeding the inert landfill criteria, without exceeding the limits for non-hazardous waste landfills.

Table 13 lists the leaching behaviour of various MTs, considering physicochemical parameters, metals, metalloids, and anions, as well as their comparison with landfill acceptance criteria for inert, non-hazardous, and hazardous waste. The data include materials from different studies and leaching tests, with different L/S ratios and standards, allowing the variation in element mobility to be assessed according to the test conditions.

MTs exhibit markedly different leaching behaviours. Among the studies using EN 12457 procedures, the samples analysed by Mahapatra and Jayanthu [40] display pH

values close to neutrality and generally low concentrations of leached species. However, considering the inert landfill limit, As exceeds the threshold, whereas Zn concentrations in samples B and C only slightly exceed the limit. Likewise, the iron ore tailings and tungsten tailings analysed by Monteiro et al. [15] using EN 12457-2 present acidic pH but different leaching behaviours. The tungsten mine tailings [15] represent the most critical case, due to elevated concentrations of Cd, Ni, and especially Zn, with Zn exceeding the hazardous landfill limit. In contrast, iron ore tailings present several elements below detection limits [15]. Studies using other leaching procedures showed different trends. The iron ore tailings analysed by Wang et al. [100] using SPLP exhibited generally low concentrations of leached constituents. The Mn and Zn mine tailings analysed by Lee et al. [101] using TCLP and KSLT display near-neutral but still relevant concentrations of As, Cd, and sulphate. Indeed, sulphate concentration also exceeds the inert landfill limit, although it remains below the non-hazardous landfill limit. Because these procedures simulate different exposure scenarios and extraction conditions, their results should be interpreted as complementary indicators of environmental behaviour rather than directly compared with those obtained using EN 12457 methods.

Comparing both materials, IBA and MTs exhibit distinct leaching behaviours, which influence their suitability for use in transportation infrastructure embankments. IBA are generally alkaline, and their leachability tends to decrease with ageing, particularly for Cu, Cl^- , SO_4^{2-} , Ba, Mo, and Ni. However, fresh IBA may exceed the inert landfill limits for Cu, Cl^- , and SO_4^{2-} but, below the non-hazardous landfill limits, MTs show greater heterogeneity, with pH ranging from acidic to near-neutral, reflecting differences in mineralogical and chemical composition. Some materials show low leaching and comply with inert landfill criteria, whereas others exhibit relevant concentrations, especially for Zn, As, Cd, and SO_4^{2-} . Thus, aged IBA and low-leaching MTs offer greater environmental potential for valorisation in transportation embankments. Nevertheless, the environmental suitability of these materials should also consider field exposure conditions, including rainfall infiltration, groundwater contact, wetting–drying cycles, carbonation, sulphide oxidation, acid mine drainage potential, and long-term contaminant mobility, as these processes may significantly influence contaminant release over time.

4.2.3. Ecotoxicity Assessment

Ecotoxicity tests complement chemical characterisation by enabling the detection of biological effects that may be overlooked or underestimated when assessments are based solely on the total concentrations of hazardous substances [102]. The application of bioassays to eluates obtained from leaching tests is particularly relevant, as it captures the combined effects of leachable substances, including possible transformation products, while accounting for factors such as bioavailability and interactions between contaminants [83,103]. Therefore, the use of a battery of bioassays with organisms from different trophic levels is recommended, as these organisms may respond differently to the same sample [104]. The literature reports some studies on the ecotoxicological assessment of IBA, including investigations aimed at its ecotoxicological classification. In contrast, studies specifically focused on mine tailings remain relatively limited. Results are also available for mixtures of IBA with mine tailings, although these remain scarce.

Table 14 summarises the main results of ecotoxicological tests performed with eluates from IBA, eluates from mixtures of IBA with mine tailings, and solid mine tailings. The reported bioassays cover organisms from different trophic and functional levels, including bacteria, microalgae, macrophytes, microcrustaceans, higher plants, and terrestrial invertebrates. The inclusion of organisms from both aquatic and terrestrial compartments provides a broader view of the ecotoxicity potential of materials.

The available studies indicate that aged IBA generally induced inhibitions below 50% across the different endpoints assessed. Consequently, in several cases, the median effect concentration (EC₅₀), defined as the concentration causing a 50% effect or inhibition in the tested organism or endpoint, could not be estimated.

When EC₅₀ values were reported for aged IBA, they generally did not indicate ecotoxicity according to the frequently recommended EC₅₀ ≤ 10% threshold for waste ecotoxicity assessment [105–107]. For instance, *A. fischeri* exhibited EC₅₀ values > 100%, *D. magna* showed EC₅₀ values of 18–29%, and seed germination did not display a clear dose–response relationship [108]. Similarly, IBA aged for 3 or 12 months produced inhibitions below 50% in assays with *A. fischeri*, *R. subcapitata*, *L. minor*, *D. magna*, and *L. sativum* [14,84], while IBA aged for 12 months caused only 12.5% maximum inhibition in the *A. fischeri* bioluminescence assay [15]. These findings suggest low ecotoxicological effects for aged IBA under the specific experimental conditions applied. In contrast, Lapa et al. [109] reported more variable responses for IBA eluates, with EC₅₀ values ranging from <1% to >99% for *P. phosphoreum*, 2.3–25.7% for *R. subcapitata*, and 1.2% to >99% for *D. magna*, whereas *L. sativa* seed germination showed EC₅₀ values > 100%. These results indicate that some IBA eluates may induce relevant aquatic ecotoxicological effects, particularly under testing conditions associated with more alkaline eluates, with pH values of 8.9–12.5. Such conditions are more representative of fresh IBA, as aged IBA typically exhibits pH values closer to neutrality. Nevertheless, the sample with the lowest pH induced the lowest inhibition and did not cause relevant ecotoxic effects.

Table 14. Ecotoxicological test results following exposure to eluates prepared from IBA and mixtures of IBA with MTs (EN 12457-2), as well as to solid MTs.

Ref.	Material	Bioassay	Ecotoxicological Test Results
[109]	IBA	Bioluminescence inhibition with <i>Photobacterium phosphoreum</i> (ISO 11348-3 [110]) Growth inhibition with <i>Raphidocelis subcapitata</i> (ISO 8692 [111]) Mobility inhibition of microcrustaceans with <i>Daphnia magna</i> (ISO 6341 [112]) Seed germination inhibition with <i>Lactuca sativa</i> (AFNOR X31-201 [113])	EC ₅₀ (%): <1–>99 EC ₅₀ (%): 2.3–25.7 EC ₅₀ (%): 1.2–>99 EC ₅₀ (%): >100
[108]	Aged IBA	Seed germination of <i>Trifolium repens</i> Bioluminescence inhibition with <i>Aliivibrio fischeri</i> (ISO 11348-3) Mobility inhibition of <i>Daphnia magna</i> (ISO 6341)	EC ₅₀ no dose–response relationship EC ₅₀ (%): >100 EC ₅₀ (%): 18–29
[86]	IBA aged for 3 months	Bioluminescence inhibition with <i>A. fischeri</i> (ISO 11348-2) Growth inhibition of <i>R. subcapitata</i> (OECD 201 [114]) Growth inhibition of macrophytes with <i>Lemna minor</i> (OECD 221 [115]) Mobility inhibition of <i>D. magna</i> (OECD 202 [116]) Seed germination and root growth inhibition with <i>Lepidium sativum</i> (ISO 18763 [117])	Inhibition < 50% Inhibition < 50% Inhibition < 50% Inhibition < 50% Inhibition < 50%
[15]	IBA aged for 12 months	Bioluminescence inhibition with <i>A. fischeri</i> (ISO 11348-2)	Max. Inhibition: 12.5%
[14]	IBA aged for 3 months	Bioluminescence inhibition with <i>A. fischeri</i> (ISO 11348-2) Growth inhibition of <i>R. subcapitata</i> (OECD 201) Growth inhibition of <i>L. minor</i> (OECD 221) Immobilisation of <i>D. magna</i> (OECD 202)	Inhibition < 50% Inhibition < 50% Inhibition < 50% Inhibition < 50%
	IBA aged for 12 months	Seed germination and root growth inhibition of <i>L. sativum</i> (OECD 202) Bioluminescence inhibition of <i>A. fischeri</i> (ISO 11348-2) Growth inhibition of <i>R. subcapitata</i> (OECD 201) Growth inhibition of <i>L. minor</i> (OECD 221) Immobilisation of <i>D. magna</i> (OECD 202) Seed germination and root growth inhibition of <i>L. sativum</i> (OECD 202)	Inhibition < 50% Inhibition < 50% Inhibition < 50% Inhibition < 50% Inhibition < 50% Inhibition < 50%
[15]	90% IBA + 10% IMTs 90% IBA + 10% TMTs	Bioluminescence inhibition with <i>A. fischeri</i> (ISO 11348-2) Bioluminescence inhibition with <i>A. fischeri</i> (ISO 11348-2)	Max. Inhibition: 26.2–27.4% Max. Inhibition: 17.7–22.2%
[118]	FGMTs mixed with soil CGMTs mixed with soil	Acute toxicity with earthworms <i>Eisenia andrei</i> (ISO 11268-2 [119]) Avoidance with <i>E. andrei</i> (ISO 17512-1 [120]) Acute toxicity with <i>E. andrei</i> (ISO 11268-2) Avoidance with <i>E. andrei</i> (ISO 17512-1)	EC ₅₀ (%): >50 EC ₅₀ (%): >50 EC ₅₀ (%): 23.1 EC ₅₀ (%): 8.4
[121]	IIMTs	Inhibition of reproduction with <i>F. candida</i> (NBR ISO 11267 [122]) Effects on reproduction with <i>E. crypticus</i> (ISO 16387 [123]) Emergence and early growth with <i>A. Strigose</i> (ISO 11269-2 [124]) Emergence and early growth with <i>Brassica rapa</i> (ISO 11269-2)	EC ₅₀ (%): 89–94 EC ₅₀ (%) > 100 EC ₅₀ (%) > 100 EC ₅₀ (%) > 76

Notes: IBA: Incineration bottom ash; EC₅₀: Effective concentration causing 50% effect or inhibition in the tested organism or endpoint; OECD: Organisation for Economic Cooperation and Development; FGMTs: Flotation gold mine tailings; CGMTs: Cyanidation gold mine tailings; ISO: International Organization for Standardization; AFNOR: Association Française de Normalisation; Max: Maximum; NBR ISO: Brazilian standard based on ISO methodology; IMTs: Iron mine tailings; TMTs: Tungsten mine tailings.

Mixtures containing 90% IBA and 10% iron mine tailings or tungsten mine tailings also showed maximum inhibitions below 50% in the *Aliivibrio fischeri* bioluminescence inhibition assay, with values of 26.2–27.4% and 17.7–22.2%, respectively [15]. This suggests a low ecotoxicological effect for these IBA–tailings mixtures under the tested conditions. In contrast, mine tailings exhibited more heterogeneous responses. Flotation gold mine tailings showed EC_{50} values $>50\%$ in earthworm acute toxicity and avoidance assays, whereas cyanidation gold mine tailings caused stronger effects, particularly in the avoidance assay with *Eisenia andrei*, for which an EC_{50} of 8.4% was reported, falling within the ecotoxic range according to the $EC_{50} \leq 10\%$ criterion [118]. Iron ore tailings showed comparatively low toxicity in terrestrial assays, with EC_{50} values of 89–94% for *Folsomia candida* reproduction and $>76\%$ to $>100\%$ for the remaining tested endpoints [121]. Overall, the low ecotoxicological effects reported for aged IBA and for some IBA with tailings mixtures should not be interpreted as conclusive evidence of environmental safety. A case-by-case assessment remains necessary, particularly for individual tailings and for IBA samples exhibiting variable leaching behaviour. Moreover, both aquatic and terrestrial compartments should be evaluated under leaching or exposure scenarios representative of their intended use in transportation infrastructure embankments.

Overall, from an environmental perspective, IBA and MTs show distinct behaviours and should be assessed through an integrated approach that considers chemical composition, leaching behaviour, and ecotoxicological response. IBA generally contains elevated levels of salts and metals, particularly Cl, Cu, Pb, Zn, Cd, and Hg, with finer fractions concentrating higher contaminant contents. However, ageing reduces their leaching potential, especially for Cu, Cl^- , SO_4^{2-} , Ba, Mo, and Ni, improving their environmental performance. Even so, Sb in aged IBA and Cu, Cl^- , and SO_4^{2-} in fresh IBA may remain critical, as they can exceed inert landfill acceptance criteria while generally remaining below non-hazardous landfill limits. Ts are more heterogeneous and their environmental behaviour depends strongly on tailing origin and mineralogical composition. Tungsten and sulphidic gold mine tailings may contain high concentrations of potentially toxic elements, such as Cu, Zn, Cd, As, and S, and may show significant leaching, whereas some iron ore tailings present low leaching potential and may comply with inert landfill criteria. Therefore, MTs require case-by-case assessment rather than generalised classification. Ecotoxicological results suggest that aged IBA and mixtures containing 90% IBA and 10% MTs generally have low ecotoxicological effects under the tested conditions, with inhibitions mostly below 50%. Nevertheless, alkaline IBA eluates and specific MTs, such as cyanidation gold mine tailings, may induce relevant ecotoxic effects. Accordingly, aged IBA and environmentally stable MTs show the greatest potential for valorisation in transportation infrastructure embankments, provided that their environmental suitability is experimentally verified.

4.3. Overview of the Potential of IBA and MTs for Zone Embankment Construction

The results presented in Sections 4.1 and 4.2 prove that the use of inorganic wastes in transportation infrastructure embankments requires an integrated assessment of both geotechnical and environmental performance. This is particularly relevant for zoned embankments, where each zone has specific functional requirements and different levels of environmental exposure (Figure 1). Therefore, material selection should consider not only mechanical behaviour but also the environmental sensitivity of each zone, especially water accessibility. Landfill acceptance criteria were used only as a screening reference, because they were developed for waste acceptance at landfills and do not directly represent real reuse conditions in transportation embankments. Therefore, compliance with landfill criteria was not interpreted as automatic approval for reuse, and exceedance of inert criteria was not interpreted as automatic rejection. A qualitative classification system was

adopted to compare the reviewed materials. The proposed ratings do not correspond to fixed numerical thresholds but instead represent a qualitative synthesis of the reviewed literature, and they are not intended to replace the systematic testing required for these or other comparable materials. They were assigned considering the overall consistency of the reported geotechnical and environmental performance, together with the relative suitability of each material for transportation embankment applications in comparison with the performance typically required from conventional embankment materials. Accordingly, +++ = very good; ++ = good; + = acceptable; 0 = poor; and N.A. = not available or not applicable. Aged IBA showed the best overall performance, mainly due to its predominantly granular behaviour, low plasticity, good compactability, low to moderate compressibility, high shear strength and very high CBR. In addition, ageing reduces the leaching of several elements. IMTs showed high solid particle density, good compactability and high shear strength and CBR; however, its finer particle-size distribution reduces its suitability for structurally demanding zones. TMTs showed relevant geotechnical potential, particularly due to its low plasticity, high solid particle density and good compactability. Nevertheless, its lower permeability and critical leaching behaviour significantly reduces its environmental suitability. Table 15 summarises the geotechnical and environmental potential of the three wastes for use in transportation infrastructure embankments.

Table 15. Potential of inorganic wastes for the construction of transportation infrastructure embankments.

Properties	Aged IBA	IMTs	TMTs
Geotechnical properties			
Physical properties	+++	++	+
Compactability	+++	+++	++
Compressibility	+++	++	++
Shear strength	+++	++	++
Permeability	+++	++	+
CBR	+++	++	N.A.
Geotechnical performance	+++	++	+
Environmental properties			
Leaching behaviour	+++	++	0
Ecotoxicity	+++	++	N.A.
Environmental performance	+++	++	0

Notes: +++ = very good; ++ = good; + = acceptable; 0 = poor; N.A. = not available in the literature. The ratings represent a qualitative synthesis of the reviewed literature considering the overall geotechnical and environmental performance of each material and its relative suitability for transportation embankment applications. They do not represent fixed numerical thresholds or design criteria.

Considering the functional logic of zoned embankments, the foundation (A) and superstructure (S) were not considered direct waste-placement zones. The core (B) is the most favourable zone for the valorisation of these materials, as it represents the largest embankment volume and is less exposed to water infiltration, drying and erosion. In contrast, the shoulders (C), transition layer (D) and capping layer (L) are more sensitive zones, either because they are more exposed to environmental actions or because they require materials with higher stiffness, lower deformability, low plasticity, adequate bearing capacity and sufficient drainage. Therefore, materials with higher environmental risk or lower geotechnical quality should preferably be placed in the core, whereas transition and capping layers should only incorporate materials with better geotechnical performance. Table 16 summarises the geotechnical and environmental potential of the three wastes for use in zoned embankments. The proposed potential of each material for each specific location in the zoned embankment is based on a qualitative assessment of the results presented in Table 15 and are not intended to replace the case specific analysis to be carried

out by the designer based on specific experimental data. In real applications, the assessment of each material should consider geotechnical and environmental suitability altogether.

Table 16. Inorganic wastes for applications in zoned embankments.

Embankment Zone	IBA– Geotechnical	IMTs– Geotechnical	TMTs– Geotechnical	IBA– Environmental	IMTs– Environmental	TMTs– Environmental
A—Foundation	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
B—Core	+++	++	++	++	++	+
C—Shoulders	++	+	+	++	+	+
D—Transition layer	++	+	+	+	+	0
L—Capping layer	+	0	0	+	+	0
S—Superstructure	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.

Notes: +++ = very high suitability; ++ = high suitability; + = moderate suitability; 0 = low suitability. The suitability ratings were established considering the qualitative performance assessment presented in Table 15 together with the functional requirements and environmental exposure conditions of each embankment zone; N.A.—not applicable.

Overall, aged IBA is the most promising material for zoned embankment construction, particularly for the core and, with adequate environmental control, also for more demanding zones. IMTs may be used mainly in less critical zones, due to their larger variability and lower CBR values. TMTs show geotechnical potential in protected zones, but their low permeability and environmental limitations restrict its direct use without treatment, stabilisation or encapsulation. Thus, application of these wastes should follow the zoning principle: materials with better performance and lower environmental risk should be prioritised in exposed or structurally demanding zones, while materials with more limited performance should be restricted to internal and less critical zones of the embankment. Given that both IBA and MTs are highly dependent on their origin, composition, and processing history, their suitability should always be verified on a case-by-case basis through integrated geotechnical and environmental assessment.

The proposed zoned approach does not necessarily imply direct contact between different waste materials, as their placement and separation depend on the specific embankment design and may include conventional geomaterials, transition layers, drainage layers, geosynthetics, or other engineering measures.

5. Forthcoming Developments

Despite the apparent technical and environmental potential of IBA and MTs for transportation infrastructure embankments, their large-scale application still requires validation under representative field conditions.

Most of the available data result from laboratory tests, frequently carried out under controlled conditions that do not fully reproduce the variability of in situ environmental conditions, compaction, preferential flows, infiltration, load cycles, material ageing, and the evolution of leaching behaviour. Full-scale studies are relevant to the simultaneous monitoring of mechanical and environmental performance, including leachate quantity and quality, flow patterns, and the influence of surface covers [125,126]. From a mechanical point of view, Spreadbury et al. [46] showed that moisture content can significantly control resilient modulus and permanent deformation, reinforcing the need for moisture control during and after construction. Thus, future studies should include pilot embankments or instrumented physical models, with monitoring of deformations, water content, suction, pore pressures, permeability, leachates, and response to loading.

The use of these wastes in zoned embankments constitutes a particularly promising approach. Instead of assuming a homogeneous application, wastes should be placed in zones compatible with their geotechnical and environmental performance. Materials with better

mechanical behaviour and environmental safety may be used in more structurally demanding and/or exposed zones, while materials with greater environmental requirements and poorer mechanical behaviour should be confined to internal zones, protected by soil layers, drainage systems, or sandwich-type configurations. This is particularly important when building embankments with unconventional materials, such as IBA and MTs, which show considerably variable and sometimes substandard mechanical and environmental characteristics, as previously shown. This approach is consistent with the principle of assigning lower-quality natural soils to less critical zones of the embankment and with the possibility of intercalating wastes and conventional soils to reduce risks of erosion, leaching, and direct exposure to water [21,23]. However, research is still needed on interfaces between layers, hydraulic compatibility, differential settlements, contaminant transport, the efficiency of confinement systems, and potential geochemical interactions between different waste materials, particularly when direct contact occurs. Such interactions may include acid–base neutralisation, secondary mineral precipitation, and changes in contaminant mobility, with possible implications for hydraulic and long-term environmental performance.

The effects of extreme events associated with climate change should also be incorporated into future assessment criteria. Intense precipitation, floods, prolonged droughts, and wetting and drying cycles may simultaneously alter stability, deformability, permeability, and contaminant mobility. Johnston et al. [127] have highlighted that research on conventional embankments subjected to floods is still mainly focused on isolated events, with limited understanding of the effects of repeated flooding and progressive degradation of strength. For mine tailings, physical models with wetting–drying cycles demonstrate the relevance of cracking, the evolution of water content, preferential oxidation pathways, and leachate quality [128].

Additionally, cyclic and dynamic performance should be more systematically investigated. Future studies should report resilient modulus, cumulative permanent deformation, shear modulus degradation, cyclic stress ratio, cyclic resistance ratio, excess pore-pressure ratio and number of cycles to failure. These parameters should be measured under representative density, moisture, saturation and drainage conditions. However, this is particularly relevant for transition layers, capping layers, and upper embankment zones, where traffic-induced stresses are higher, although these applications are outside the scope of the present study.

Beyond technical and environmental performance during the use phase, future research should also address broader sustainability aspects related to the use of IBA and MTs in transportation embankments. These include life cycle assessment, transport distances, pre-treatment requirements, replacement rates of natural aggregates, potential benefits for decarbonization, economic feasibility, regulatory constraints, and barriers to large-scale implementation. Such assessments should be performed on a case-specific basis, as these aspects strongly depend on local conditions, material characteristics, and project requirements.

Future work should also evaluate pH-dependent leaching, percolation leaching, carbonation, sulphide oxidation, wetting–drying cycles, freeze–thaw cycles, ageing, redox evolution and long-term contaminant mobility.

In addition, biotests consider bioavailability, component interactions, and exposure pathways, providing a relevant approach by which to analyse potential environmental impacts, and when conducted with leachates and material obtained from physical models and full-scale tests allow one to evaluate ecotoxicity under real conditions in the field. This may show that laboratory results cannot always be directly extrapolated to field scenarios, where dilution, accumulation, and exposure pathways may alter environmental risk [128,129]. Therefore, future research should move towards an integrated and risk-

based assessment, combining geotechnical performance, hydraulic behaviour, leaching, ecotoxicity, durability, and field monitoring. This approach will make it possible to define more robust criteria and evaluate more properly the technical and environmental performance of materials towards the safe valorisation of IBA and mine tailings in transportation infrastructure embankments.

6. Conclusions

The extensive data reviewed in this paper indicate that IBA and selected MTs have potential for use as secondary geomaterials in transportation infrastructure embankments, contributing to the reduction of natural aggregate consumption and to the large-scale valorisation of inorganic waste. However, their application should not be seen as a generalised replacement for conventional materials, but rather as a solution governed by the geotechnical, hydraulic, and environmental performance of each material.

Among the materials analysed, IBA showed the most consistent potential. In general, aged and properly processed IBA exhibits predominantly granular behaviour, adequate compactability, moderate compressibility and satisfactory shear strength when properly compacted, with bearing capacity compatible with embankment applications. Nevertheless, its use requires prior characterisation, as its properties depend on origin, ageing degree, particle-size fraction, and pre-treatment processes. From an environmental perspective, although ageing may contribute to reducing pH and leaching potential, the mobility of soluble salts, metals, and metalloids must be assessed before application.

MTs exhibited more variable behaviour and should therefore not be treated as a single material category. Some iron and tungsten tailings may present favourable geotechnical properties, including high dry density, good compactability, adequate strength, and controlled deformability. Under specific conditions, these materials may be considered for internal or less critical embankment zones. However, fine, plastic, low-permeability, or chemically reactive tailings may present important limitations related to drainage, settlement, bearing capacity, release of potentially toxic elements, and/or acid drainage generation.

Therefore, the use of these materials should follow a zoned embankment approach. Materials with better mechanical performance and lower environmental risk may be placed in zones with higher functional requirements, whereas materials with poorer performance or greater environmental uncertainty should be restricted to internal, protected, or encapsulated zones. In such cases, appropriate hydraulic control, drainage, cover, or isolation measures should be adopted to reduce water contact and limit contaminant mobilisation.

Overall, IBA and selected MTs may contribute to more sustainable transportation infrastructure, provided that their suitability is assessed on a case-by-case basis through integrated geotechnical and environmental evaluations, given that both materials are highly source-dependent. Their application should be supported by appropriate criteria for characterisation, design, construction, and monitoring. Future research should prioritise pilot embankments, full-scale field trials, and instrumented models to validate the mechanical, hydraulic, and environmental behaviour of these materials under real service conditions and over time.

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Abbreviations

The following abbreviations are used in this manuscript:

AMD	Acid mine drainage
Au–Cu	Gold–copper
CBR	California bearing ratio
CD	Consolidated drained
CH	High-plasticity clay
CL	Low-plasticity clay
CL-ML	silty clay
CU	Consolidated undrained
DIN	Deutsches Institut für Normung
EC	Electrical conductivity
EC ₅₀	Effective concentration causing 50% effect or inhibition
EN	European Standard
EU	European Union
GP	Poorly graded gravel
Gs	Specific gravity of solids
GW	Well-graded gravel
GW-GC	Well-graded gravel with clay
IBA	Municipal solid waste incineration bottom ash
ICP-MS	Inductively coupled plasma mass spectrometry
IMTs	Iron mine tailings
ISO	International Organization for Standardization
KSLT	Korean standard leaching test
LL	Liquid limit
LOI	Loss on ignition
L/S	Liquid-to-solid ratio

MC	Water content
MH	Elastic silt
ML	Silt
MPC	Modified Proctor compaction
MSW	Municipal solid waste
MTs	Mine tailings
NBR ISO	Brazilian standard based on ISO methodology
N.R.	Not reported
OECD	Organisation for Economic Co-operation and Development
OM	Organic matter
PI	Plasticity index
PL	Plastic limit
SC	Clayey sand
SM	Silty sand
SM-SC	Silty sand with clay
SP	Poorly graded sand
SPC	Standard Proctor compaction
SPLP	Synthetic precipitation leaching procedure
SP-SM	Poorly graded sand with silt
SW	Well-graded sand
SW-SM	Well-graded sand with silt
TCLP	Toxicity characteristic leaching procedure
TDS	Total dissolved solids
TMTs	Tungsten mine tailings
USCS	Unified soil classification system
W–Sn–Cu	Tungsten–tin–copper
C_c	Coefficient of curvature
C_c	Compression index
C_r	Recompression index
C_s	Swelling index
C_u	Coefficient of uniformity
C_v	Coefficient of consolidation
D_r	Relative density
d_p	Particle diameter
e_0	Initial void ratio
e_f	Final void ratio
k	Coefficient of permeability
p'_0	Initial mean effective stress state
S	Degree of saturation
S	Superstructure (in the context of Figure 1)
w_{opt}	Optimum water content
$\gamma_{d,max}$	Maximum dry unit weight
Δe	Variation in void ratio
σ_n	Total normal stress
σ'_n	Effective normal stress
σ_3	Confining stress
σ'_3	Effective confining stress
τ_f	Shear stress at failure
ϕ'	Effective friction angle
c'	Effective cohesion

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