

Recovery of Mining Wastes in Building Materials: A Review

Alinabiwe Nyamuhanga Ally^{1,2}, Manjia Marcelline Blanche³, Ursula Joyce Pettang Nana³,
Masika Muhiwa Grâce^{1,2}, Ngague François⁴, Chrispin Pettang³

¹Laboratory Engineering Civil and Mechanics, Doctoral Research Unit for Engineering and Applications, University of Yaoundé I, Yaoundé, Cameroon

²Department of Civil Engineering, Faculty of Applied Sciences and Technologies, Free University of Great Lakes Countries, Goma, DRC

³Department of Civil Engineering, National Advanced School of Engineering of Yaoundé, University of Yaoundé I, Yaoundé, Cameroon

⁴Department of Civil Engineering, Fotso Victor University Institute of Technology, University of Dschang, Bandjoun, Cameroon
Email: ir.alny111@gmail.com

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Abstract

The use of materials from waste in buildings compensates for the lack of natural resources, solves the problem of waste management and provides an alternative technique for protection of the environment. There are a large number of industrial wastes that are used for full or partial replacement of raw materials in some construction materials. This review assesses mining waste in concrete as a substitute for aggregates and cement; in fired bricks as a substitute for soil; and in road backfill as a substitute for soil. This paper reviews some mining tailings, mine waste rocks and some slags obtained in the exploitation and/or processing of some ores including iron, gold, lead, phosphate, copper, coal, etc. Different physical properties, mechanical properties, chemical properties, heavy metal content, mineralogic composition, geotechnical properties and environmental properties (leaching test) of the mine wastes were examined. The physical, mechanical and environmental properties of the materials obtained by substitution of raw materials by mine waste were examined and compared to reference materials. Mining waste in cementitious materials offers good compressive strengths, while the porosity of the concrete and/or mortar is a factor influencing its toxicity. As for the waste in fired bricks, fired at a temperature of 900°C or more, it offers convincing compressive and flexural strengths. The few research studies obtained on the use of mining waste in road embankments have shown that mining waste can be used as a sub-base layer and backfill as long as it is not toxic. In addition, several other mining wastes require special attention as substitutes for raw

materials in construction materials, such as coltan, cobalt.

Keywords

Mining Waste, Tailings, Waste Rock, Slug, Fired Brick, Backfill Material, Cement Materials

1. Introduction

From an economic and environmental point of view, the treatment of the large volumes of waste continuously produced by industrial and urban activities on the one hand, and the depletion of resources on the other, are currently causing problems. Among these waste-producing activities, the mining industry is criticized for the large quantities of mining waste produced during the exploitation of mineral deposits [1]. Nearly 250000 million tonnes of solid waste are produced annually by mining activities in several forms [2]. Mining activities include mining, mineral processing and metallurgical extraction. Underground or open pit mining operations generate three main types of solid waste: rock waste in the form of rock fragments representing the non-commercial portion of the extracted rock, concentrator tailings consisting of gangue, water and sometimes chemical additives used during the ore processing phase, and finally contaminated water treatment sludge [2]. In addition to rock waste and tailings, dead soil excavated during mining operations is also considered to be mining waste. Geologically heterogeneous, mining waste is a material made up of sedimentary, metamorphic or igneous rocks, soils and loose sediments ranging in size from fine particles to boulders. In addition to occupying large areas, mining waste causes serious environmental problems and significant ecological disturbances if not properly controlled. It represents one of the major sources of industrial waste requiring particular attention from the scientific community due to the enormous volumes involved [3] [4]. Increasing attention has been paid to the use of waste in construction materials, including concrete, road backfill, fired bricks and ceramics [1] [5] [6]. This application is motivated by the exhaustibility of natural resources and the promotion of sustainable development by promoting a circular economy.

Researchers around the world have multiple views on the potential use of mining waste; some researchers suggest that depending on their properties, mining waste can partially or fully replace aggregates and cement in concrete, clay, fired bricks, etc. This review collects, categorizes and summarizes the use of different types of mining waste in construction materials including concrete (cement, sand and aggregate), fired bricks (clay) and backfill materials (soil).

This paper presents an overview of the characteristics of mining waste and its use in construction materials, particularly in concrete, fired bricks and backfill materials. The results will be expressed in origins and typologies of mining wastes,

characteristics of mining wastes and characteristics of materials containing mining wastes. The review presented is structured in two main sections, namely the methodology used (Section 2) and the results obtained (Section 3).

2. Methodology

The methodology used to obtain an overview of the use of mining waste in construction materials is based on a thorough review of research into the use of mining waste in construction materials, particularly in cementitious materials (concrete and mortar), fired bricks and backfill materials. The bibliography reviewed in this paper includes publicly defended theses, articles published in academic journals, peer-reviewed thematic conferences and case studies. The keywords and terminology used in the literature were associated with mine waste and construction materials including mine waste (tailings, waste rock, slag), concrete, mortar, mechanical strength, workability, fired bricks and road fill. The literature review consisted of

- Highlighting the main origins and typologies of mining waste;
- Highlighting some properties of mining wastes, in particular physical properties (particles gradation, specific gravity, bulk gravity, water absorption); mechanical properties (the modulus of elasticity; wear resistance; Los Angeles coefficient); chemical composition; heavy metals and metalloids content, mineralogical composition, geotechnical properties (angle of internal friction, cohesion, Atterberg limits, ...) and environmental properties (leaching test), compared to the US-EPA standard on waste characteristics;
- Presentation of the physical, mechanical and environmental properties of construction materials (concrete, mortar, fired bricks, backfill materials) obtained by partial or total substitution of the raw material by mining waste.

3. Presentation of the Results

3.1. Origins and Typology

In mining, mineralized wastes come from three main sources: mining exploitation, mineral processing and metallurgical processing.

The typology of mining waste depends on its origin. Indeed, inefficiencies due to multiple factors at each level lead to mineral losses in waste rock, tailings, slag and leached ore. Mining water, which comes into contact with solid waste, either naturally or by being introduced during one of the production stages, is also a mining waste. When used, it is loaded with dissolved metals and is characterized by its mobility, thus contributing to the spread of environmental contamination [7]. Lottermoser provides a comprehensive overview and detailed description of the different types of mining waste and their sources, summarized in **Figure 1**. In addition, any mineralized material that is not exploited on site can be considered as mining waste [2]. In particular, a portion of the ore body left exposed and unmined may also come into contact with mining waters, contributing to dissolved metal releases.

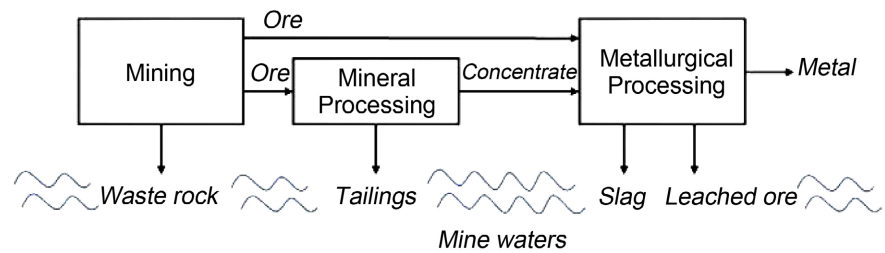


Figure 1. Origins of mineralised waste [2].

3.2. Characteristics of Mining Waste

3.2.1. Physical Properties

The physical properties of mining wastes, such as particle size distribution, specific gravity, bulk density and water absorption rate are sufficient to confirm their ability for use in construction materials (concrete, fired bricks, road fill) to be recognised.

1) Particles gradation

The size distribution of phosphate miningrock waste is about 100% between 6.3% and 25 mm according to El Machi [8]. The particle size distribution of gold mining waste rock is between 0 and 20 mm, of which 14% is less than 0.1 mm; 10% is between 0.1 mm and 0.6 mm; about 30% is between 0.6 mm and 5 mm and about 46% is between 5 mm and 20 mm [9]. The particle size distribution of dry compacted phosphate miningrock waste is between 0.001 mm and 100 mm of which 25% is between 0.001 mm and 0.5 mm; 10% is between 0.5 mm and 20 mm and 50% is between 20 mm and 100 mm [10].

More than 30% of phosphate processing slags consists of ultrafine particles (<5.0 μm), while its equivalent diameter (D_{50}) is 8.3 μm , with more than 80% of the particles being fines (<25 μm) [11]. **Table 1** shows the particle size of some mining waste obtained by some researchers.

On the one hand, it can be observed that the particle distribution of mining waste ranges from fines to gravel, and on the other hand, the particle size of mining waste depends on the type of waste, the ore mined and the process used to obtain the ore.

2) Specific density

The specific gravity of iron tailing obtained by Xingfong *et al.* [6] is about 3.51 ± 0.4 ; that of gold mine tailing obtained by Ceren Ince is 3.46 [13]. The specific gravity of gold mine waste rock reported by Youssef Bernachid *et al.* [9] and Y. Taha *et al.* [14] is approximately between 2.7 and 3.5. Several researchers have reported the specific gravity as shown in **Table 2**.

3) Bulk density

The bulk density of some mining wastes obtained by some researchers is mentioned in **Table 2**. Y. Taha *et al.* [14] mention that the bulk density of gold miningrock waste is 1.56 - 1.65 while R. Argane *et al.* [15] have a bulk density between 1.380 and 1.56.

4) Water absorption

Table 1. Granulometric characteristics.

Wastes	d (μm)	D (μm)	<63 μm	<80 μm	D10 (μm)	D30 (μm)	D50 (μm)	D80 (μm)	D90 (μm)	MF
Iron tailing [6]	0	5000	-	-	-	-	-	-	-	-
	5000	20,000	-	-	-	-	-	-	-	-
	20,000	40,000	-	-	-	-	-	-	-	-
	40,000	80,000	-	-	-	-	-	-	-	-
	80,000	150,000	-	-	-	-	-	-	-	-
Gold tailing [12]	1	100	-	-	1.8	-	5.6	-	43.67	-
	1	100	-	-	1.8	-	4.4	-	13.0	-
	50	100	-	-	11.0	-	30.6	-	52.0	-
	50	300	-	-	81.2	-	128.6	-	205.4	-
Gold-mine tailings [13]	1	100	-	-	-	-	-	-	-	-
Waste rock gold mining [9]	0	5000	-	-	-	-	-	-	-	2.12
	5	20,000	-	-	-	-	-	-	-	-
Waste rock gold mine [14]	0	20,000	-	20 - 24	-	-	-	-	-	-
Lead tailing [15]	5	704	14	-	-	-	-	-	-	-
	5	418.6	48.24	-	-	-	-	-	-	-
Phosphate mine waste rock [16]	800	80,000	-	-	-	-	-	-	-	-
Flint from phosphate mine waste rock [17]	6300	15,500	-	-	-	-	-	-	-	-
	12,500	25,000	-	-	-	-	-	-	-	-
Phosphate processing sludge [11]			-	-	2.4	5	8.3	17.2	-	-
(Dry compacted phosphate mine waste rock) [10]	0	100,000	-	-	-	-	-	-	-	-
Phosphate mine waste rocks [8]	10,000	20,000	-	-	-	-	-	-	-	-
Copper tailing [5]	0	2000	-	-	-	-	-	-	-	1.573

Xingdong *et al.* [6] performed the absorption of iron tailings and found 0.2% and 1.22%. Sukhoon Pyo *et al.* [12] observed that the water absorption of gold tailings is 1.21% and 2.67%, while Ceren Ince [13] stated that the water absorption of gold tailings is 7.15%. The water absorption capacity of gold mine waste rock reported by Youssef Bernarchi *et al.* [9] is 2.05%. A. El. Machi *et al.* [8] found the water absorption of 5.2% for phosphate mine waste. **Table 2** reports the water absorption of mining waste obtained by researchers.

It can be seen from the physical properties presented in this section that the distribution of mining waste particles ranges from fine to coarse; the specific gravity is between 2.55 and 3.925 and water absorption is between 0.2% and 5.2%. Furthermore, it can be noted that the physical properties, in particular the granulometry, specific density and water absorption of mining waste, are a function of the type of waste, the ore mined and the process used to obtain the ore.

Table 2. Specific density, bulk density, water absorption.

Mining wastes	Abs (%)	Specific density	Blaine specific surface area (cm ² /g)	Bulk density (kg/m ³)	w (%)
Iron tailing [6]	1.22	3.120	-	-	-
	0.4	3.715	-	-	-
	0.2	3.225	-	-	-
	0.2	3.285	-	-	-
	0.2	3.925	-	-	-
Gold tailing [12]	2.67	-	-	-	-
	2.1	-	-	-	-
	2.6	-	-	-	-
	2.6	-	-	-	-
Gold-mine taillings [13]	7.15	3.46	368	-	-
Waste rock gold mining [9]	2.04	2.68	-	-	-
	0.84	3.42	-	-	-
Waste rock gold mine [14]	0.7	2.73	-	1650	-
	2.04	3.45	-	1560	-
Tailing plomb [15]	0.7	2.7	-	1380	-
	0.7	3.12	-	1560	-
Flint from phosphate mine waste rock [17]	1.57	2.57	-	-	0.2
	1.58	2.55	-	-	0.18
Phosphate processing sludge [11]	-	2.47	-	-	-
Dry compacted phosphate mine waste rock [10]	2.664	-	-	-	-
Phosphate mine waste rocks [8]	5.2	-	-	-	0.1
Copper tailing [5]	-	3.10	-	-	-

3.2.2. Mechanical Properties

Xingdong *et al.* [6] performed the compressive test on iron tailings, and found the compressive strength of 160 Mpa and 131 Mpa in dry and wet state respectively, with iron tailings Young's modulus of 81 Mpa in the dry state and 65 Mpa in wet state. Aiman and Machi *et al.* [17] working on the flint from phosphate mine waste rock found the microdeval wear resistance of 9.8% and Los Angeles coefficient of 19%. A. El Machi *et al.* [8] working on phosphate mine waste rock observed Los Angeles coefficient is 41% and Microdeval wear resistance is 43%; while Mustapha Amran *et al.* [16] noted that the Los Angeles coefficient of phosphate mine waste rock is between 45% - 58% with a Microdeval coefficient between 50% - 70%. In the light of the results of these researchers, it is observed that the resistance to impact and wear is primarily related to the mineralogical constitution of the mine waste tested.

3.2.3. Chemical Properties

Xingdong *et al.* [6] observed that almost 85.5% of iron tailings consist of silica, alumina, ferric oxide and calcium oxide distributed as follows: 38.3% SiO₂; 15.8% Al₂O₃; 15.6% Fe₂O₃ and 15.8% CaO. Sukhoon Pyo *et al.* [12] found that Gold tailings consist of 60% to 80% by silica. M. Ettoumi *et al.* [11] observed that 55.9% of the phosphate processing slag consists of silica and calcium oxide (39% SiO₂; 16.9% CaO). Aiman and Machi *et al.* [8] observed that 92% of the flint from phosphate mine waste rock is silica. The chemical constitutions of some mining wastes obtained by some researchers are presented in **Table 3**.

It is observed from the afore presented chemical constitutions that the chemical properties of iron tailings are functions of the nature of ore exploited, the treatment of the minerals and the metallurgical treatment employed.

Table 3. Chemical composition of some mining wastes.

Mining wastes	SiO ₂ (%)	Al ₂ O ₃ (%)	Fe ₂ O ₃ (%)	MnO (%)	MgO (%)	CaO (%)	Na ₂ O (%)	K ₂ O (%)	TiO ₂ (%)	P ₂ O ₅ (%)	SO ₃ (%)	CuO (%)	Cl (%)	ZnO (%)	Mn ₂ O ₂ (%)	Cr ₂ O ₃ (%)	V ₂ O ₅ (%)	S _{total} (%)	C _{total} (%)	BaO (%)	Cl ⁻ (%)	LOI (%)
Iron tailing [6]	38.3	15.8	15.6	0.2	5.8	15.8	2.5	0.1	4.9	-	0.5	-	-	0.01	-	-	-	-	-	-	0.01	0.4
Gold tailing [12]	79.53	9.52	3.22	0.16	0.64	0.51	0.72	3.24	0.52	0.06	-	-	-	-	-	-	-	-	-	-	-	2.46
	80.60	9.33	3.99	0.15	0.66	0.42	0.64	3.57	0.60	0.05	-	-	-	-	-	-	-	-	-	-	-	0.15
	59.60	8.57	11.59	0.49	1.83	10.94	0.09	1.53	0.62	0.27	-	-	-	-	-	-	-	-	-	-	-	<1
	59.60	8.57	11.59	0.49	1.83	10.94	0.09	1.53	0.62	0.27	-	-	-	-	-	-	-	-	-	-	-	<1
Gold-mine taillings [13]	44.62	8.64	26.1	0.09	0.51	14.89	1.63	0.55	0.41	-	2.31	0.02	0.11	-	-	-	-	-	-	-	-	-
Waste rock gold mining [9]	56.19	13.77	7.35	0.11	3.97	5.76	2.94	0.97	0.58	0.17	-	-	-	-	-	0.24	0.02	0.31	1.24	-	-	5.21
Waste rock gold mine [14]	75.0	12.3	3.6	-	0.49	0.16	-	4.297	0.013	-	-	0.32	-	-	0.01	-	-	-	-	-	-	2.1
Tailling plomb [15]	68.44	9.38	2.2	-	0.48	1.99	0.7	5.46	-	-	-	-	-	-	-	-	-	0.449	-	1.2	-	-
	9.16	3.09	2.11	-	11.27	29.83	0.1	0.48	-	-	-	-	-	-	-	-	-	0.651	-	9.3	-	-
	41.30	0.40	-	-	9.10	18.70	-	-	4.22	-	-	-	-	-	-	-	-	0.30	0.21	-	-	24.20
	50.10	0.44	-	-	7.20	16.20	-	-	5.40	-	-	-	-	-	-	-	-	0.40	0.18	-	-	18.30
Phosphate mine waste rock [16]	55.50	4.10	0.50	-	4.90	12.10	1.60	5.10	-	-	-	-	-	-	-	-	-	0.20	0.31	-	-	15.50
	53.90	3.80	0.40	-	5.50	12.90	1.31	4.70	-	-	-	-	-	-	-	-	-	0.30	0.44	-	-	17.40
	56.40	3.10	0.30	-	5.40	12.50	1.00	4.20	-	-	-	-	-	-	-	-	-	0.30	0.38	-	-	16.90
Flint from phosphate mine waste rock [17]	92	0.22	1.1	0.06	-	2.85	0.1	0.05	0.82	-	-	-	-	-	-	-	-	-	-	-	-	-
Phosphate processing sludge [11]	39.1	7.3	2.6	-	2.9	16.9	1.5	0.8	0.3	6.5	-	-	-	-	-	-	-	-	-	-	-	19.5
Dry compacted phosphate mine waste rock [10]	52.1	3.2	0.5	-	6.8	14.2	0.4	1.2	4.6	-	-	-	-	-	-	-	-	-	0.1	-	-	16.6
Phosphate mine waste rocks [8]	32.23	0.58	0.21	0.06	9.20	23.20	-	0.10	0.05	7.26	-	-	-	-	-	-	-	-	-	-	-	-
Copper tailing [5]	75.0	12.3	3.6	-	0.49	0.16	-	4.297	0.013	-	-	0.32	-	0.01	-	-	-	-	-	-	-	2.1
Coal mine waste [18]	59.5	12.4	4.3	-	1.34	2.00	0.64	1.20	0.76	-	-	-	-	-	-	-	-	0.47	7.2	-	-	8.2

3.2.4. Heavy Metal Content

In addition to different chemical compositions presented above, there is a particular interest in heavy metals and metalloids present in mining waste. **Table 4** shows some of the heavy metals and metalloids that some researchers have observed in some mining wastes. Furthermore, it can be observed that the content of heavy metals in mining waste is related to the nature of ore exploited.

3.2.5. Mineralogic Composition

Several researchers evaluated the mineralogical composition of mine waste. Xingdong *et al.* [6] observed that iron tailings consists of 31% of Quartz, 26.1% of Albite and 15.8% of Chamosite. Y. Taha *et al.* [14] observed that gold mining waste consists of 37.6% quartz, 27.1% albite and 15.3% albite. Mustapha Amrani *et al.* [16] observed that phosphate miningrock waste consists of 41% quartz and 40.89% dolomite. M. Ettoumi *et al.* [11] as for them observed a mineralogical composition of phosphate processing sludge of 29% quartz, 23% calcite, 15% fluorapatite and 11.9% vermiculite. **Table 5** explicitly presents the different mineralogical compositions of some mining wastes obtained by researchers. It can be seen that the mineralogical composition of the different mining wastes is closely related to the chemical composition, but also depends on crystallization conditions of the ore that is exploited. Furthermore, the mineralogical composition of rock waste depends on the type of rock and its associated primary and secondary minerals; that of tailings and slags depends not only on the mineral processed but also on its degree of oxidation (exposure to water, bacteria and oxygen).

3.2.6. Geotechnical Properties

Some researchers tried to evaluate the geotechnical properties of mining waste such as coal mining waste and phosphate miningrock waste; the results are

Table 4. Heavy metal content (mg/kg).

	As	Ba	Cd	Co	Cr	Cu	Mn	Mo	Ni	Pb	Se	Zn	Fe
Gold tailing [12]	282.4	-	-	-	-	75.2	-	-	-	195.9	-	78.8	325
	0.84	-	-	-	-	70.1	-	-	-	190.48	-	70.1	335
	225.4	-	13.5	-	-	-	-	-	-	11.5	-	93.5	3154
	225.4	-	13.5	-	-	-	-	-	-	11.5	-	93.5	3154
Gold-mine tailings [13]	-	-	0.31	-	7	32	-	-	-	62	-	287	-
Waste rock gold mining [9]	607	300	<5	40	1320	309	724	55	429	<5	33	<55	-
Waste rock gold mine [14]	<30	-	<5	36	225	-	387	37	67	8	-	<55	-
	607	300	<5	40	1320	309	724	55	429	<5	33	<55	-
Tailling plomb [15]	30	-	-	-	90	130	-	110	-	4210	-	230	-
	20	-	-	-	50	20	-	2.3	-	20	-	260	-
Phosphate processing sludge [11]	0.03		0.06		0.6				0.05	0.05		0.2	-

Table 5. Mineralogical composition of some mining wastes.

	Quartz	Albite	Labradorite	Orthoclase	Calcite	Dolomite	Biotite	Chamosite	Actinolite	Anorthite	Epidote	Cristobalite	Fluorapatite	Illite
Iron tailing [6]	31.3	26.1	-	-	7.3	4.5	7.8	15.8	-	-	-	-	-	-
Waste rock gold mine [14]	37.6	27.1	-	-	7.1	4.7	8.2	15.3	-	-	-	-	-	-
	29.4	24.1	13	-	-	-	24	9.4	-	-	-	-	-	-
Phosphate mine waste rock [16]	41.21	5.06	-	-	6.04	40.89	-	-	-	0.38	-	-	6.42	-
	49.8	6.4	-	-	5	32	-	-	-	0.6	-	-	6.2	-
	32	6.2	-	-	3.9	21.1	-	-	-	0.44	-	17.4	8.3	11
	30.1	5.6	-	-	3.5	24	-	-	-	0.8	-	18.4	8.1	9.2
	33.6	4.9	-	-	3.7	24	-	-	-	0.9	-	18.4	7.9	6.5
Flint from phosphahate mine waste rock [17]	92.3	-	-	-	-	4.8	-	-	-	-	-	-	2.91	-
Phosphate processing sludge [11]	22.3	-	-	-	23.1	6.9	-	-	-	-	-	-	15.6	-
Dry compacted phosphate mine waste rock [10]	42	-	-	-	1.8	30	-	-	-	-	-	-	10.2	10.4
Coal mine waste [18]	40.8	3.7	-	-	-	-	-	-	-	-	-	-	-	-

	Bassanite	Heulandite Ca	Palygorskite	Hematite	Vermiculite	Plagioclase Albite	Muscovite	Gypsum	Pyrophilitis	Titanite	Pyrite	Goethite	Chlorite lib
Iron tailing [6]	-	-	-	-	-	-	-	-	-	-	-	-	-
Waste rock gold mine [14]	-	-	-	-	-	-	-	-	-	-	-	-	-
	-	-	-	-	-	-	-	-	-	-	-	-	-
Phosphate mine waste rock [16]	-	-	-	-	-	-	-	-	-	-	-	-	-
	-	-	-	-	-	-	-	-	-	-	-	-	-
	-	-	-	-	-	-	-	-	-	-	-	-	-
	-	-	-	-	-	-	-	-	-	-	-	-	-
Flint from phosphahate mine waste rock [17]	-	-	-	-	-	-	-	-	-	-	-	-	-
Phosphate processing sludge [11]	9	1	9.3	0.9	11.9	-	-	-	-	-	-	-	-
Dry compacted phosphate mine waste rock [10]	-	-	-	0.6	-	5.0	-	-	-	-	-	-	-
Coal mine waste [18]	-	-	-	-	-	-	34	3	7.7	0.8	0.3	3.2	6.3

presented in **Table 6**, which shows that their geotechnical properties function on the particle size of the mine waste.

3.2.7. Environmental Properties (Leaching Test)

The general objective of leaching tests is to determine the number of chemical species present in waste or waste-based materials in a given leachant. In other words, the leachate test is a test in which a material is brought into contact with a leachant and certain constituents of the material are extracted. The results of the TCLP (Toxicity Characteristic Leaching Procedure) test of some mining wastes obtained by some researchers are summarized in **Table 7**. The concentrations of leached heavy metals and metalloids are mostly low and below the thresholds set for granular wastes in the US-EPA Waste Characteristic Specifications [19]. Furthermore, it is observed that the mobility of chemical species present in mining waste in a given leachate is directly related to the level of heavy materials containing it, but also to the leachate used.

3.3. Overview in Building Materials

3.3.1. Mining Waste in Cementitious Materials

Infrastructure and civil engineering development keeps on increasing each year, making concrete the most widely used construction material in the world compared to steel, wood, plastic and aluminum [20]. Each year, the use of concrete is estimated to around 11 billion metric tons [21]. Coarse aggregates occupy 60% - 80% of the volume of concrete and play a crucial role in the development of the mechanical properties of concrete [22] [23] [24]. The demand for aggregates for the concrete industry is constantly increasing, resulting in the depletion of natural resources. In order to reduce the dependence on natural aggregates, many researchers have investigated the substitution of natural aggregates with industrial by-products as an alternative for the construction industry [25]-[30].

A. El Machi *et al.* [8] showed in an experimental study that mixing concrete with Flint from phosphate mining rock waste required an additional amount of water compared to mixing natural aggregates in order to obtain the desired workability. Furthermore, in terms of compressive, flexural and tensile strength at 28 days, waste rock concretes have a lower range of strengths compared to natural aggregate based concretes and are therefore not intended in terms of performance for structural concretes, but may be suitable for other uses such as perimeter walls and sidewalks. This approach can also be beneficial to mining

Table 6. Geotechnical properties of mine waste.

Waste	ρ (°)	C (Mpa)	W1 (%)	WP (%)	IP (%)	Cc	Cs	σ (P) (kPa)	VBM
Coal mine waste rock [18]	30	13	42	25	17	0.15	0.04	80	0.89
Phosphate mine waste rock [16]	27 - 32.4	4 - 7	37 - 45	25 - 30	12 - 15	-	-	-	0.58 - 0.71

Table 7. Environmental property (mg/litre).

Mining wastes	As	Ba	B	Cd	Cr	Hg	Pb	Se	U	Cu	Fe	Mo	Zn	V	Be	Bi	Co	Mn	Ni
Waste rock gold mining [9]	<0.06	0.19	0.03	<0.003	<0.003	0.00012	<0.0003		-	-	-	-	-	-	-	-	-	-	-
Waste rock gold mine [14]	0.0011	0.22		0.001	0.001		0.0011			0.043		0.001	0.08		0.0011	0.0011	0.007	7.25	0.0011
	0.0011	0.63		0.001	0.007		0.0011			0.0011		0.001	0.04		0.0011	0.0011	0.0011	3.15	0.021
Plomb tailling [15]	<0.06	1.08			<0.003		232			0.454	0.221	<0.009	0.645		-	-	-	-	-
	0.072	0.586		<0.003		5.26			0.18	0.07	<0.009	103	0.072		-	-	-	-	-
	<1			<0.10	<0.20		<0.60	<0.10		<0.50			0.55	<1	-	-	-	-	-
Phosphate mine waste rock [16]	<1			<0.10	<0.20		<0.60	<0.10		<0.50			0.62	<1	-	-	-	-	-
	<1			<0.10	<0.20		<0.60	<0.10		<0.50			0.73	<1	-	-	-	-	-
	<1			<0.10	<0.20		<0.60	<0.10		<0.50			0.54	<1	-	-	-	-	-
	<1			<0.10	<0.20		<0.60	<0.10		<0.50			0.56	<1					
Phosphate processing sludge [11]	0.07	0.016	0.071	0.011	-	<0.02	-	-	-	-	-	-	0.058	-	-	-	-	-	-
Limits (US-EPA) [19]	5	100	500	1	5	0.2	5	1	2	-	-	-	2	-	-	-	-	-	-

companies, who can ensure the manufacture of sidewalks and boundary walls at their mining sites, rather than importing these materials from outside.

Aiman El Machi *et al.* [17] showed that the complete replacement of natural aggregates by flint aggregates, from phosphate waste rocks in the production of B25 concrete showed significant performance in terms of compressive strength, which reached an average of 29 MPa at 28 days, with a slightly lower dry concrete density than the reference concretes, significant flexural strength indicating the good interlocking between the flint aggregates and the hardened cement paste. Their results were able to show that flint aggregates, derived from phosphate waste rocks in concrete, is an alternative to reduce the environmental and economic problems related to the production of mining waste and the depletion of natural resources.

Ceren Ince [13] showed that the compressive strength of cement mortars with replacement of cement and sand by gold residues respectively is increasing up to 30% replacement. This observed increase was mainly due to the finer particle size of the gold residues used as filler material, which reduced the porosity and densified the microstructure of the matrix on the one hand and on the other hand it was due to the pozzolanic character of the gold residues. The porosity decreases with the substitution of the sand and cement by the gold residues.

R. Argane [15] was able to show that the use of lead tailings as aggregates in cement mortar requires an additional quantity of water thus implying an increase of the W/C ratio. The tailings-based mortars present relatively good properties at 28 days between 8.58 Mpa and 10.9 MPa. Furthermore, R. Argane explains that the presence of heavy metals such as Pb and Zn in the residues delays the process of main cement hydration products (CSH and Zn), cement hydration products (CSH and portlandite) by creating an impermeable coating around the clinker, impermeable coating around the non-hydrated cement clinker grains.

Some researchers have had to quantify the variability of chemical elements present in mine waste-based cementitious materials. The leaching test is a test in which a material is put in contact with a leachant so that certain constituents of the materials are extracted. **Table 8** presents the characteristics of cementitious materials derived from mining waste while **Table 9** presents the leaching results observed by some researchers on cementitious materials made from mining waste. The different values in **Table 9** indicate that most of the leaching test results carried out on cementitious materials with mining waste show that the leaching of heavy metals and sulphates is below the limit requirements set by the Soil Quality Decree.

It is observed from the results of previous studies that cementitious materials offer the possibility of absorbing mining wastes especially wastes rocks and tailings in different proportions. The results that mining wastes offer in cementitious materials are usable in civil engineering. Furthermore, the porosity of concrete and/or mortar is a factor that affects their toxicity.

3.3.2. Mining Waste in the Manufacture of Fired Bricks

M. Ettoumi *et al.* [11] observed that the optimum properties of fired bricks obtained from Phosphate sludge were at 1100 C, with a porosity of 9%, a firing shrinkage of 7.5%, a water absorption of 12.5%, a bulk density of 1.4 g/cm³ and a flexural strength of 13.4 MPa; with satisfaction in terms of metal concentrations and potential mobility and toxicity requirements.

Table 10 presents the different characteristics of the bricks obtained from mining waste where it can be read that there is a significant improvement of physical and mechanical properties with the increase of the firing temperature. Therefore, it appears that the production of bricks from mining waste is a promising option for the sustainable management of waste materials, which are worthless and abundant, to preserve soils that are currently often overexploited for their disposal, to reduce their environmental footprint and to minimize the exploitation of nonrenewable resources already used in the manufacture of bricks.

In general, the results of previous studies have shown that the use of mining wastes especially slags is practical in fired bricks. These offer preponderant properties. Moreover, the firing of these influences the decrease of the toxicity of the produced bricks.

Table 8. Properties of cementitious materials from mine waste.

Mining waste	Recovered as	W/C	Rate of replacement (%)	Slump in mm	Compressive stress (28 jrs) (Mpa)	flexural strength (Mpa)	splitting tensile strength (Mpa)	Density of hardened concrete (kg/m ³)	Porosity (%)
Flint from phosphate mine waste rocks [17]	aggregates in cement concrete	0.5	0	70	34.4	4.5	2.5	2370	
			100%	50	29	4.9	2.6	2360	
Phosphate mine waste rocks [8]	aggregates in cement concrete	0.5	0	70	29.6	2.5	4.5		
			0.66	100	70	13.5	1.3	2.65	
Gold-mine tailings [13]	Sand in mortar	0.5	0		~32.5				~38
			10		~35			~32	
			20		~37.5			~29.5	
			30		~42			~25.5	
			40		~41.5			-	
Gold-mine tailings [13]	cement in mortar	0.5	0		~32.5				~38
			10		~29.5			~35.5	
			20		~31.5			~34	
			30		~33			~33.5	
			40		~32			-	
Tailling plomb [15]	Sand in cement concrete	1.35	0		13.2				
			100		8.58 - 10.9			26.4 - 29.3	
Copper tailing [5]	Sand in cement concrete	0.4 - 0.5	0		~31 - 36	~4 - 4.5		2230.93	
			10		~32 - 40	~4.6 - 4.8		2243.53	
			20		~35 - 40	~4.2 - 4.7		2243.53	
			30		~36 - 40	~4.1 - 4.5		2268.73	
			40		~35 - 38	~4.2 - 4.5		2281.34	
			50		~32 - 37	~4 - 4.5		2281.34	
Waste rock gold mine [14]	aggregates in concrete	0.4	100%	80	36				
			d ≥ 0.08 mm	100%	80	33			
			Gravels	100%	75	40			
Waste rock gold mining [9]	aggregates in cement concrete	0.4	0	85	37.8				
			100%	110	34.9				

Table 9. Leaching test for cementitious materials.

Mining waste	Concentration in leachate (mg/L) (with H ₂ O)			Sulphate attack after 28 days	Cumulative concentrations of released metals during the whole period of tank leaching test (mg/m ²)								
	Cr	Pb	Cd	% of weight loss	SO ₄	As	Ba	CO	Cu	Mo	Ni	Pb	Zn
Gold-mine tailings [13]	0.141	0.0003	<0.00004										
	0.124	0.0003	<0.00004										
	0.108	0.0002	<0.00003										
Gold-mine tailings [13]	0.153	0.0004	0.00007										
	0.136	0.0002	0.00006										
	0.129	0.0003	<0.00005										
Copper tailing [5]				~1.15 - 1.3									
				~1.25 - 1.26									
				~1.18 - 1.25									
				~1.18 - 1.35									
				~1.23 - 1.35									
				~1.25 - 1.4									
				~1.25 - 1.42									
Waste rock gold mine [14]					<100	<100	<1000	<10	<10	<10	<10	<10	<10
					<1000	<100	<100	<10	<10	<10	<10	<10	<10
					<1000	<100	<100	<10	<10	<10	<10	<10	<10
Waste rock gold mining [9]					<100	<100	<100	<10	<10	<10	<10	<10	<10
					<1000	<100	<100	<10	<10	<10	<10	<10	<10

3.3.3. Mining Waste in Road Embankments

Table 11 shows the characteristics of some mining wastes used in embankment materials such as coal mine waste rock and phosphate mine waste rock. It can be observed that mining wastes are used in road embankments according to their main properties, notably granulometry, sensitivity to water...

Mustapha Amrani *et al.* [18] 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 by respecting the compaction table proposed by the French guide for road works. Because of their CBR, they can be used as foundation materials.

Mustapha Amrani *et al.* [16] showed that Phosphate Mine Waste Rock can be

Table 10. Characteristics of bricks from mining waste.

Authors	Raw materials	Drying/firing conditions	Apparent density (g/cm ³)	Water absorption (%)	Apparent porosity (%)	Firing shrinkage (%)	Flexural strength (Mpa)	Compressive strength (Mpa)
M. Ettoumi <i>et al.</i> [11]	100% phosphate sludge	Air drying for 24 h Oven drying at 60°C for 24 h Firing at 900°C, 1000°C and 1100°C for 3 h (heating rate of 120°C/h)	~1.3	12.5 - 17.2	9 - 13	5.2 - 7.5	3.9 - 13.4	-
Luo <i>et al.</i> [31]	48% - 60% iron ore tailings 10% shale 30% coal gangue powder 0 - 12% sewage sludge	Air drying for 48 h Oven drying at 105°C for 24 h Firing at 950°C, 1000°C, and 1100°C for 2 h, 2.5 h, 3 h, 3.5 h and 4 h (heating rate of 300°C/h)	~1.62 - 1.74	14 - 18	-	-	-	8.5 - 17.5
Loutou <i>et al.</i> [32]	100% clay by-product (red clay) from phosphate mines	Air drying for 24 h Oven drying at 105°C for 24 h Firing at 900°C, 1000°C and 1100°C for 2 h	~1.7 - 2.6	3 - 17	7 - 22	~1.5 - 3.4	17 - 36	
Taha <i>et al.</i> [33]	10% - 50% treated calamine processing mine tailing 5% - 15% glass waste 45% - 85% shale for brick	Air drying for 24 h Oven drying at 60°C for 24 h Firing at 900°C, 1000°C and 1100°C for 5 h (heating rate of 48°C/h)	~1.6 - 1.9	12 - 26	22 - 42	1 - 8	3.5 - 11.8	
Yang <i>et al.</i> [34]	80% - 100% iron tailings 0 - 20% fly ash	Air drying for 12 h Oven drying at 35°C for 12 h then at 105°C for 8 h Firing at 900°C, 950°C and 1000°C for 2 h (heating rate of 120 C/h)	~1.8 - 2.0	15.5 - 17.5	27 - 34	0.9 - 1.2		6 - 27

used as an alternative material in the construction of dry compacted embankments. The results show that these water insensitive materials can be dry compacted, with dry densities above 95% of the Proctor. Due to their CBR, they can

Table 11. Characteristics of backfill from mine waste.

Waste	Proctor Normal		Modified Proctor		CBR		Use in road construction
	Wopt (%)	Pd opt (kN/m ³)	Wopt (%)	Pd opt (kN/m ³)	CBR 4i%	IBI %	
Coal mine waste rock [18]	11.2	19	10.11	20.4	9	29	Sub-base layer
Phosphate mine waste rock [16]	12.9 - 14.60	17.9	-	-	13	-	Sub-base layer and backfill

be used as foundation materials.

In general, mining wastes with characteristics of road materials such as grading, impact and wear resistance are a good choice for road embankments. Furthermore, the results of different studies have shown that these materials (mine waste) should be tested for leaching to prevent soil contamination. However, the mixing of mine waste with other constituents such as stabilisers is a factor influencing the behaviour of mine waste fills.

4. Conclusion

This paper is based on an extensive review of about thirty authors who have dealt with the valorisation of mining waste in construction materials. In addition to the presentation of the origins of mining waste, the different properties have been sculpted firstly the physical, mechanical, chemical, mineralogical, heavy metal content, geotechnical and environmental properties have been examined and secondly the properties of the materials containing the mining waste have been sculpted. The use of tailings and waste rocks in cementitious materials offers convincing results; the valorisation of slags is practical in fired bricks. The few research studies obtained on the use of mining waste in road embankments have shown that mining waste can be used as a sub-base layer and backfill as long as it is not toxic. Several other mining wastes produced in mining operations, which are subject to pollution and clutter, require special attention with regard to their likely use in construction materials. By way of illustration, attention can be drawn to coltan mining waste, cobalt and cassiterite waste, where there is not enough literature.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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