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Posted Date: 19 December 2025

doi: 10.20944/preprints202512.1785.v1

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Review

Mining Waste as a Resource in Construction: Applications, Benefits, and Challenges

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Abstract

Mining activities generate vast quantities of waste each year, including mine tailings, bauxite residue, waste rock, and various metallurgical slags. Although these materials have traditionally been regarded as environmental liabilities, many possess physical and chemical properties that make them promising candidates for use in construction. This review synthesizes recent research on the utilization of major mining waste streams, with particular emphasis on pavement applications and other construction materials. The findings indicate that bauxite residue exhibits both pozzolanic and filler characteristics, demonstrating potential in asphalt mastics, asphalt mixtures, and other construction products. Nonetheless, its widespread adoption is constrained by issues such as high alkalinity, leaching risks, and concerns related to naturally occurring radioactivity. Mine tailings can substitute for fine aggregates and cement in a range of mixtures, though challenges including pronounced material variability and environmental risks persist. Waste rock offers favourable geotechnical properties for use in road bases and embankments, while metallurgical slags (e.g., copper, nickel, and lithium slags) provide functional pozzolanic activity and suitable aggregate qualities. Across all waste types, their incorporation into construction materials can conserve natural resources, reduce material costs, and support circular-economy and low-carbon development objectives. However, progress remains contingent upon advancements in material standards, pretreatment technologies, environmental protection measures, and large-scale field validation. Overall, this review underscores both the significant potential and the practical challenges associated with transforming mining waste into valuable and sustainable construction resources.

Keywords: bauxite residue; circular economy; Mine tailings; mining waste; pavement materials; slags; supplementary cementitious materials (SCMs); sustainable construction; waste rock

1. Introduction

The global mining industry is one of the largest generators of industrial waste, producing an estimated over 100 billion tonnes of waste each year, including mine tailings, waste rock and overburden, bauxite residue, and slags [1]. As global demand for minerals continues to rise and ore grades decline, waste volumes are expected to grow, leading to a significant increase in waste generation and creating long-term challenges for health and safety, environmental protection, and land use. More than 90% of solid mine waste is disposed of in waste dumps or long-term storage facilities, with only a small percentage currently being reused [2]. These waste materials often pose complex environmental and social challenges, including tailings dam failures, groundwater contamination, dust pollution, and long-term landscape damage.

In response to these issues, there is a growing drive to reposition mining waste as a valuable secondary resource, particularly within the construction industry. This approach aligns with the concept of the circular economy [3] and global ambitions to achieve net-zero emissions. By incorporating mining waste into construction materials, industries can reduce the extraction of natural aggregates, reducing landfill burden, lowering carbon emissions, and decreasing the footprint of long-term waste storage [4,5]. Among these opportunities, pavement construction stands

out because road bases, subgrades, and bitumen and asphalt mixes can accommodate large quantities of mining residues. Beyond pavement engineering, researchers are also investigating the use of these materials in concrete, geopolymers, bricks, and ceramic products, though suitability and performance vary depending on the type and characteristics of each waste.

This review examines four major mining waste streams—mine tailings, bauxite residue (red mud), waste rock and overburden, and metallurgical slags generated from copper, nickel, and lithium processing. Particular emphasis is placed on their emerging potential in pavement engineering, followed by an assessment of their wider applications in construction materials. Unlike previous reviews that typically address individual waste types or focus on isolated applications, this paper provides a comprehensive, comparative synthesis that integrates material properties, engineering performance, environmental considerations, and practical implementation challenges across all four waste categories. The novelty of this review lies in its multidisciplinary perspective: it consolidates scattered findings from materials science, pavement engineering, and environmental assessment to identify cross-cutting principles that govern the safe and effective utilization of mining waste in construction. By systematically evaluating both the shared and unique behaviours of these waste streams, the review highlights their respective advantages, limitations, and knowledge gaps. It also outlines the critical technical, regulatory, and environmental considerations necessary to enable large-scale, sustainable adoption within the construction industry. Overall, this work offers a unified framework that not only clarifies the state of current research but also advances understanding of how diverse mining wastes can be strategically repurposed to support resource efficiency, circular-economy transitions, and low-carbon construction pathways.

2. Methodology

This review used a structured literature review to evaluate the use of mining waste materials in the construction industry and their benefits and challenges. Relevant peer-reviewed journal articles, technical standards, and conference papers from 2015 to 2025 were sourced using the ECU online library and academic databases such as Scopus, Web of Science, Google Scholar, and ScienceDirect. Combination of keywords “ mining waste”, “bauxite residue”, pavement engineering”, “construction”, “mine tailing”, “waste rock”, “overburden”, “slags”, “Lithium”, “Copper”, and “Nickel” were used to search, nearly 180 publications were selected based on their relevance, experimental detail, and applicability of assessing the performance, benefits, and challenges of mining waste utilization. The articles were manually screened to ensure authenticity and confirm their relevance to the selected mining waste topics, including global generation, properties of mining waste, asphalt and asphalt mixture modification and performance, applications in other construction industries, benefits and challenges, and to avoid duplication and non-peer-reviewed studies.

3. Mine Tailings

3.1. Mine Tailing Global Generation

Mine tailings are a type of mine waste produced during the mineral beneficiation process. They are typically produced from mills and may consist of aqueous solutions from slurries or cyaniding of finely ground particles, which contain dissolved heavy metals and hazardous chemical reagents [6]. In the tens of billions of tonnes annually, tailings form the finely ground material remaining after ore processing. While specific global numbers are less uniformly reported, much research indicates tailings volume is enormous and often poses storage and environmental risk due to fine particle size and chemical content [7]. The quantity of tailings generated is also dependent on the quality of ore, the type of material extracted, and the extraction process [8]. Hence, there is an increasing interest in recycling and utilizing mine tailings more effectively and sustainably. Its utilization as a construction material will contribute to eco-friendly production, resource conservation, economic design, improved durability of infrastructures, and reduced carbon footprint of the construction industry.

3.2. Properties of Mine Tailings

The properties of mine tailings reported across several studies are summarized in Table 1. A typical particle-size distribution of tailings shows that they can be categorized into silt-size, clay-size, and sand-size fractions, making them suitable for various construction applications. This particle size distribution is dependent on ore type and extraction process [9]. For instance, fine-grained tailings (such as copper or gold flotation) often have 80% of particles below 37 μm , while coarser tailings (such as iron ore) can have over 60% above 74 μm [9]. Tailings have a rather rough surface, as the grindability of the various mineral phases in the tailings is different [10]. They possess a density greater than 2 g/m^3 .

The chemical composition of several mine tailings studied across several research is depicted in Table 1. The Table depicts a considerable variation in chemical composition across the different tailing types. Nonetheless, they are characteristically rich in SiO_2 , Al_2O_3 , CaO and Fe_2O_3 , making them potential materials in construction industry [11]. The mineralogy composition of mine tailings mostly consists of Quartz, Kaolinite, Calcite, and Muscovite [8].

Generally, tailing properties such as physical, chemical, and mineralogical composition are important factors that greatly impact their performance as construction materials. These compositions also depend on the ore type, geographical location, and ore extraction process. Furthermore, their composition offers valuable insights necessary to evaluate them for different construction applications.

Table 1. Chemical and Physical Properties of Mine Tailings.

Properties	Tailings								
	Manganese	Iron	Gold	Copper	Bauxite	Molybdenum	Tungsten	Graphite	Coal gangue
CaO	0.11	4.56	5.92	6.75	2.21	3.362	-	-	0.29
SiO_2	46.95	66.70	41.08	49.24	27.64	71.842	44.83	23.52	50.42
Al_2O_3	34.10	8.06	14.76	21.19	32.61	11.472	18.39	2.28	46.11
Fe_2O_3	7.33	9.52	13.04	6.63	20.65	1.853	11.85	55.30	0.56
SO_3	0.40	-	2.76	3.34	0.69	-	10.94	-	0.01
P_2O_5	0.17	0.43	-	-	1.77	-	-	-	0.51
MgO	-	5.28	2.40	1.47	-	-	-	-	0.10
MnO	14.95	-	2.02	1.47	0.019	0.047	-	-	-
K_2O	0.98	2.53	10.79	9.02	0.018	7.32	3.62	-	0.23
Ref.	[12]	[13]	[14]	[15]	[16]	[17]	[18]	[19]	[20]
Density (g/m^3)	2.95	2.95	2.75	2.87	3.12	2.64	2.89	2.94	2.27
Water absorption (%)	-	1.2	-	0.3	-	0.24	0.18	-	-
Ref.	[12]	[21]	[14]	[15]	[16]	[17]	[22]	[19]	

3.3. Utilization and Potential Applications of Mine Tailings

3.3.1. Application in Pavement Engineering

Pavement is a superimposed layer of processed materials with hard surfaces made typically with asphalt mixtures or cement concrete, even though the asphalt mixture type is the most common. Specifically, about 90% road network globally is made of asphalt mixtures [18,23], implying that a considerable amount of non-renewable resources, such as aggregates and soils, are required for its construction. Hence, a strong dedication to affordable pavement construction with waste by-products is required.

Mine tailings possess remarkable potential as materials leading to sustainable pavement construction. Due to their properties, they have innovative applications in various layers (surfacing, base, subbase, and subgrade) of pavement. Due to tailings particle size, they are commonly used as both a fine aggregate and a mineral filler in asphalt mixtures. Its chemical composition (particularly SiO_2 , Fe_2O_3 , and Al_2O_3) and angularity contribute to improved asphalt mixtures' performance. Mine tailings are also suitable as pavement base and subbase material after stabilization with pozzolanic

materials [24]. This stabilization aids in enhancing their engineering performance for construction purposes [25–27].

Table 2 summarizes the influence of tailings on pavement performance. The utilization of tailings in pavement construction will reduce the overreliance on non-renewable materials, reduce pavement construction costs, and minimize the adverse environmental impact associated with tailings disposal. In summary, at an appropriate substitution rate, tailings can effectively improve the performance of asphalt pavement. This improvement is due to the chemical and mineral composition and their physical properties, which are comparable to conventional materials utilized in pavement construction. Nonetheless, for enhanced performance in pavement, tailings should be pretreated.

Table 2. Applications of Mine Tailings in Pavement Applications.

Reference	Tailings	Application	Findings
[28]	Iron tailings	Road base	The iron tailings addition of 10% and 20% displayed a reduction in the compression resistance, with the mixtures satisfying the strength requirement for pavement base layer application.
[29]	Molybdenum tailings	Road base	At 15% molybdenum tailings stabilized with 7% cement are suitable for a heavy traffic base of expressways.
[30]	Graphite tailings	Fine aggregates	Graphite tailings' optimal replacement rate of 50% effectively increases the asphalt mixtures' high temperatures, bending performance, water damage, and frost resistance.
[31]	Iron tailings	Coarse aggregates and fine aggregates	Asphalt mixtures incorporating iron tailings as aggregates, used either to fully replace the coarse aggregate fraction (74%) or partially replace fine aggregates (12%), showed satisfactory high temperature performance, while exhibiting adverse effects on moisture stability and low-temperature performance.
[15]	Copper tailings	Filler	When copper tailings were used as mineral filler at filler-to-asphalt (F/A) ratios ranging from 0.3 to 1.2, the asphalt mastic exhibited enhanced high-temperature performance, while its moisture stability and low-temperature performance showed a slight decline but remained within acceptable limits.

3.3.2. Mine Tailings in Cementitious and Construction Applications

The construction industry requires a huge number of non-renewable resources, such as stone and natural sand, creating a huge burden on natural resources. Stones and sand as coarse and fine aggregate are usually sourced through mining exploration, damaging the ecosystem. The construction industry also uses cement as a binder in its operations. Studies have quantified the negative environmental impact of construction using cement. This situation suggests the use of waste materials may present a sustainable alternative to minimize this environmental footprint and aid in the circular economy transition. This has inspired several studies [10,32–51] to investigate the use of mine tailings as sustainable alternatives and found they can be effectively used as partial replacements for cement and fine aggregates in construction applications.

The pozzolanic activity (based on the chemical content) of tailings makes them a promising supplementary cementitious material (SCM). As depicted in Table 1, the sum of tailing's Al_2O_3 , SiO_2 , and Fe_2O_3 contents is more than 70%, which is the SCM's limit defined by international standards. A recommendation of 5 and 20% cement replacement with tailings has been established to avoid the adverse effects on mixture performance [10,33]. For instance, in Zaid et al. [34], 15% tailings as cement replacement in UHPC enhances the compressive strength by 12.49%, sulfate resistance with a residual compressive strength of 115.2 MPa, and a mass loss of 25.4% and significantly reduces shrinkage by 49.28%. However, the need for more cement replacement to reduce the environmental

footprint of its production has resulted in treatment methods to increase the reactivity and replacement level of tailings [35]. Various treatment methods, such as alkali activation, mechanical, chemical, heat, and a combination of these methods, have emerged [36]. In Ramanathan et al. [33], tailing was mechanically activated for use as SCM, and a 30% replacement level in cementitious pastes was obtained without any negative effects.

The properties of the tailings are comparable to those of normal sand used in engineering construction [37]. This comparison offers tailings as a potential use in concrete mixtures as an alternative source of sand in sustainable concrete production. Studies have found that using tailings sand replacement significantly improves the mixture performance [38–40]. In a study conducted by Li et al. [38], it was found that replacing sand with 20% molybdenum tailings has a 10.9% and 14.9% increment in the concrete 28-day compressive strength and tensile strength, respectively. Liu et al. [32] investigated the effects of graphite tailings as sand in concrete production and found at 10% replacement, the compressive and split. While various studies confirmed the suitability of tailings as sustainable sand materials, undoubtedly, there is irregularity regarding its optimal proportion. The inconsistency may be a result of variations in tailings properties and mixture design. Nonetheless, tailings range of 10 and 40% are found suitable to be substituted as fine aggregate [10,41].

The construction application of tailings is depicted in Table 3. Tailings are suitable as fine aggregates and cement, making them a suitable material for various construction applications, such as concrete, mortar, bricks, and geopolymer productions. Hence, tailings can be regarded as a versatile and promising alternative material for construction applications. Nevertheless, the utilization of tailings as construction materials should be reasonably controlled in practical applications.

Table 3. Applications of Tailings in Construction Applications.

Tailings	Applications	
	As Sand	As Cement
Gold	<ul style="list-style-type: none"> The concrete exhibits a satisfactory compressive and split tensile strength at replacement levels up to 25% and 50%, respectively [37]. 	Calcined gold tailings exhibit pozzolanic activity, with only a 9% strength reduction at 20% substitution [42].
Magnetite	<ul style="list-style-type: none"> Magnetite-rich iron ore tailings can be fully utilized (100%) as a sand-equivalent granular backfill in Mechanically Stabilized Earth (MSE) wall construction, resulting in approximately 70% reduction in horizontal facing displacement compared to conventional sand [52]. 	The pozzolanic activity of magnetite tailings enhances the rate at which the strength values increase with increasing curing age [43].
Iron	<ul style="list-style-type: none"> The iron tailings reduce slump and increase water absorption and pressure bleeding rate. A maximum compressive strength of 45.6 MPa was achieved at a tailings content of 40% [44]. 	Cement substitution by of 5% iron tailings achieved satisfactory mechanical properties at all curing ages [45].
Copper	<ul style="list-style-type: none"> A higher value of 51.1 MPa and 5.3 MPa for compressive and flexural strength was achieved at 35% sand replacement [46]. 	The 28-day compressive strength of the concrete sample made of cement-substituted copper tailings was 42 MPa, which was 9% lower than that of the control sample [47].
Lead-zinc	<ul style="list-style-type: none"> An optimum blending ratio of 40 – 60% lead-zinc tailings as sand replacement improved the concrete compressive strength [48]. 	Mechanically activated lead-zinc tailings, up to 40% is suitable substitute for cement in concrete production [49].
Molybdenum	<ul style="list-style-type: none"> At 50% sand replacement by molybdenum tailings, an increase of 14.4% was observed in the mechanical properties [50]. 	The concrete achieved the best compressive strength and splitting tensile strength of 45.6 MPa and 2.91 MPa at 10% molybdenum substitution [51].

3.4. Benefits and Challenges of Mine Tailings in Construction

Mining waste in form of tailings present both opportunity and challenge as construction material. When carefully characterized, processed, and applied, they can serve many constructions uses, particularly in pavement systems and concrete, offering benefits in sustainability, cost, and resource conservation. However, significant challenges remain such as variability of material

properties, environmental risks (leaching, acid generation, heavy metals), lack of long-term performance data and insufficient regulatory and standardization frameworks.

4. Bauxite Residue (Red Mud)

4.1. Bauxite Residue Global Generation

The global aluminium production rate is pivotally increased with the increasing demand for aluminium products [53]. Aluminium is the most common metal and is found it makes 8% of the Earth's crust. According to The international Aluminium Institute (AIA) [54], China is the leading aluminium producer in the world, and Figure 1. illustrates the world aluminium production from 2022 to 2024, which clearly shows the growth trend. Aluminium can only be found in its oxide form due to its pronounced chemical activity. Bauxite is the primary feed ore used to produce aluminium through a process called Bayer, and the residue produced during this process is called "Bauxite Residue (Red Mud)"[55]. With the development of the aluminium industry, the Bauxite residue production rate is also rapidly increasing.

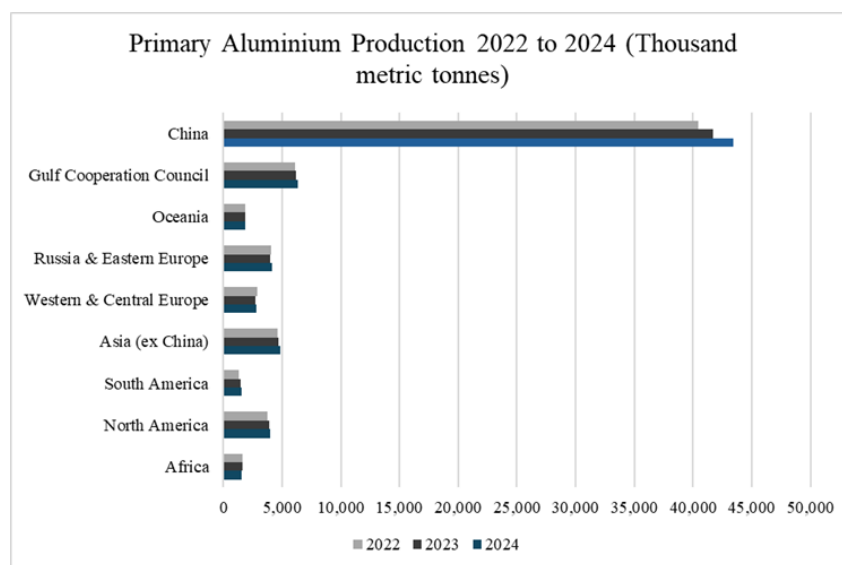


Figure 1. Primary Aluminium Production 2022 to 2024 [54].

Bauxite is available in many countries, and it is estimated that globally available bauxite resources range from 55 to 75 billion tonnes. Among the available countries, Africa has the most significant quantity with 32% of availability, and Oceania (23%), South America and the Caribbean (21%), Asia (18%), and elsewhere (6%)[56]. According to the U.S. Geological Survey [56] data, Figure 2. describes the world bauxite mine production in 2023 and 2024. Accordingly, Guinea and Australia dominate the top world production, and China and Indonesia also maintain higher production. Primarily, to produce 2 tonnes of alumina, it needs 4 tonnes of dried bauxite.

Bauxite is not a distinct mineral; it's a combination of hydrated aluminium oxides and other gangue minerals like iron-bearing minerals ($\text{FeO}(\text{OH})$ and Fe_2O_3), clay minerals, and Titanium minerals. The most common aluminium bearing minerals are Gibbsite: $\text{Al}(\text{OH})_3$, Boehmite: $\text{AlO}(\text{OH})$, Diaspore: $\text{AlO}(\text{OH})$ [55].

During the Bayer process, 1 tonne of alumina production resulted in 1.5 to 2.5 tonnes of bauxite residue byproduct [53]. As described in Figure 3, the Bayer process consists of several steps, including milling, desilication, digestion, clarification, precipitation, and finally being fed into a calciner to remove the moisture and yield solid alumina (Al_2O_3). The leftover solid waste after the digestion and clarification processes is the bauxite residue [53].

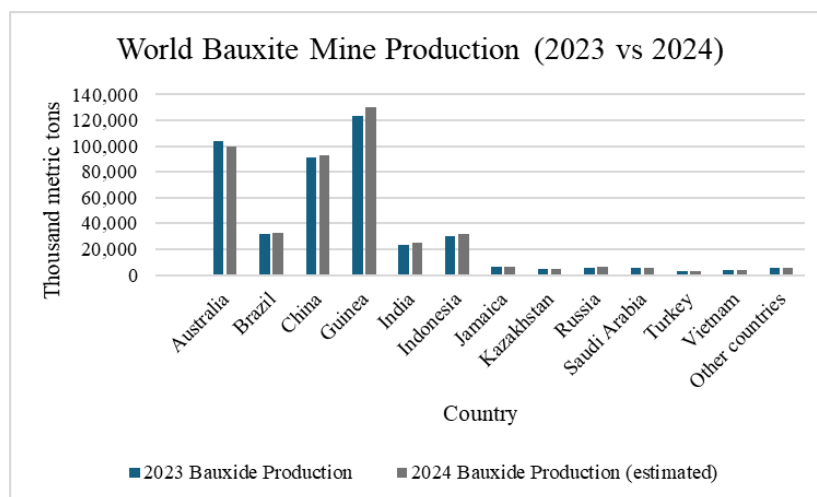


Figure 2. World Bauxite Mine Production (2023-2024) [56].

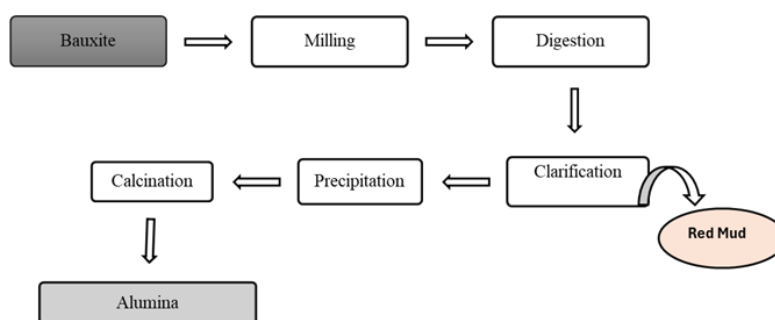


Figure 3. Primary Steps in Bayer Process[53].

The amount of bauxite residue production is primarily based on the aluminium content of the bauxite ore, the production rate of the alumina, and the processing conditions of the Bayer refinery. Figure 4 describes the global annual bauxite residue generation from 2005 to projected for 2050, which shows that the projected residue generation amount in 2050 will be more than 200 million tonnes per annum[57]. Accordingly, it is pivotal to review the production, physical and chemical composition, environmental impact, health and safety aspects, and utilization of bauxite residue in a sustainable manner, focusing on the circular economy.

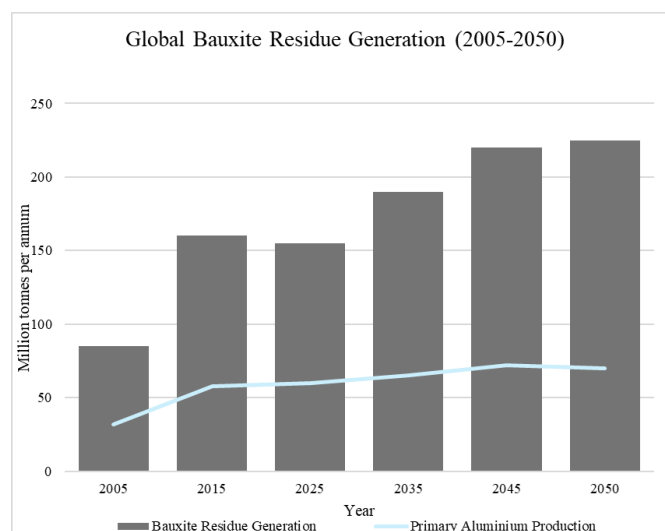


Figure 4. Global Annual Bauxite Residue Generation (2005-2050)-History and Projection, Values approximated and figure redrawn based on[57].

4.2. Properties of Bauxite Residue

4.2.1. Physical Properties of Bauxite Residue

The properties of the bauxite residue primarily depend on the nature of the Bauxite ore and the production process. It is crucial to identify the characteristics of bauxite residue to investigate several utilization studies. Bauxite residue can be identified as a solid waste consisting of various radioactive materials, heavy metals, and high alkaline substances [58]. Table 4 describes the comparative analysis of the typical values of bauxite residue properties with those of the clay. Accordingly, the physical properties, including specific surface area, particle size, porosity, density, and moisture capacity, are noticeably higher than those of clay.

Table 4. Comparison of Basic Physical Properties with Clay [58,59].

Physical properties	Index value	Comparative evaluation with clay
Specific surface area (m ² ./g)	15–58	»Clay (10–25)
Particle size (mm)	0.075–0.005	»Clay (<0.002)
Porosity ratio (%)	2.53–2.95	>Clay (0.69–1.78)
Specific gravity (kNm ⁻³)	2.7-3.7	>Clay
Moisture capacity (%)	80 (82.3–105.9)	»Clay (<30)
Cation exchange capacity (m ^g g ⁻¹)	25–35m ^g ×10 ^{-2g}	Destabilization
Density (kgm ⁻³)	2700–2900	>Clay (1490–1900)

Bauxite residue has a high specific surface area, a higher density, and a higher void ratio [60]. The study [61], done a characterization of bauxite residue from Brazilian alumina refinery, and the results show 8.3 m²/g surface area, 2.8 g/cm² of density, 4.8 g/cm³ of rigid voids, and 12.4 of PH value. Due to the high specific surface area of the bauxite residue, it exhibits a poor settling rate, low hydraulic conductivity, and also consists of high water holding[59].

The bauxite residue comprises particles with different shapes, such as angular and spherical. Numerous studies have evaluated the shape of the bauxite residue using scanning electron microscopy (SEM), and in most cases, bauxite residue shows uneven shapes, including flaky and round shapes [62,63]. Bauxite residue has low plasticity due to particle morphology with angular to sub-granular shape and absence of clay minerals. The bauxite residue has high angle of internal friction and low permeability compared with fine-grained soil [64].

Specific gravity (G_s) is another key property, and previous studies revealed that the specific gravity of the bauxite residue varies between 2.7 and 3.7, which is comparatively higher than that of natural soils. [63]. The high concentrations of particular minerals in the bauxite residue are responsible for the high specific gravities, particularly the iron-rich phase hematite and fine goethite [59]. When considering the particle size distribution, the researchers highlighted the importance of this factor as it affects the rheological properties of the bauxite residue and possible applications. However, the size of the particles may vary according to the nature of the bauxite. According Ram Kumar and Ramakrishna [62], the particle size of bauxite residue varies between 0.1 μ m and 90 μ m. Industries pay close attention to bauxite residue for replacing conventional powder elements like mortar, cement and bitumen due to the excellent particle size of the bauxite residue, which can easily blend with other materials. Despite that, the fine particles and porous structure enhance the water absorption rate of the bauxite residue, which can negatively affect the concrete modification when applied[65].

The high alkalinity of bauxite residue is a significant factor in classifying the bauxite residue as hazardous waste. Generally, the pH value of bauxite residue varies between 11 and 13. The residue slurries have high pH values due to residual soluble Na species, which are mostly a combination of

sodium aluminate and sodium carbonate. The incomplete removal of residual Na species like hydroxide, bicarbonate, silicate, carbonate, and aluminate, from the undissolved material in the counter-current decantation washing process imparts significant alkalinity to the bauxite residue. Moreover, due to the addition of slaked lime during pre-desilication, pre- and post-digestion, solid-phase hydroxides, carbonates, and aluminates of calcium are formed, which contribute to the increased alkalinity of solid bauxite residue [59]. The pH value of bauxite residue is higher than that of other waste materials like fly ash. Recently disposed bauxite residue presents potential threats to the environment, such as leakage of alkaline compounds into groundwater, risk of caustic exposure to organisms, overflow of alkaline substances during storm events and the loss of alkaline dust and efflorescence forming at the surface of bauxite residue disposal areas, which require sustained and intensive resources to manage and transform their alkalinity [66]. The previous studies state that lowering the pH value of bauxite residue up to 9 or below significantly lowers the environmental impact [53].

4.2.2. Chemical Properties of Bauxite Residue

The chemical composition of the bauxite residue varies significantly based on the location of the bauxite ore. Generally, iron oxides (Fe_2O_3) and aluminium oxides (Al_2O_3) can be considered as major components of the bauxite residue; however, not in all cases. Oxides of titanium, silicon, sodium, and calcium are the other mineral oxides that are present in bauxite residue. Table 5 shows the variation of the chemical composition of bauxite residue in different countries. According to Table 5, Wang et al. [67] and Zhang et al. [68] both conducted their research based on bauxite residue supplied by China. The main chemical composition of Wang is Fe_2O_3 , which is 59.37%, but the Zhang sample was only 17.54% Fe_2O_3 , which has 44.64% of CaO as the major composition. The chemical composition of both samples has major differences, although they were obtained from the same country. Further, K, P, Mg, Cr, Mn, Cl, P, S, Zn, Sr, and Y are also identified as some of the other chemical contents in bauxite residue [62].

Table 2. Variation of Chemical Composition of Bauxite Residue.

Country	Composition %						Reference
	Fe_2O_3	Al_2O_3	TiO_2	CaO	SiO_2	Na_2O	
China	59.37	16.16	-	2.17	9.11	2.78	[67]
India	53.75	16.07	4.24	1.48	8.25	3.82	[69]
China	17.54	8.03	4.81	44.64	18.19	3.21	[68]
India	44.3	18.2	10.5	1.11	14.5	9.29	[70]
Turkey	8.09	14.3	2.95	-	11.4	9.35	[71]
Brazil	31.45	35.47	5.84	1.81	12.68	-	[72]
Australia	36.48	23.53	6.84	1.83	14.88	9.41	[73]
Iran	32.67	11.64	4.92	20.09	13.17	3.89	[74]

There are several mineral compositions in the bauxite residue, and the different chemical oxide components make its mineralogy more complex. It has been evaluated that there are various mineral compositions in bauxite residue, and a typical range of some of the major mineralogical compositions is summarized in Table 6. Accordingly, Sodalite, Goethite, and Hematite show a higher value range. The mineralogy of bauxite residue varies depending on the nature of the Bauxite ore and the production process of the aluminium. Previous research shows that the bauxite residue obtained from the sintering process has a higher composition of Calcite, Dicalcium Silicate, and Pervskite, and bauxite residue from the Bayer process has more hematite, Gibbsite and goethite [75]. Overall, this variability in mineralogy plays a critical role in governing the reactivity, environmental behaviour, and suitability of bauxite residue for different construction applications.

Table 3. Typical Range of Mineralogical Components of Bauxite Residue [76].

Mineralogical Component	Range (%)
Sodalite	4–40
Goethite	10–30
Hematite	10–30
Magnetite	0–8
Silica	3–20
Calcium Aluminate	2–20
Boehmite	0–20
Titanium dioxide	2–15
Muscovite	0–15
Diaspore	0–5
Calcite	2–20

4.3. Environment and Disposal Challenges

The statistical and forecasting data of the global bauxite mining industry underscore the significance of addressing the management of bauxite residue proficiently, effectively, and sustainably. The high alkalinity (pH 10–12.5) and the complex chemical and mineralogical species of bauxite residue cause a major impact on the environment.[77]. The proper disposal of the bauxite residue is one of the key aspects in aluminium plants. The adopted bauxite residue deposition methods brought major environmental, safety, and economic burdens. The seawater disposal method is one of the disposal methods that directly discharges the bauxite residue into the sea. Currently, it is considered the least preferred method as it significantly affects the marine ecosystem by releasing toxic metals into the marine environment and poses a threat to the human food chain.

Lagooning is another method that involves pumping the bauxite residue after the Bayer process and requires a large amount of land area. The methods should be applied with high consideration to avoid the containment and spill of caustic waste and include a sealant layer for the bottom of the store area in order to prevent any liquid seeping into the soil. The lagooning method needs long-term planning and considerable cost to prevent failures [53,76]. The study Wang et al. [78], stated that the aluminium plant at Shandong cost nearly \$15 million to construct the storage area, and the service life is only five years, with additional maintenance costs of \$2 million exceeding. Further, various tragic industrial accidents have been reported due to failures in bauxite residue disposal areas. For instance, the accident at the Ajka Alumina Plant in Hungary in 2010, the failure of the HINDALCO plant at Muri in 2019, and an incident at the Xiangjiang Wanji Aluminium Plant in Luoyang in 2016, which threatened human life, the ecosystem, and livestock [63]. Due to the possibility of structural failures, leaks, and seepage into the ground during the lagooning method, the industry has recently developed the dry bauxite residue disposal method. The dry stacking technology consists of various methods, including thickening/flocculants, dry stacking slurry, and dry stacking cake. The process needs a dust mitigation strategy; otherwise, it could lead to serious environmental pollution from the toxic elements in bauxite residue. Also, the process is challenging to install in high rainfall and low evaporation areas[76]. However, when considering the transportation ability, dry bauxite residue can be easily transported elsewhere to use in applications.

The high alkalinity of bauxite residue is a major factor in the classification of its hazardousness. Sufficient neutralization of bauxite residue using various methods can lower its pH value to a considerable extent and decrease its negative effects on the environment, making it suitable for use in various applications. Acid treatment, seawater neutralization, Gypsum neutralization, CO₂ neutralization, and microbial neutralization are some of the common neutralization methods utilized on an industrial scale. It is evident from previous research that neutralization is a successful method with several advantages. Among the above neutralizing processes, the most recommended method is seawater neutralization, which reduces the alkalinity of bauxite residue without losing acid-neutralizing capacity [79]. Treating the bauxite residue at temperatures ranging from 200 °C to 1000

^oC is another approach that can enhance the physico-chemical properties of the bauxite residue by improving the adsorption capacity[77].

Table 7 summarizes the environmental effects associated with bauxite residue. These include soil and groundwater pollution, air pollution from alkaline dust, dam failures, ecosystem damage, and long-term health problems for people. While newer methods, such as dry stacking and residue neutralization, have reduced certain risks, they remain expensive, difficult to operate, and unsuitable for all sites. Given these ongoing problems, it is vital to adopt sustainable approaches to managing bauxite residue. Approaches that focus on safe reuse and the creation of value-added products can help reduce waste and avoid long-term environmental and economic harm.

Table 7. Summary of the Environmental Effects of Bauxite Residue.

Environmental Challenge	Description	Probable issues	Reference
alkalinity of bauxite residue	The incomplete washing of residue after digestion with caustic soda (NaOH) leads to the retention of Na ₂ CO ₃ and NaAl(OH) ₄ , resulting in high alkalinity.	<ul style="list-style-type: none"> • Directly contributes to land and groundwater contamination. • The food chain and human health risk. • Accelerate dam corrosion and increase the risk of dam failure. 	[63,80]
Leaching of toxic elements	Leaching out of metal elements, including Al, Ca, Fe, Cr, Cu, Pb, Mg, Ba, and Mn	<ul style="list-style-type: none"> • Groundwater contamination and health and safety issues for livelihood. • Long-term ecological toxicity 	[76,81]
Pollution due to dust	Due to its small size, bauxite residue is able to easily cause dust under wind, Alkaline dust formed pollutes the air (Bauxite residue stored by the dry process)	<ul style="list-style-type: none"> • Affecting the air quality and endangering the surrounding livelihood and vegetation. • Evaporation of high alkaline components can cause high alkaline rainfall 	[75,78]
Dam failure and leakage	Large slurry impoundments and weak dike structures tend to collapse (Tragic industry accidents, for instance, Ajak Alumina plant Hungary-2010, HINDALCO plant in Muri-2019, Xiangjiang Wanji Aluminium Plant in Luoyang, Henan Province of China-2016)	<ul style="list-style-type: none"> • Contamination of the plant environment. • Increase in the caustic nature of native soils with the deposition of fine particles. • Release of potentially toxic elements (PTEs, viz., As, Ba, Ni, Zn, Cu, Zr, Pb, Cr, V, Hg, etc.), and formation of fine dust upon drying up of the surface. 	[63]
Impacts on marine disposal	Release toxic metals to the marine environment	<ul style="list-style-type: none"> • Destroy the marine ecosystem. • Formation of Mg and Al compounds increases the turbidity of seawater, • The food chain and human health risk. • Directly threatening sea animals with profound influence 	[76,78]
Land scarcity	Lagooning of bauxite residue requires a large amount of land area	<ul style="list-style-type: none"> • Loss of significant land area. • Need long-term maintenance with expensive engineering 	[53,76]
Salinity and sodicity of residue	High Na content	<ul style="list-style-type: none"> • Soil degradation, reduced fertility, restricted plant growth 	[78]

4.4. Utilization and Potential Applications of Bauxite Residue

Bauxite residue has strong alkalinity and complex composition and properties. It is rich in metallic oxides, particularly iron. It also exhibits good particle dispersion, a large specific surface area, and other characteristics similar to those of porous materials, as well as good stability in solution. Herein, they have made many achievements in building materials, metallurgy, environmental protection, and other fields [78].

The utilization of bauxite residue can be processed in several different ways. First, the valuable metals in bauxite residue, such as Fe, Al, Na, Ti, Cr, Sc, V, and Ga, can be extracted from it. Secondly,

it can be used as an environmental protection application, such as the management of wastewater treatment and waste gas. Also, due to the richness of the alkalinity, high adsorption, it can be applied for soil improvement in agricultural fields [60]. Finally, the previous studies evidently proved the susceptibility of utilization of bauxite residue in the construction industry.

4.4.1. Application in Pavement Engineering

In road construction, bauxite residue can be used in various applications, including as a filler, a modification for bitumen and asphalt mixture, or in pavement base layer. The application is still in an innovative stage, but with better prospects. The physical and chemical structure of the bauxite residue is suitable for interaction with bitumen, facilitating the potential modification of the performance of flexible pavements.

The mineral filler stiffens the bitumen, which requires bonding with aggregate properly to improve the performance of the asphalt mixture. Generally, limestone powder, fly ash, diatomite cement, and steel slag are the common powder materials used in industry. Recently, utilizing bauxite residue as a replacement material for mineral filler has also attracted the researchers' attention. Researchers found that bauxite residue improves the softening point, penetration performance, complex modulus, and viscosity of the asphalt mastic, thereby enhancing the stiffness and indicating a positive effect on the rutting resistance of the asphalt mixture [75].

It is essential to understand the mechanism and modification behavior of bauxite residue in asphalt mixtures to comprehend its performance enhancement ability. According to the study by Fu et al. [82], Fourier transform infrared (FTIR) analysis reveals that there are no new peaks that appeared in asphalt with bauxite residue, which suggests that no chemical reaction occurs between bauxite residue and asphalt, but rather physical adsorption. Fe_2O_3 , Al_2O_3 , SiO_2 , CaO , and Na_2O can be considered as the main components of the bauxite residue, and among those, Al_2O_3 provides a higher number of adsorption interfaces for asphaltene. Furthermore, bauxite residue has excellent fine particles, a large specific surface area, and high surface energy, which enable it to attract and adsorb molecules. During the bauxite residue with asphalt, the bauxite residue absorbs the oil in the asphalt and thereby increases the asphaltene and gum content, reducing the wax content in the asphalt. Oil in the asphalt is one of the main factors for the fluidity of asphalt. Softening during high temperatures and brittleness during low temperatures depend on the wax content of the asphalt. Hence, the decrease in wax content and increase in asphaltenes and gum content enhance the temperature performance of the asphalt [82]. The study Zhang et al. [83] illustrates a clear trend of performance enhancement of softening points and penetration of asphalt mastic with increasing bauxite residue content. The softening point consistently rises with higher residue values, indicating that adding bauxite residue enhances the resistance to high-temperature deformation, creating a more rigid structure. At the same time, penetration values decrease, showing that with the increase in the bauxite residue, the binder becomes stiffer and more resistant to deformation. The study also highlights the difference in performance of asphalt mastic with bauxite residue with increasing bauxite residue content, which depends on the industrial processes used to produce alumina: Sintering and the Bayer process.

Many studies [61,82,84–89] that have engaged with bauxite residue in asphalt mastic have compared its performance with blending other typical fillers and minimizing the drawbacks, such as moisture resistance issues. Lima et al. [61] evaluated the performance of mastics with bauxite residue, fly ash, limestone, and dolomite at different proportions. The study performed several standard tests, including wettability and hydrophobic tests, and adhesion test. The results indicate that mastic composed with bauxite residue offers a high resistance against moisture permeation and acts as a better adhesion. The higher porosity of bauxite residue positively influences the penetration of bitumen and enhances the adhesiveness. Furthermore, a combination of different fillers yields different mastic properties, and bauxite residue performed well alongside the fly ash. Increasing the percentage of bauxite residue enhances the hydrophobicity of mastic, thereby improving its adhesive

properties. The alkalinity of bauxite residue may cause a negative effect on the moisture resistance of the asphalt mastic.

The penetration index (PI), as per Equation 1, assesses the thermal susceptibility of bitumen mastic, where a higher PI value indicates low temperature susceptibility, and a lower value signifies high temperature susceptibility. Figure 5 illustrates the increase in temperature performance of bitumen with varying filler content, including bauxite residue. Binder content with low filler indicates higher negative values, which means it has higher temperature sensitivity. As the filler content increases, the PI index increases, showing reduced thermal susceptibility. Asphalt mastic with a high content of bauxite residue shows balanced thermal susceptibility.

$$PI = \frac{500 \cdot \log(P) + 20 \times SP - 1951}{120 - 50 \times \log(P) + SP} \quad (1)$$

where, P = penetration and SP = softening point values.

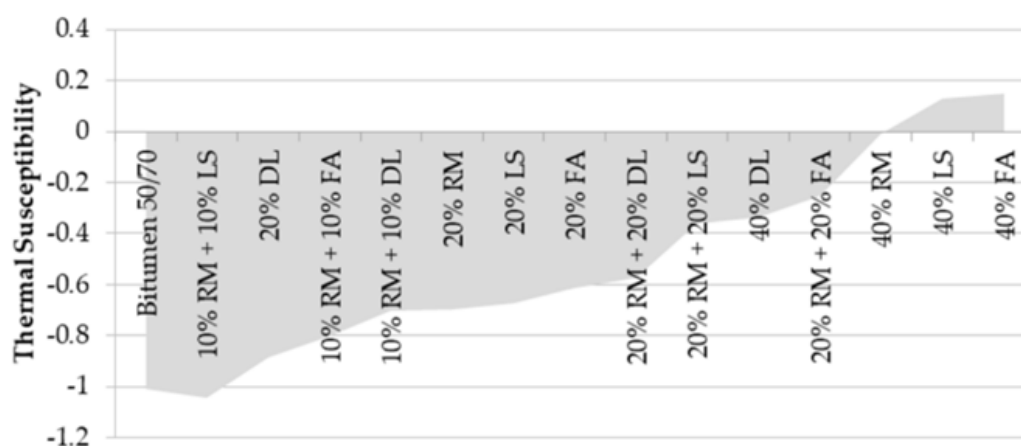


Figure 5. Thermal Susceptibility Index of Asphalt Mastic with Bauxite Residue, Limestone, Dolomite, and Fly Ash. Reproduced from [61] © 2020 by the authors. Licensed under CC BY 4.0.

Zhang et al. [84] conducted an experimental study on the utilization of bauxite residue as an alternative mineral filler in asphalt mastic as a replacement for limestone powder. According to the previous studies, the moisture resistance of mastics prepared with bauxite residue has weaker performance; the study used an anti-stripping additive -hydrated lime to improve moisture resistance. The XRD results indicated that bauxite residue, composed of mineral phases CaCO_3 , Fe_2O_3 , SiO_2 , and Al_2O_3 , may influence the adhesive between bitumen and powder material. However, the replacement of the limestone by bauxite residue proved to be practicable using white mud as a modification agent. Similarly, Zhang et al. [85] engaged in a study to investigate the rheological behaviour and moisture resistance of asphalt mastic prepared with bauxite residue waste, comparing the performance with limestone, hydrated lime, and fly ash. The study shows that the mastic prepared with the bauxite residue obtained a higher complex modulus and a lower phase angle compared to the limestone. This can directly improve the rutting resistance and make the binder stiffer and more elastic. Recognizing the optimal content of bauxite residue is vital, as high bauxite residue content may lead to over-stiffness and fatigue cracking. According to the findings of the linear amplitude sweep (LAS) test conducted by Chaudhary et al. [86], at a 20% bauxite residue content, the particle reached its complete interlocked skeleton. It decreased its fatigue resistance beyond that point. Table 8 summarizes previous studies on asphalt mastic with bauxite residue. Most studies report increases in stiffness, viscosity, and softening point, thereby enhancing resistance to rutting. These improvements are linked to the fine particle size, rough surface texture, and mixing conditions used for bauxite residue, which enhance its interaction with bitumen. However, some studies also report reductions in ductility, fatigue resistance, and low-temperature cracking performance, particularly at higher replacement levels of bauxite residue.

Table 8. Summary of Previous Studies Related to Asphalt Mastic Vs Bauxite Residue.

Ref	Country	Base Bitumen	Mixing Conditions	Content of bauxite residue	Major finding
[61]	Brazil	50/70	Hand mixing, Bitumen temperature 155 °C, Filler temperature 160 °C, Hand mix for 3-4 min	20%,40%	<ul style="list-style-type: none"> Enhance the penetration and softening point. Increasing the filler content lowers the effect of aging. Bauxite residue performed well alongside the fly ash. Bauxite residue improves the hydrophobicity of mastics and enhances their adhesive properties. The influence of fillers in the mastics is proportional to the amount inserted.
[84]	China	60/80	high-speed stirrer, 150 °C at 1000 rpm for 30 min	Bitumen: Powder material=1:1 (Filler powder composition with different proportions of bauxite residue, limestone powder, white mud)	<ul style="list-style-type: none"> Compared to the limestone powder, the bauxite residue asphalt mastic has a higher softening point value and a lower penetration. Replacing the limestone with bauxite residue reduced the ductility from 36.5 mm to 30.5 mm. The ductility of bauxite residue asphalt mastic can be improved, and even better than that of the limestone powder, with appropriate hydrated lime or white mud. Bauxite residue increases mastic stiffness and viscosity of the asphalt mastic, hence improving the rutting resistance. Reduced cracking resistance, fatigue resistance. Bauxite residue can replace the limestone by combining with the white mud.
[85]	China	Grade 70	high-speed stirrer, 150 °C at 1000 rpm for 30 min	Bitumen: filler=50%:50% (filler consists of different compositions of bauxite residue, limestone filler, fly ash, hydrated lime)	<ul style="list-style-type: none"> The size of the bauxite residue particles, smaller than the limestone, and having a rough surface texture, positively affect the rheological properties of the asphalt mastic. Bauxite residue increased the shearing deformation resistance of the mastic. Addition of bauxite residue increased the viscosity. The mastic prepared with the bauxite residue obtained a higher complex modulus and a lower phase angle compared to the limestone. Bauxite residue increased the stiffness and elastic behaviour of mastic, which in turn improves the rutting resistance.
[86]	India	VG-30	manually operated mixer, 180 °C for 10min	10%,20%,30%	<ul style="list-style-type: none"> Bauxite residue can markedly improve mastic fatigue behaviour when used up to 20%. 30% of the RM filler could make strong interfacial bonding between filler and bitumen.
[87]	India	VG-30	Mechanical stirrer, 160 °C at 1000 rpm 20min	Filler/bitumen= 0.6,0.9,1.2 and 1.5	<ul style="list-style-type: none"> Bauxite residue enhances the stiffness of the binder. Bauxite residue changed the viscoelastic response of the base binder with improvement in percent recovery and a lower compliance (implying higher rutting resistance)
[82]	China	AH-70	High shear mixer, 170 °C, 4000 rpm, 30.min	11%	<ul style="list-style-type: none"> Bauxite residue modifier uniformly fractionates in asphalt and improves the thermal stability of asphalt Bauxite residue modified samples show less brittleness at low temperatures Increasing the content of Al₂O₃ or decreasing the content of Fe₂O₃ in bauxite residue is beneficial to the adsorption of asphaltene
[88]	China	60/80	High-speed shearing and mechanical stirring, 150 °C, 1 h high-speed shearing at 4000 rpm and 1.5 h mechanical stirring at 2000 rpm	5%	<ul style="list-style-type: none"> There is a tendency to segregate in bauxite residue-modified asphalt at high temperatures. The softening point of asphalt increases after the incorporation of bauxite residue. 5% bauxite residue decreases the ductility by 97.5 cm. The viscosity of asphalt increases with the bauxite residue introduced. Compared to bauxite residue, organic bauxite residue enhances the resistance of asphalt to high-temperature deformation and low-temperature cracking.

					<ul style="list-style-type: none"> Organic bauxite residue enhances thermal oxidation and UV aging of asphalt due to its small particle size, large specific surface area, and other characteristics.
[89]	China	60/80	150 °C.,3000 r/min for 60 min and 2000 r/min for 60 min	ZnO/RM 1%,3%,5% and 7%	<ul style="list-style-type: none"> Zinc oxide/bauxite residue composite (ZnO/RM) has sufficient bonding strength with bitumen and exhibits satisfactory storage ability. ZnO/RM enhances the high-temperature performance and rutting resistance before aging. 3% ZnO/RM-modified bitumen can improve the thermal-oxidative and UV aging resistance of bitumen. Optimal dosage 3%.

4.4.2. Bauxite Residue in Cementitious and Construction Applications

Bauxite residue has excellent characteristics, positioning it as a potential sustainable construction material for reuse. It is gaining significant attention among researchers for reducing reliance on ordinary Portland cement (OPC) and natural aggregate. Bauxite residue is used to produce various construction materials, including mortar, bricks, concrete, and ceramics. Utilizing bauxite residue as a partial replacement for cement in concrete drives towards sustainable construction and reduces environmental impact. Venkatesh et al. [90] investigated the strength, durability, and microstructure of bauxite residue concrete and revealed that the material offers more resistance to chloride-iron penetration, water absorption, and crack resistance, as the finer particles of bauxite residue fill the pores in concrete. However, due to insufficient pozzolanic reaction between bauxite residue and other minerals in concrete, C-S-H gel formation was reduced, and only up to 12.5% replacement of cement with bauxite residue resulted in improved mechanical performance. Further, Wu et al. [91] Studied utilizing bauxite residue as a viscosity-modifying agent in self-compacting concrete (SCC). The study's findings show a novel approach to utilizing bauxite residue, as the material decreased the bleeding rate of SCC while increasing the yield stress and plastic viscosity. Further, using 12% bauxite residue decreased segregation of SCC to 6.88%, compared with 17.12% in conventional SCC. Geopolymer concrete is a sustainable alternative to traditional concrete that is made by mixing industrial byproducts. Jothilingam and Preethi [92] Conducted a study about developing M30 material using 50% fly ash and varying percentages of ground granulated blast furnace slag and bauxite residue. Increasing bauxite residue to 15% increases both the compressive and split strengths of concrete. Water absorption increased with bauxite residue, and the carbonation depth also increased accordingly.

Nikbin et al. [93], have conducted a study to evaluate the performance of bauxite residue on light-weight concrete (LWC) by replacing up to 25% of the cement mass. The results indicated that bauxite residue in lightweight concrete reduced its mechanical properties, including compressive, flexural, and tensile strengths. Despite that decline, the study highlighted a decrease in CO₂ emissions from 556.8 to 409.9 kg/m³ and a 31% reduction in cumulative energy demand. According to Qureshi et al. [94], bauxite residue enhances the mechanical properties at a lower replacement level, as high dosage levels tend to decrease the performance. The study recommended a 10-15% substitution of bauxite residue as the optimal dosage. Similarly, Zhang et al. [95] developed a high-performance, low-carbon, lightweight concrete using bauxite residue-based sulphur-aluminate cement and lightweight aggregates. This lightweight concrete achieved structural-grade compressive strengths (45.5–63.5 MPa), enhanced interface transition zone (ITZ) characteristics, lower thermal conductivity (0.47–1.13 W/m·K), and reductions of 21.5% in carbon emissions and 20.1% in production cost. Collectively, the evidence shows that bauxite residue in lightweight concrete exhibits both positive and negative mechanical performance, while all studies emphasize its environmental benefits.

In a cementitious binder, untreated bauxite residue accelerates the hydration kinetics and increases the initial stiffness, and treated bauxite residue that 10–30 wt.% can typically be incorporated into blended cements when the residue is suitably processed, improving sustainability while maintaining acceptable performance [55,96]. Further, Hertel et al. [97] explore the potential of using 100% bauxite residue-based inorganic polymer mortar. Unlike most studies that rely heavily

on fly ash or slag, the study showed that bauxite residue can be used as a primary geopolymer precursor by heating it to 1100 °C, adding a minor amount of C and silica, and activating the resulting material with the K-silicate solution. The resulting material demonstrated a compressive strength exceeding 40 MPa, making it most suitable for non-structural construction materials, such as tiles for floors and roofs.

Utilizing industrial byproducts in construction raises concerns about heavy metals and radionuclides in construction materials, which may pose health risks. Arroyo et al. [98] Investigated the physical, mechanical, radiological, and heavy metal leaching properties of fired bricks with bauxite residue. When the firing temperature was higher than the sintering temperature, bricks achieved higher density, lower water absorption, and higher compressive strength. In heavy metal leaching test results, all the bricks sintered at 1373K showed leaching values below the Soil Quality Decree (SQD) limits, except for Vanadium (V). Utilizing bauxite residue in Ceramic material production is another significant application that could help conserve natural clay resources and reduce bauxite residue. The bauxite residue was modified by dewatering, and it was found that containing 30% of modified bauxite residue sintered at 1015 °C exhibits 64.9 MPa of higher compressive strength. Finally Li et al. [99] developed bauxite residue-based 3D printing mortar. Adding bauxite residue revealed benefits, including increases in packing density, flexural strength, compressive strength, and bond strength of 3.85%, 13.94%, 6.40%, and 16.82%, respectively. Also, reduce the cement content and carbon emission by 10% and 9.57% respectively. Table 9 shows the performance of bauxite residue in construction applications. The table shows that bauxite residue has been applied in a wide range of construction materials, including concrete, lightweight concrete, blended cement, mortars, bricks, ceramics, geopolymers, and 3D-printing mortars. The results indicate that bauxite residue often improves mechanical properties and durability of construction materials while also reducing CO₂ emissions and energy demand. However, higher replacement contents can lead to reductions in strength, increased water absorption, or changes in fresh properties, highlighting the importance of optimising dosage and processing conditions for each application.

Table 9. Summary of Bauxite Residue in other Construction applications.

Reference	Application	Major Findings
[93]	Lightweight concrete	<ul style="list-style-type: none"> Compressive strength, Tensile strength, Flexural strength, and Elastic modulus reduced by 29.5%, 35%, 28.4% and 26% respectively, at 25% RM. Increased the water absorption and ITZ density. CO₂ and energy demand reduced by 26% and 31%.
[94]	Supplementary Cementitious material	<ul style="list-style-type: none"> Bauxite residue enhanced the mechanical properties and durability of concrete while reducing its fluidity. Recommend a 10-15% substitution of bauxite residue as the optimal dose.
[95]	Lightweight concrete	<ul style="list-style-type: none"> Incorporation of bauxite residue reduced the density of concrete up to 1890–2100 kg/m³. Compressive strength and modulus of elasticity were 45.5–63.5 MPa and 25.6 GPa, respectively, meeting the requirements for high-strength lightweight concrete. CO₂ emissions and costs were reduced by 21.5% and 20.1%, respectively.
[55]	Supplementary Cementitious material	<ul style="list-style-type: none"> Untreated bauxite residue accelerates hydration (higher heat release, faster aluminate formation). Increases in storage modulus. Chemical effect, not dilution. Performance depends on the local pairing of bauxite residue and cement.
[96]	Blended cement	<ul style="list-style-type: none"> 10–30% of bauxite residue is feasible in blended cement, depending on Na–Fe phases. Thermal treatments (slagging, calcination) improve reactivity. Identifies durability and phase assemblage gaps.
[97]	Polymer Mortar	<ul style="list-style-type: none"> Proposes 100% bauxite use in inorganic polymer mortar. Moderate compressive strength can be achieved, exceeding 40 MPa. Strength levels depend strongly on temperature treatment and alkali concentration.

		<ul style="list-style-type: none"> Performance is most suitable for non-structural construction materials such as tiles for floors or roofs.
[90]	Concrete	<ul style="list-style-type: none"> Bauxite residue offers greater resistance to chloride-ion penetration, water absorption, and cracking. C-S-H gel formation was reduced, and up to 12.5% replacement of cement by bauxite residue showed improved mechanical performance. A denser microstructure formation was observed with the red-mud replacement, as compared to standard concrete.
[91]	Self-compacting concrete	<ul style="list-style-type: none"> Compared to cement paste, the bauxite residue paste exhibited excellent water retention. An increase in dosage led to a notable decrease in bleeding rate and increases in yield stress and plastic viscosity. Using 12% bauxite residue led to a decrease in segregation of SCC to 6.88%, compared with 17.12% in conventional SCC
[98]	Bricks	<ul style="list-style-type: none"> The higher the temperature at which bricks are fired, the higher the mechanical properties, including compressive strength, density, and lower water absorption, while increasing the bauxite residue percentage. The leaching test results showed leaching values below the Soil Quality Decree (SQD) limits, except for Vanadium (V).
[100]	Ceramic Material	<ul style="list-style-type: none"> Mixture containing 30% of dewatered bauxite residue, which was sintered at a temperature of 1015 °C, exhibits substantially higher compressive strengths (64.9 MPa)
[92]	Geopolymer Concrete	<ul style="list-style-type: none"> Bauxite residue up to 15% increases compressive & split tensile strength, beyond 15% strength decreases. Water absorption increases with bauxite residue. Microstructure shows improved aluminosilicate gel formation.
[99]	3D Printing mortar	<ul style="list-style-type: none"> Paste-replacement approach using bauxite residue (0–6% vol). Achieved improvements in packing density, flexural strength, compressive strength, and bond strength, with increases of 3.85%, 13.94%, 6.40%, and 16.82%, respectively. 10% reduction in cement, 9.6% reduction in CO₂. Maintained printability and accelerated hydration.

4.5. Benefits and Challenges of Bauxite Residue in Construction

The valorisation of bauxite residue in the construction industry offers significant benefits in environmental and engineering terms. The major advantage is the potential to reduce the environmental burden associated with the long-term storage of highly alkaline waste and to support circular economy goals. As described above, depending on the application, bauxite residue can offer several advantages, including acting as a pozzolanic material when mixed with lime and cement, enhancing the strength of the construction materials and compressive strength of stabilized soil, and improving the durability of the material and further, utilizing bauxite residue as a partial replacement of cement, clay or aggregate lower the material cost and solution for the scarcity of the natural materials. Further reduce the cost of aluminum refineries in managing and originating the bauxite residue. As described, bauxite residue is not only suitable for one construction material but also has several applications, including pavement engineering, cement and clinker production, fire bricks, geopolymers, and lightweight materials. Overall, the reuse of bauxite residue transforms an environmentally challenging waste into a technically useful, cost-effective, and sustainability-enhancing construction resource.[55,90–100]

Despite the benefits of using bauxite residue in construction, several significant challenges remain. One of the major issues is its high alkalinity (pH > 13), which poses handling hazards and requires pre-treatment, such as thermal treatment, washing, carbonation, or neutralisation, before it can be safely incorporated into construction materials. Also, leaching toxicity (PHEs) of bauxite residue, such as As, Cr, V, and Pb, poses significant environmental concerns, as these elements may leach under certain conditions, thereby limiting their large-scale application in construction and requiring strict environmental assessment and stabilization measures. Furthermore, bauxite contains radioactive elements, classified as NORM (naturally occurring radioactive material), particularly U and Th. In bauxite residue, this concentration doubles, which requires extra consideration when used

in construction materials. Although measured activity levels are generally low, public perception and regulatory caution around radioactivity have prevented several promising applications from advancing. In some countries, products such as red-mud-based bricks, ceramic insulation fibres, and other building materials were halted primarily due to these concerns, underscoring the importance of ensuring public safety [78,101]. Other challenges include sodium content, electrical conductivity, and smaller particle size distribution (<100 μm in 80% of particles), moisture levels, and transportation expenses also limiting the potential of volatilization [102]. These technical and environmental challenges remain significant barriers preventing widespread implementation of bauxite residue in the construction industry.

5. Waste Rock and Overburden

5.1. Waste Rock / Overburden Global Generation

Mining waste in the form of overburden and waste rock is one of the largest industrial waste streams globally, it is generated at all mining sites in spite of the ore targeted or extractive process taken [103]. It is the first waste generated during mining and excavation activities to access the ore. The quantity of waste rocks depends mainly on the local geology, shape of ore body and extraction technology [104]. Nonetheless, the rock-to-metal ratio (the mass of waste rock / overburden needed per unit mass of valuable metal produced) can be very large, especially for low-grade ores Nkuna et al. [105], presenting waste rock/overburden as the primary and most dominant waste generated in mining operations [6]. For example, rare earth mining and certain metal ores have very high ratios, meaning more waste rock per ton of metal. They often dominate bulk by mass of waste in mining operations. Waste rock and overburden quantities vary by mining type: open pit and surface mining produce large volumes compared to underground mining. Also, mineral grade, deposit geometry, and regulatory and economic practices influence how much overburden must be removed [106]. According to Ait-khouia et al. [107], about 50 billion tonnes of waste rock is generated annually during global mining operations. These wastes are usually deposited on the surface, close to the production site, in large structures called waste rock piles or dumps [108], constituting environmental concerns. One promising avenue is to reuse some of these wastes not as discard, but as raw materials for construction, thus contributing to circular economy goals, reducing demand for virgin materials, and mitigating environmental impacts [3].

5.2. Properties of Waste Rocks/Overburden

Physical properties: Waste rock/overburden typically ranges from large blocks to fines; particle size distribution is highly variable. Coarse fraction may consist of large boulders, gravels; finer fraction may include sands, silts. Porosity, permeability, compaction behaviour, influence strength and stability [109]. They are characterized by the large variability of their particle sizes, ranging from blocks (the diameter of which can exceed several meters) to clay-size particles.

The chemical composition depends on the parent rock type. Trace heavy metals such as Arsenic, Chromium, lead, and copper are present in waste rock [110,111]; hence, leachability may be a concern. The pH buffering capacity, presence of silicates, carbonates, etc., influence safety. The oxides composition in waste rocks includes varying proportions of SiO_2 , Al_2O_3 , Fe_2O_3 , CaO , SO_3 , P_2O_5 and small proportion of other oxides [110,111].

The mineral content of waste rock depends on geology; rock types may include quartz, feldspar, micas, clay minerals, iron oxides, and sometimes sulfides. The mineral composition of waste rock from different sources is shown in Table 10. As revealed in Table 10, the waste rock is composed of varying proportions of mineral content. Also, some waste rocks contain sulfide minerals (pyrite, arsenopyrite) that, upon oxidation, can generate acid mine drainage (AMD)[112]. The mineralogy affects mechanical strength, durability, weathering, potential expansion/shrinkage, and reaction to stabilizers. Mineralogical studies have shown that some overburden rock is sufficiently 'clean' to be used as aggregate; others require treatment [113].

Table 10. Mineral Composition of Waste Rock.

Mineral	Composition				
Quartz	31.3	17.96	39.78	41.21	40.8
Pyrite	7.2	4.06	-	-	0.3
Calcite	2.8	4.97	13.40	6.04	-
Albite	8.7	-	-	5.06	3.7
Anorthite	18.9	-	-	0.38	-
Muscovite	8.3	-	-	-	34
k-feldspar	1.4	-	-	-	-
Chlorite	17.9	10.76	-	-	6.3
Gypsum	1.8	-	-	-	3.0
Ferrihydrite	0.4	-	-	-	-
Jarosite	1.3	-	-	-	-
Clinochlore	-	5.36	-	-	-
Mica	-	26.75	-	-	-
Amphibole	-	20.15	-	-	-
Pyroxene	-	3.45	-	-	7.7
Fluorapatite	-	-	42.25	6.42	-
Dolomite	-	-	4.57	40.89	-
Goethite	-	-	-	-	3.2
References	[108]	[107]	[110]	[114]	[115]

5.3. Utilization and Potential Applications of Waste Rock / Overburden

5.3.1. Application in Pavement Engineering

The properties of waste rock/overburden, such as excellent mechanical strength and durability, confirm their ability for use as road construction materials [116]. The coarse fractions of waste rock/overburden have been used to form subbase and base layers in roads. When properly crushed and compacted, such materials can provide sufficient bearing capacity and drainage [4,116]. Also, waste rock/overburden can be used for embankments, fill for landform reshaping, or mine restoration [117]. Also, due to the fact that they are located at the site, transport distances are small, and their coarse particle size, they can be applied on mining sites for internal roads and haul routes [116]. In Amrani et al. [115], sustainable embankments and pavement layers using coal mine waste rock were investigated. observed that coal mine waste rock corresponds to very silty sands and gravels of medium hardness that can be used in the construction of pavements. The results from the CBR experiment further confirmed that waste rocks can be used as a sustainable alternative material for the embankment, and stabilized waste rock is suitable in road sub-base layers for high-traffic pavements. Amrani et al. [114] demonstrated the suitability of phosphate mine waste rock as a sustainable alternative material in the construction of dry compacted embankments. They obtained the specific density (ρ_s) of 26 kN/m³, organic matter of 1%, Los Angeles abrasion of 58%, plasticity index (PI) of 20% and methylene blue value (MBV) of 1 g/100g, confirming the waste rock possesses satisfying geotechnical characteristics to be used as embankment materials.

Studies have also found that mine waste rock can improve asphalt's performance when incorporated as a substitute for conventional materials. In Alhomaidat et al. [118], feasibility of mine waste rocks as an aggregate replace natural aggregate in asphalt mixtures was conducted. It was reported that mine waste rock achieved a cantabro loss of 20% than the limestone aggregate. They attributed the high cantabro loss of the mine waste rock mixture to the aggregates' high smoothness, low internal friction, and high susceptibility to abrasion. Nonetheless, the mine waste rock was still found suitable for use in asphalt mixtures.

Table 11 presents the various applications of mine waste rocks in pavement. In general, the studies presented in the Table have shown that the use of waste rocks is practical in pavement

application, offering improved performance. The utilization of mine waste rock in pavement application is a promising option for the sustainable management of waste materials, reducing their environmental footprint and preserving non-renewable resources that are currently often overexploited for pavement construction. Despite the profitability of mine waste rock in pavement applications, its utilization can still be deemed emerging, and further studies are needed to fully understand its benefits in pavement applications. For instance, the Table clearly demonstrates that most studies on mine waste rock for pavement application have centered on its use as base/subbase materials, with its application as an asphalt mixture being limited, reflecting the need for more research in this area.

Table 11. Various Applications of Mine Waste Rock in Pavement Applications.

Reference	Application	Findings
[119]	pavement base/subbase	<ul style="list-style-type: none"> Overburden has good stiffness and acceptable abrasion strength; it can be a viable substitute for a conventional granular base in favorable contexts.
[118]	Aggregate in asphalt mixtures	<ul style="list-style-type: none"> Mine waste rock modified asphalt mixtures achieved a cantabro loss of 20% to the limestone aggregate.
[120]	Pavement base/subbase	<ul style="list-style-type: none"> Waste rock used as base and subbase materials has comparable load deformation behaviour to natural aggregate as base and subbase material.
[121]	Aggregate in concrete pavement	<ul style="list-style-type: none"> Concrete pavement with 40% waste rock resulted in about an 18% increase in the 28-day compressive strength compared to the control mix.
[122]	Pavement base	<ul style="list-style-type: none"> The utilization of waste rock meets the standard material requirement in the base layer in terms of CBR and did not pose an environmental risk.

5.3.2. Waste Rocks in Cementitious and Construction Applications

Mine waste rocks have excellent characteristics, positioning them as potential for their reuse as sustainable construction material. This material has been found suitable in various forms for production of concrete, mortar and in production of bricks, making them the most versatile construction material. In [111], the feasibility of mine waste rock as cement replacement for mortar production was investigated. The mine waste rock was sieved through 75 μ m sieve and used to partially replace cement with 10%, 20% and 30%. The density, compressive strength, split tensile strength, water absorption and porosity was conducted on the prepared mortar. The results obtained showed about 20% increase in water absorption, 8.60% and 26% decrease in density and compressive strength, respectively. They attributed this phenomenon higher porosity, lower density of the waste rock and lower cement content in the waste rock-mortars. Despite the reduction in mortar strength, they assert that the waste rock-mortar is eco-efficient than the conventional mortar based on the binder intensity (bi) index, indicating the sustainability of waste rock mortar.

Nguyen et al. [123] investigated concrete performance containing waste rock for sustainable development. The waste rock was to substitute fine aggregate with 0 – 50% at 10% increment and its effects on the concrete mechanical properties, durability, and environmental impact were conducted. They obtained a decrease of about 10 – 25% in the mechanical performance of mine waste rock-concrete compared to the conventional concrete when waste rock content increased from 10 – 50%. Nonetheless, the waste rock-concrete meets the technical requirements for compressive strength of 35 MPa with reduced environmental impact, indicating the effectiveness of waste rock as fine aggregate in concrete for sustainable development.

The possibility of using mine waste rocks as alternative raw material for the manufacturing of fired bricks was conducted by Benahsina et al. [124]. The mine waste rocks were crushed and used to replace natural clay at substitution of 0 to 100%. The results showed a reduction in the mechanical resistance of the bricks and an increase in the porosity and water absorption rate of mine waste rock-bricks. Nonetheless, up to 80% mine waste rock substitution, the strength of the bricks was greater than 2.5 MPa, which satisfied the minimum requirements set by the applicable civil engineering and environmental standards.

Table 12 shows the performance of some waste rocks used as construction materials. It can be observed that waste rocks are relevant in different construction applications and can also be processed into different forms such as coarse aggregates, fine aggregates and as cement replacement according to their properties (physical and chemical properties). From studies, one can retain primarily that the technical requirements and the resulting products are specific to the properties of each individual mine waste rock [125].

Table 12. Construction Applications of Mine Waste Rocks.

Reference	Application	Findings
[104]	Aggregates (coarse and fine) in concrete	<ul style="list-style-type: none"> The substitution of the fraction 0–5 mm improved the concrete compressive strength by 11%.
[126]	Aggregate in concrete	<ul style="list-style-type: none"> Mine waste rock-concrete achieved 28-day strength of 12 MPa, 1.3 MPa, and 2.65 MPa for compressive strength, flexural strength, and splitting tensile strength, respectively.
[127]	Aggregate in concrete	<ul style="list-style-type: none"> Concrete with coarse aggregate from mine waste improved the compressive strength by 12–15% with a sufficient level of durability compared to the conventional concrete.
[128]	Cement in tile production	<ul style="list-style-type: none"> The mine waste rock tiles have a strength above the recommended minimum strength of 3.5 MPa.
[129]	Fine aggregate	<ul style="list-style-type: none"> Compared to M-sand, overburden resulted in less 50%, 30%, 18% and 28% in environmental burden, climate change, human health, and resource depletion, respectively.
[130]	Geopolymer	<ul style="list-style-type: none"> Waste rock utilization enhances the geopolymer's reaction dynamic with maximized compressive strength.
[131]	Aggregate in Concrete	<ul style="list-style-type: none"> Concrete with waste rock has 28-day compressive and splitting tensile strengths of 28.72 MPa and 5.36 MPa, respectively.

5.4. Benefits and Challenges of Mine Waste Rock in Construction

The utilization of mine waste rock as construction materials will result in several benefits[132], such as:

- Resource conservation: Substantial reduction in the use of natural aggregates, preserving quarries and reducing extraction impacts.
- Environmental benefits: Less landfill, less waste storage; potentially reduced CO₂ emissions associated with the extraction & processing of virgin materials.
- Cost savings: Lower transport costs if local waste is used; savings from reduced raw material purchases.
- Circular economy and sustainability: Turning waste into value aligns with SDGs (Sustainable Development Goals).

The utilization of mine waste rock in construction applications is a promising option. However, to fully utilize their benefits as construction materials, the following challenges need to be addressed.

- Variability of material properties: Wide variation in physical, chemical, and mineralogical properties; site-by-site characterization required.
- Environmental risks: Potential for leaching of heavy metals, acid generation from sulfide-bearing waste. Must assess and mitigate.
- Regulatory and standardization issues: Lack of standard design guidelines, codes, and specifications for using waste rock/overburden in structural layers or concrete, particularly across different jurisdictions.
- Long-term performance concerns: Durability under cycles (freeze-thaw, wetting/drying), moisture sensitivity, shrink/swell behavior.

6. Slags (Lithium, Copper, Nickel)

6.1. Slags Global Generation

As demand for alkali and transition metals (in particular, lithium, copper, and nickel) has increased due to their tied to batteries, electronics, and green energy, the generation of slags from their extraction and metallurgical processing has also risen. Lithium extraction and processing (e.g., from spodumene / lithium-ion battery recycling) produce lithium slag as a by-product. It has been reported that for each ton of lithium carbonate produced, 8–10 tons of lithium slag (LS) may be generated [133]. The precise global tonnage of slags (especially non-ferrous metal smelting slags) is harder to pin down in open literature; estimates vary, but their cumulative global volume is substantial. Non-ferrous metal smelting — copper, nickel, zinc — is a major contributor. [134] indicate that industrial slags are among the residues of concern regarding waste volume and hazard potential. Furthermore, slag volumes are tied to the production of metals and energy transition demands, so scaling is dynamic.

6.2. Properties of Slags

The slags from copper, nickel, etc., often have a granular texture, can be glassy or crystalline depending on cooling, and may have irregular but often angular particles. The rough, angular, and microporous texture of slag aids strong mechanical interlock and moisture resistance when utilized as a construction material [4,135,136]. They may have high density, hardness [137], making them suitable potential as aggregate replacement. Also, their particle sizes can be ground to fine fractions for use as supplementary cementitious materials.

In accordance with their chemical composition, slags are rich in silicate, alumina, iron oxide, and sometimes magnesium oxide, indicating pozzolanic reactivity and potential application in construction. Slags are rich in SiO_2 , Al_2O_3 , Fe_2O_3 , MgO , and may contain traces of heavy metals such as Cu, Zn, Pb; hence, pH, leachability, and hazard potential are concerns [138].

The mineralogical properties of slags depict presence of glass phases, crystalline phases such as spinels, fayalite, magnetite etc. For lithium slag, there may be phases of silicates, aluminosilicates; in copper and nickel slags, there are similar complexities. These affect their reactivity (e.g., pozzolanic behavior), durability, and stability [137].

6.3. Utilization and Potential Applications of Slags

6.3.1. Application in Pavement Engineering

Slag has excellent properties that qualify it as a sustainable alternative to natural aggregates in pavement construction. In asphalt mixtures, slags have been used as aggregate or filler replacements with the potential to improve some properties, such as abrasion resistance [139]. The suitability of slag as aggregate in asphalt mixtures is due to its high hardness and hydrophobic properties [140].

Technically, slags conform to the standard requirements as aggregate and are permitted to be used in asphalt pavement. Furthermore, the limited calcium content in the slags (lithium, nickel, and copper) eliminates the concerns about expansion issues commonly associated with calcium-rich slags [141]. For instance, the practicability of copper slag (CS) as aggregates in asphalt mixtures was conducted by Oreškovi'c et al. [142]. They observed that the addition of CS does not compromise the mechanical and chemical properties of the asphalt mixtures, suggesting CS as a good potential for utilization as an aggregate substitute in asphalt mixtures. Azizah et al. [143] also confirms that nickel slag improved the permanent deformation resistance of asphalt mixtures because of its interlocking properties, hardness, and the silica content that enhances its adhesion with bitumen. Furthermore, the engineering characteristics of slag can be improved through various methods for enhanced performance in asphalt mixtures. Slags can also be ground into powder and used as filler material in asphalt mixtures. Modarres and Bengar [144], studied asphalt mixture performance containing CS as filler, and they obtained 7.5, 8.5, 10.2, and 21.6% improvement in the mixture M_r, T_{lit}, ITS, and fatigue life compared to the control mix.

Similarly, slag's physical hardness and chemical stability make it a viable material in high-stress pavement base or subbase layers [145]. Its use as a base/subbase material reduces the need to use natural materials, resulting in less exploitation of natural aggregate deposits. Raj and Rai [146] studied the suitability of stabilized copper slag as a pavement construction material. They found out that stabilization of copper slag with 9% cement achieved 10 MPa and 1.5 MPa at 28-day compressive and tensile strength, indicating its effectiveness as a base and subbase material in pavement. The suitability of copper slag as a base material in pavement, with a service life ratio as high as 1.78 and a cost efficiency of 17.4% was also confirmed by Pai et al. [147]. The load-bearing capacity performance of nickel slag in pavement was studied by Arifin et al. [148]. The slag attained a CBR value of 60%, suggesting the suitability of nickel slag as a subbase material for pavement construction. Yuan et al. [149] employed lithium slag in cement-stabilized macadam bases. The cement-stabilized macadam attained optimal performance at 3.0% and 10% of cement and lithium slag substitution, respectively.

Table 13 depicts the applications of slags from lithium, nickel, and copper in pavement construction. Slag's engineering characteristics make it suitable for use in embankment, sub-grade, subbase, base, and bituminous layers of road pavement. They are viable and environmentally sustainable materials for pavement, as they provide benefits such as reducing industrial waste, conserving natural resources, improving road durability, and lowering production costs.

Table 13. Applications of Slags in Pavement Applications.

Slag	Application	Findings	Reference
Lithium	Base/subbase	<ul style="list-style-type: none"> The stabilization of LS with 8% magnesium slag satisfied the minimum strength requirement of 2.7 MPa for subgrade stabilised soil strength criteria in a pavement under heavy traffic loads. 	[150]
Copper	Asphalt mixture	<ul style="list-style-type: none"> The fatigue and indirect tensile strengths of asphalt mixtures increased with the addition of copper slag as a filler. 	[151]
	Base/subbase	<ul style="list-style-type: none"> Copper slag stabilized with 6% lime or cement content satisfied the strength and durability requirements as a base material in road pavements. 	[152]
Nickel	Asphalt mixture	<ul style="list-style-type: none"> The measured rut depths for the nickel slag-asphalt mixtures were comparable to those of the control mixtures, suggesting a good permanent deformation resistance potential. 	[153]

Base/subbase	<ul style="list-style-type: none"> The CBR value of 115% (higher than the specified value of 90%) meets the requirement for the utilization of nickel slag as pavement base material. 	[154]
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6.3.2. Slags in Cementitious and Construction Applications

An estimation of 70-75 billion tonnes of concrete with aggregate constitution of about 60-75% is consumed globally by the construction industry [155]. This massive resource requires significant energy and resource utilization, and is not sustainable for our environment, as it could lead to planetary depletion and limit the ability of future generations to meet their infrastructural needs. Hence, there is a need to shift to more sustainable resource utilization, such as the use of waste materials, such as slags, to promote resource conservation and consequently minimize the environmental footprint of the construction industry. Studies have shown that the utilization of slag as cement and aggregates in concrete improves material durability and enhances structural strength.

Slag's silicon dioxide and aluminum oxide content makes it suitable for construction as a supplementary cementitious material (SCM) by partially replacing cement. The assessment of lithium slag as cement replacement in autoclaved aerated concrete (AAC) was conducted by [156]. Lithium slag (LS) was found to show acceptable properties; it can be used with AAC, with a favorable microstructure and strength when processed. A similar study by [157] also confirms LS contribution to AAC's microstructure and hydration properties. [158] investigated concrete properties using LS as SCM. It was reported that 40% LS addition improved the 180-day compressive strength by 18.34% and reduction of 38.46%, 15.96%, 24.79% in the concrete's sorptivity coefficient, volume of permeable voids, and water penetration depth, respectively. Several studies also confirmed the use of copper slag [159–161] and nickel slag [162,163] as SCMs. It is important to note that when used as SCMs, up to 20% replacement of cement is appropriate for balanced performance. Also, combining slags with other byproducts (fly ash, metakaolin) to form geopolymers or alkali-activated materials can serve as an improved binder for construction applications [164]; thereby leading to an increase in its substitution level.

Slags are also found suitable as aggregate replacements for construction applications with promising properties. Ernawan et al. [165] studied the concrete properties containing nickel slag (NS) as fine aggregate. Using NS up to 50% showed a 3.4% increase in density and a 21.1% increase in compressive strength of the concrete at 28 days. Similar studies also validated that replacing 50% of the natural aggregate with copper slag improved the properties of concrete [166,167].

Table 14 shows the various applications of slags in construction. The application of slag as construction material is a sustainable approach that will promote material circularity, reduce the carbon footprint of construction, and conserve non-renewable resources.

Table 14. Applications of Slags in Construction.

Slag	Application	Findings	Reference
Lithium	Cement	<ul style="list-style-type: none"> About 20% lithium slag addition improved compressive strength by approximately 12.7%, tensile strength by 11.9% and flexural strength by 9.16%; mitigated performance loss from recycled aggregates. 	[168]
	Fine aggregate	<ul style="list-style-type: none"> 20% LS substitution significantly improves the pore structure of the mortar, leading to a reduced chloride ion permeability coefficient. 	[169]
	Precursor	<ul style="list-style-type: none"> The addition of lithium slag alkali-activated materials increased the workability by 20 - 34%, the setting time by 45 - 94% and the 	[170]

		compressive strength by 29% (25% LS addition)	
Copper	Coarse aggregate	<ul style="list-style-type: none"> 60% substitution of copper slag has 18%, 19% and 31% improvement in the split tensile strength, flexural strength, and compressive strength, respectively. 	[171]
	Cement	<ul style="list-style-type: none"> The addition of 10% CS as cement replacement at 28 days and 180 days improves the flexural strength by 3.2% and 3.5%, respectively, compared to the control mixture. 	[172]
	Fine aggregate	<ul style="list-style-type: none"> A maximum compressive strength (at 28 days) of 59.29 MPa was achieved at 35.90% copper slag as fine aggregate. 	[173]
	Precursor	<ul style="list-style-type: none"> The substitution of copper slag as a precursor in AAMs reduced and delayed strength development. Nonetheless, 50% CS incorporation still results in satisfactory strength property. 	[174]
Nickel	Fine aggregate	<ul style="list-style-type: none"> The utilization nickel slag up to 30% resulted in reduction in the porosity and harmful pores, and increased strength in the concrete samples. 	[175]
	Cement	<ul style="list-style-type: none"> The nickel slag is suitable for SCMs at 20% substitution without comprising the concrete properties. 	[176]
	Precursor	<ul style="list-style-type: none"> The AAMs produced with nickel slag attained a maximum compressive strength of 99 MPa at 7-days. 	[177]

6.4. Benefits and Challenges of Slags in Construction

Based on several studies [168,178] the benefits of mine slags in construction applications can be illustrated as follows

- High performance potential: Some slags afford high mechanical strength, durability, chemical resistance, and low permeability, thus suited for demanding applications.
- Reduced carbon footprint: Using slags as SCMs (as a replacement for cement) can reduce the greenhouse gas emissions associated with producing OPC (Ordinary Portland Cement). Also reduces the extraction of virgin aggregates.
- Waste valorization: Instead of disposing of slags (which may be landfilled or pose environmental hazards), using them creates value while mitigating environmental burden.
- Potential for enhanced properties: Slags can improve certain properties like abrasion resistance, durability against chemical attack, or even high-temperature performance in pavements.

Challenges of utilization slags in construction applications,

- Heavy metal content and leachability: Some slags contain toxic metals (e.g., copper slag, lead, zinc), which may leach under certain environmental conditions. Requires rigorous testing, possibly treatment, or encapsulation.
- Variability in slag chemistry and mineralogy: Depending on source, smelting process, cooling rates etc., slag properties differ. This affects performance and reproducibility.
- Processing and cost: Grinding, screening, and cleaning slags (to remove deleterious phases) may require energy and cost. Transportation and handling may be more expensive than local conventional materials.
- Standardization, codes and regulations: Lack of universally accepted guidelines in many regions for safe use; environmental regulations must be met (e.g., leachate, stability).

- Long-term durability and performance: Limited long-term field data, especially under varying climatic and load conditions (freeze–thaw, wet cycles, etc.).

7. Comparative Analysis of Mining Wastes in Construction

Consolidating the insights discussed throughout this review, a comparative summary of the major mining waste types is provided below. Table 15 highlights their annual global production, material properties, potential construction applications, and the critical advantages and limitations associated with each waste stream.

Table 15. Summary and Comparative Analysis of Mining Waste in Construction.

Waste	Global production per annum (Approx)	Key composition	Main applications	Benefits in construction	Challenges
Bauxite Residue	150 million tonnes/year	Fe ₂ O ₃ , Al ₂ O ₃ , TiO ₂ , SiO ₂ , Na ₂ O, CaO	Asphalt mastic, asphalt mixture, Pavement base/subbase, bricks, geopolymers, cement replacement, aggregates	<ul style="list-style-type: none"> • Large global volume available • Fine particle size and high surface area improve packing and bonding in mixes. • Provides pozzolanic activity when blended with lime or cement. • Enhances compressive strength and durability in stabilised soils and binders. • Acts as an effective filler in concrete, mortar, and pavement materials. • Suitable for multiple construction products 	<ul style="list-style-type: none"> • Very high alkalinity (pH > 13) requiring pre-treatment. • Potential leaching of PHEs (As, Cr, V, Pb). • Presence of NORM (U, Th), causing regulatory and public concerns. • Fine particle size and high sodium content affecting workability. • High moisture content and high transport/handling costs.
Mine Tailings	10 billion tonnes/year	CaO, SiO ₂ , Al ₂ O ₃ , Fe ₂ O ₃ , SO ₃ , P ₂ O ₅ , MgO, MnO, K ₂ O	Road base, Filler, concrete, mortar, bricks, and geopolymer productions,	<ul style="list-style-type: none"> • Suitable as fine aggregate and filler in asphalt and concrete. • Pozzolanic activity allows partial cement replacement. • Improves strength and durability when properly treated. • Suitable for multiple construction products • Reduces demand for natural sand and cement 	<ul style="list-style-type: none"> • Highly variable material properties. • Potential leaching, acid generation, and heavy metals. • Limited long-term performance data. • Lack of standards and regulatory guidance. • Requires pretreatment for consistent performance
Waste Rock / Overburden	50 billion tonnes/year	SiO ₂ , Al ₂ O ₃ , Fe ₂ O ₃ , CaO, SO ₃ , P ₂ O ₅	Asphalt mixture, pavement base/subbase, coarse and fine aggregate in concrete, ceramic production, Geopolymer	<ul style="list-style-type: none"> • High mechanical strength and durability suitable for road base, subbase, and embankments. • Good bearing capacity and drainage when properly crushed and compacted. • Can replace natural aggregates in asphalt, concrete, mortar, and bricks. • Suitable for internal mine roads due to on-site availability and low transport distance. • Supports resource conservation and sustainable construction. 	<ul style="list-style-type: none"> • Highly variable physical, chemical, and mineralogical properties. • Potential risks of heavy metal leaching or acid generation (if sulfide-bearing). • Lack of consistent standards, codes, and regulatory guidance. • Durability concerns under freeze–thaw, wetting–drying, and moisture sensitivity.
Copper Slag	70 million tonnes/year [179]	SiO ₂ , Al ₂ O ₃ , Fe ₂ O ₃ , MgO	Asphalt mixture, pavement base/subbase, Coarse and fine	<ul style="list-style-type: none"> • High hardness and angularity • Does not compromise mechanical or chemical properties in asphalt mixes. 	<ul style="list-style-type: none"> • Contains trace heavy metals such as Cu, Zn, Pb, leachability, and hazard concerns

	aggregate, Cement, Precursor	<ul style="list-style-type: none"> • Can improve asphalt mixture performance (abrasion resistance, interlock). • Can be ground into powder and used as filler or SCM. 	<ul style="list-style-type: none"> • Chemical and mineralogical composition differ with source and process. • Grinding/processing increases cost. • Limited long-term performance data in pavements and concrete.
Nickel Slag 30 million tonnes/year [180]	Asphalt mixture, pavement base/subbase, Fine aggregate, Cement, Precursor	<ul style="list-style-type: none"> • Hard, angular texture improves interlock and rutting resistance in asphalt. • Achieves high CBR values, suitable for pavement base/subbase. • Improves performance of asphalt mixtures (permanent deformation resistance). • Can be ground and used as SCM for cement replacement. • Enhances strength when used as a fine aggregate. 	<ul style="list-style-type: none"> • May contain trace heavy metals • Mineralogy varies depending on smelting and cooling rate. • Requires processing (grinding/crushing) for SCM functionality. • Limited long-term durability and field data.
Lithium Slag / Spodumene Tailings 10 million tonnes/year [181]	Pavement base and subbase, Cement, Fine aggregate, Precursor	<ul style="list-style-type: none"> • Rich in silicates and aluminosilicates, suitable SCM. • Improves microstructure and strength of AAC and concrete. • Suitable for cement-stabilized bases at certain substitution levels. • Improves pore structure when used as fine aggregate. • Supports improved hydration and mechanical performance in concrete. 	<ul style="list-style-type: none"> • Complex mineralogy • Requires grinding or activation for consistent performance. • Shows varying performance depending on processing route. • Limited standards and fewer long-term studies compared to other slags.

Note: Information summarized from References [7,11–51,56,66–101,107,109,110,115–131,137–181].

8. Conclusions and Future Recommendations

This review examined the potential of four major mining waste streams, mine tailings, bauxite residue, waste rock/overburden, and slags, including Lithium, copper, and nickel, as sustainable construction materials, with particular focus on pavement engineering and other construction applications. As the mining waste poses environmental and human health risks, careful management and volatilization are significant. Upon reviewing the above waste types, the following key points can be identified.

- The findings consistently demonstrated that these materials possess valuable physical, chemical, and pozzolanic properties that can partially or fully replace traditional construction aggregates, fillers, and binders.
- Their use enhances the performance of construction materials while conserving resources, reducing pressure on natural aggregates, lowering material costs, and aligning with circular-economy and low-carbon infrastructure goals.

Despite these advantages, the following barriers still limit the large-scale adoption.

- Bauxite residue continues to face challenges related to extreme alkalinity, potential leaching of PHEs (As, Cr, V, Pb), NORM-related concerns, high sodium content, moisture, and transport limitations.
- Mine tailings exhibit high variability, environmental risks such as acid generation or heavy metal release, and lack long-term performance data and standardization.
- Waste rock displays strong geotechnical characteristics but varies widely in composition and may pose environmental risks where sulfide minerals are present.

- Slags, including copper, nickel, and lithium slags, are used less than they could be due to chemical variability, concerns about heavy-metal leachability, processing costs, lack of standards, and limited data from long-term field installations.

According to the identified challenges, several future directions can be recommended.

- Standardized classification and testing frameworks are needed to evaluate variability, leaching behavior, and engineering performance for each waste type.
- Consistency guidelines for pavement, concrete, and geopolymer applications would increase industry confidence in adoption.
- Future studies should also explore combining mining wastes with other industrial by-products, as hybrid mixtures may enhance material performance and help overcome individual drawbacks.
- Advanced pretreatment and beneficiation technologies, such as carbonation, mechanical activation, alkali activation, metal recovery, or hybrid chemical–thermal treatments, should be further developed to reduce alkalinity, immobilize contaminants, and enhance pozzolanic reactivity.
- Large-scale field trials and long-term monitoring programs are essential to validate laboratory findings, especially for pavement layers and structural applications, where durability under real environmental conditions must be demonstrated.
- Integrating life-cycle assessment (LCA) and carbon accounting into the evaluation of mining-waste-based materials will provide clear evidence of environmental benefits and help align construction practices with global commitments such as net-zero CO₂ by 2050.
- Digital tools, including AI-based material classification, geopedological modelling, and geospatial databases, offer promising pathways for optimizing waste stream selection and predicting performance.
- Finally, addressing regulatory frameworks, public perceptions of leaching and radiation concerns associated with waste and treatments, and market incentives will be crucial for achieving widespread adoption of waste-derived construction materials.

In summary, mining waste represents a substantial, largely untapped resource for sustainable construction. With coordinated advances in treatment technologies, environmental risk management, specification development, and field validation, these materials can transition from long-term liabilities into high-value assets that support resilient, low-carbon, and resource-efficient construction systems.

Author Contributions: Conceptualization, C.D., N.M. and D.O.; methodology, C.D., N.M. and D.O.; validation, C.D., N.M. and D.O.; resources, C.D., N.M. and D.O.; data curation, C.D., N.M. and D.O.; writing—original draft preparation, C.D., N.M. and D.O.; writing—review and editing, C.D., N.M. and D.O.; visualization, C.D., N.M. and D.O.; supervision, N.M.; funding acquisition, N.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data used for the study are included in the manuscript.

Acknowledgments: Guidance and support received from the School of Engineering at Edith Cowan University are highly acknowledged.

Conflicts of Interest: The authors declare no conflicts of interest.

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