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Review

Mining Wastes as Road Construction Material: A Review

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Abstract: The mining industry manages large volumes of tailings, sludge, and residues that represent a huge environmental issue. This fact has prompted research into valorization of these wastes as alternative aggregates for concrete production, embankments, pavement material, etc. The use of mining wastes as a resource for construction presents two benefits: conserving natural resources and reducing the environmental impacts of mining. In the case of road construction, the use of mining wastes has not yet been developed on a large scale and there is a major lack of specific legislation. This gap is due to the variety of exploited rocks, the diversity of tailings, mine residues, or valuable by-products slated for valorization, and the environmental specifics. This paper presents a review on recycling mine wastes as road construction material, including waste rock and mine tailings. Those materials were mostly used in infrastructure where soils had initially poor geotechnical properties (low bearing capacity, frost susceptibility, swelling risk, etc.). Different mining wastes were used directly or stabilized by a hydraulic binder through geopolymerization or, in some cases, with bituminous treatment. Overall, the use of mine wastes for road construction will have a considerable environmental impact by reducing the volume of waste and offering sustainable raw materials.

Keywords: residue; road construction; stabilization/solidification; tailings; waste management

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1. Introduction

1.1. Impact of Mining Activities

Mining activities are economically essential; however, as they are a major cause of pollution worldwide, they need to be conducted in a more ecological manner. This industry possesses several environmental challenges, yet the management of solid wastes generated during the lifetime of the mine is of major concern. Mining industries have storage issues in terms of space and risk of pollution. Indeed, ongoing monitoring is required for stability (risk of a landslide) and potentially hazardous elements (acidification and heavy metals). Leaching and washing erosion phenomenon of fine particles during rain periods are the main sources of contamination [1]. For waste management, the use of solidification/stabilization (S/S) techniques (e.g., cement paste tailings) is occasionally applied in road construction with physio-chemical stability benefits. It improves physio-chemical and environmental properties, immobilizing problematic elements and limiting the leaching potential (sulfides, heavy metals, or potential mineral swelling) in a cementitious matrix. For industrial minerals, the cost of waste management seldom exceeds 2% of the mineral's sale value. In the UK, the costs of wastes from underground coal mines are nearly 3.5% [2]. The types of waste can be defined according to the stage of the ore extraction process and the waste characteristics (Figure 1). In line with the Bureau of Geological and Mining Research report on "management of mining, quarrying and ore-processing waste in the European Union," generated mining wastes include topsoil, overburden, and waste rock [3]. In the USA only ~20% of abandoned mining sites have rehabilitation plans [4].

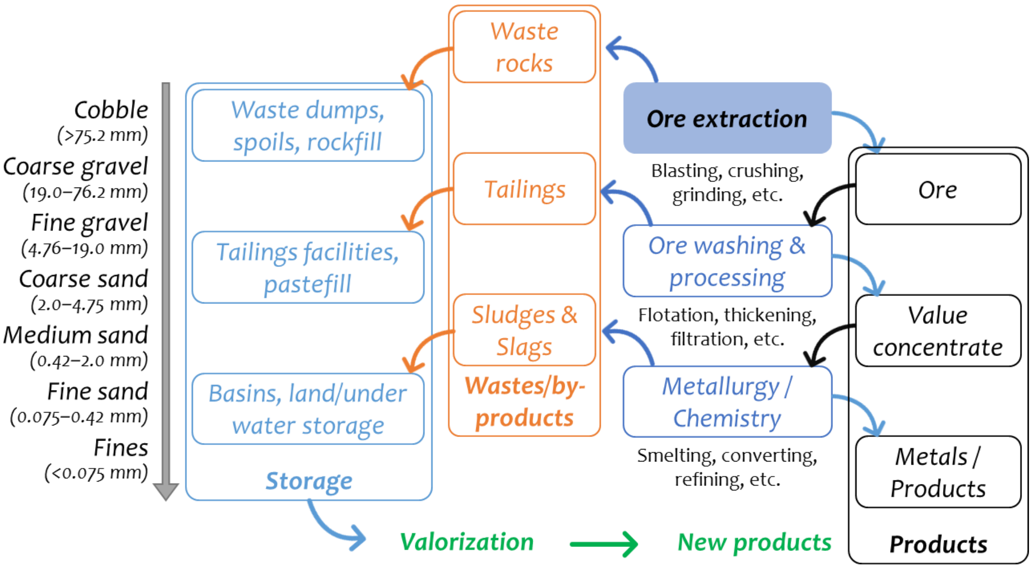

Figure 1. Mining cycle from ore extraction to metal/mineral beneficiation, developed from [5,6].

Preventing major environmental accidents linked to mining activities is still relevant, such as the 2014 tailings dam failure in British Columbia leading to the contamination of Polley Lake by a release of mining water and slurry. This shows the importance of tailings management in ponds and dams. Indeed, a defect can have catastrophic environmental impacts, including flooding and water contamination by heavy metals and acidification. The risk of a neutral- or acid-contaminated leach is one of the most common management issues, associated with the exposure of sulfides to oxygen and water by mining processes. The consequences can be observed over long periods up to thousands of years, such as in the estuary of Rio Tinto, which is still contaminated by 4500-year-old mining pollution [7]. Since the 1970s, mine waste management has progressed through technological innovations from simple storage to tailings S/S [8] and site rehabilitation [9]. Increasingly, mining companies adopt integrated into situ management methods using tailings in embankments, roads, and dams. For instance, the cement tailings backfill technique has many economic and ecological benefits compared to traditional operating pillars/cavities by securing the mine wastes in flooded basements (neutralizing the risk of sulfide oxidation). Cement paste backfill (CPB) usage can consume up to 60% of the tailings [6]. Skarżyńska [10,11] proposed potential uses of mine wastes as transformed construction resources for the rehabilitation of open pits, and restoration of quarry sites, harbours, and highway material.

1.2. Waste Rock, Tailings, and Sludge

There is no existing universal classification of mineral wastes to ease the improvement of mining sustainability. Four categories of mineral waste as a source of construction and industrial minerals were reported based on their potential usage alongside with the required degree of processing (Table 1) [12,13]. The classification suggests that Type 1 minerals can be largely used in construction in the mining site as they represent large volumes with low industrial value and minimal processing required.

The wastes separated early in the mining process can easily be transformed into aggregates with less crushing and modification of particle size distribution compared to tailings derived from the subsequent steps of ore-processing and enrichment phases, which may contain inorganic and/or organic additives. Most problems associated with the use of mine wastes as aggregates in construction are related to their relatively poor geotechnical properties in addition to their environmental characteristics. The challenge of variability inside a deposit, and even between two deposits, lead to variation in physio-chemical properties depending on the material and the nature of the geological formation. As well, the potential release of pollutants through leaching in a roadwork structure due to a high concentration of heavy metals or potential acid phases must be considered. To assess the potential use of the diverse fractions as construction material and the required treatment (crushing, sieving, stabilization), a detailed characterization must be performed to avoid any long-term environmental issues. These steps must be included from the beginning of the industrial process.

Table 1. Classification of mineral wastes according to Mitchell [14].

Group	Description	Example	Potential End Uses
Type 1	Unprocessed wastes	Quarry scalping, quarry blocks, colliery spoil	Fill, low-grade road stone, armour stone, brick clay
Type 2	Processed wastes—reclaimed mineral	Silica sand wastes, limestone wastes, building stone wastes	Silica sand, kaolin, brick clay, mineral filler, aglime, aggregate
Type 3	Processed wastes—added-value products	Lead/zinc wastes, pegmatite wastes, silica sand wastes	Fluorite, barite, feldspar, rare earth, mica, heavy minerals
Type 4	Beneficiated wastes	Certain mining wastes	Gemstones, high-value metals

1.3. Environmental Evaluation of Mining Wastes

To mitigate sustainability concerns considering a lack of regulations, different local politics were developed allowing the use of mine waste as a secondary resource of aggregates, especially given that the authorization of a new gravel quarry can take 5–10 years [14]. Several approaches were defined to evaluate non-hazardous wastes and residual material to be used as building materials, usually based on leaching tests, compared to soil criteria and risk analysis. For example, in the province of Québec the valorization guide for inorganic non-hazardous industrial wastes as construction materials excludes metallurgical slags and mine tailings when their potential for acid mine drainage is proven by the common test methods (neutralizing capacity evaluation, leaching tests, and total metal content) [15] (Québec Legislation−Q2−Environment Quality Act). In 1990, the provincial government of Ontario published the "criteria for the management of inert fill" guide for construction demolition materials (R.R.O. 1990, Reg. 347: General−Waste Management under Environmental Protection Act, R.S.O. 1990, c. E.19). The applicable laws, regulations, and standards governing the reclamation of mine wastes in Québec were already discussed in a previous paper [16]. The review of various reuse pathways led to the identification of geopolymers as a promising technology in the recovery of treatment plant residues. However, certain aspects of the law limit the applicability of alkali-activated materials (AAMs) in the civil industry, particularly the standard CAN/CSA-A3000-F13 (cementitious material compendium). In France, the Sétra guide proposes an environmental evaluation methodology to allow the use of alternative aggregate in road construction depending on leaching test results (inert, non-hazardous, hazardous material). In the Netherlands, regardless of their origin, construction materials are evaluated based on leaching criteria of inorganic contaminants, their total organic contaminant content, and a model simulating a 100-year period to evaluate the migration of the inorganic contaminants from the building material to the underlying soil or to the water. Sweden favours the use of waste materials as building materials but there is no environmental guidance.

International legislation regarding the regulation of waste management is evolving. The rehabilitation of exploited sites and the monitoring of greenhouse gas emissions are encouraged. The report "Mining, Minerals and Sustainable Development Project" of the International Institute for Environment and Development highlights industrial responsibilities for the intolerable mining damages [12]. The financial penalties are rare, but a poor management policy can impact the reputation of the mining companies and managing governments [8]. Mine waste valorization needs a strict approach to ensure environmental safety, but the gains can be sizable over the marketing of products with potential value.

1.4. State of Road Construction Materials

Roads are under the stresses of traffic, climatic variations (precipitation, variation of the groundwater level, freeze-thaw cycles), and natural soil variability (presence of clay, fine content, etc.). Depending on the geographic situation of aggregate demand and supply, compromises must be made between the different levels of requirements. Depending on expected traffic (load and frequency), the in-place soil-bearing capacity (strong or poor), and climatic regions, the total road depth structure can vary from 30 cm to more than 1 m. As a function of the selected technology, a road is usually composed of soil and three layers composed of 90% aggregate (Figure 2).

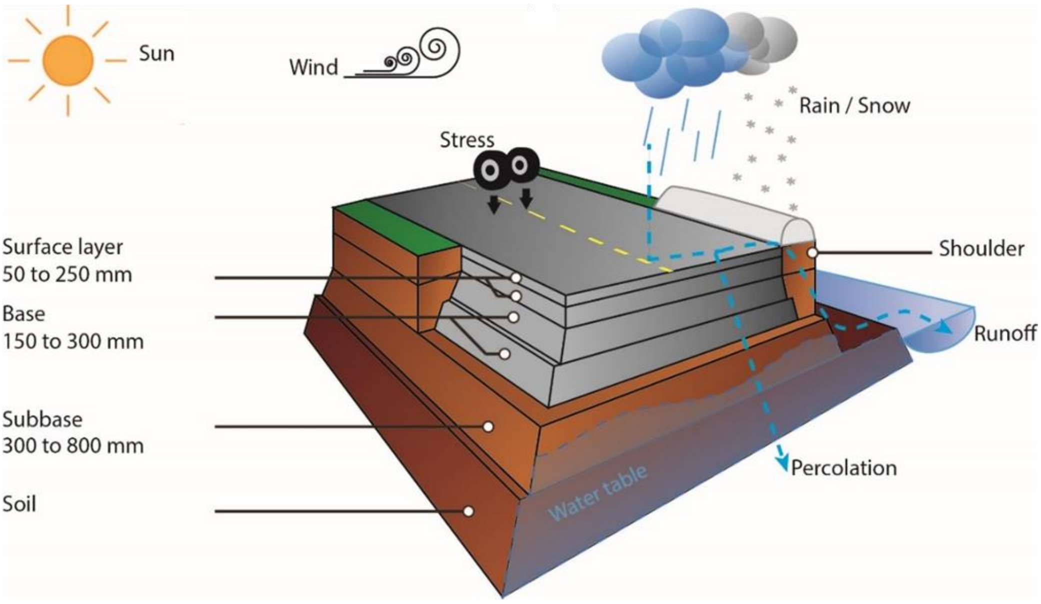

Figure 2. Schematic road structure adapted from Segui [17].

First, the surface layer or rolling layer can be composed of bituminous asphalt or concrete and require 95% aggregate. In the case of concrete, it can include sand or fine particles in the composition. This composition presents the necessary properties for safe use by vehicles (unit and adhesion). It also plays a sealing role, which contributes to road's durability. Secondly, the base layer, sometimes divided into two layers, is composed of aggregate chosen for its bearing resistance and drainage quality, ensuring the stability of the structure. These layers can be treated to improve the bearing quality of the structure over time. The base layer provides mechanical strength and distributes the vertical stress onto the platform to avoid excessive deformation. Thirdly, the subbase supports the road structure, and is generally composed of sand, gravel, or crushed stone allowing drainage and offering protection against ground movements. Finally, the in-place soil or bearing ground may need to be re-engineered with treatment, depending on its characteristics.

In the UK, aggregate sources produce roughly 300 million tons yearly, where 30% are used in road construction [18]. In France, road and rail construction, including the underground network, absorbs ~60% of the produced aggregate. The construction of 1 km of highways consumes up to 30 k tons of gravel, and the construction of 1 m of a high-speed train railway uses up to 9 tons of aggregates, according to the European Aggregates Association. Emery [12] reviewed the potential role of Canadian mining, metallurgical, industrial, municipal, and agricultural wastes as construction resources. Even if most of the development work has been accomplished and major waste inventories are accessible, optimistic use estimates must be tempered by technical and economic restrictions (inherent unpredictability, long transportation distances, etc.) that tend to limit applications. The potentially recycled wastes were identified and provided to demonstrate their use.

While conventional aggregate production includes extraction, crushing, and screening, the exploitation of mine wastes as aggregate requires only special attention to screening. An S/S treatment can be necessary to obtain satisfactory results; this type of treatment can be a part of road layer construction. The use of mine wastes as construction materials must satisfy several requirements: represent a safe application in terms of engineering and environmental properties, create economic interest, preserve natural resources, or slow their consumption, and encourage local industry and innovation while avoiding the risks of damaging the environment. The resource availability criterion should also be considered when evaluating an uncommon material. Within this framework, the Organization for Economic Co-operation and Development (OCDE) recommends a minimum annual quantity of 50 k tons per type of waste [19]. In the global approach of sustainable development, using mine wastes in road construction can be suitable for maintenance and development.

1.5. Significance of the Review

Several research projects have focused on recycling mine wastes as raw materials in the field of civil engineering. Recently, Gou et al. [6] reviewed the uses of tailings in cement and concrete production. It was concluded that such an outcome will be good both for limiting the amount of solid waste and conserving nonrenewable raw materials consumed by the construction industry. Also, Martins et al. [20] reviewed the potential for using medium and highly sulfuric tailings in construction materials including ceramics, supplementary cementitious materials (SCMs), AAMs, aggregates, and as clinker raw materials. Zhang [21] reviewed the use of waste including tailings to produce bricks and concluded that such a commercial production is still very limited due to various reasons, i.e., environmental legislation and technical parameters. A recently conducted experimental study proved that phosphate waste rock can be used as a geomaterial in the field of civil engineering, including road construction [22]. Nevertheless, to our knowledge, despite intensive research conducted on recycling mining wastes in road construction, no review has been published yet on this topic. This review paper aims to fill this research gap.

2. Mining Wastes Used as Road Construction Material

In the following, mine wastes (MW) include waste rock (WR) and mine tailings (MT). Sangiorgi et al. [23] presented a European research program entitled REMINE (H2020 RISE-Marie Curie Action) discussing the potential use of Panasqueira MW gravels and fillers to produce infrastructure materials. They presented an estimation of the economic and social impact of this recycling on the local communities and other mining activities in Portugal and Europe. The project aims to develop a design method for AAMs from mine and quarry wastes based on a targeted rheology to fit various applications. Artificial gravels made from alkali-activated MW appear to be a realistic technological option for competing with other frequently used substances and might lead to the manufacture of less porous and tougher gravels than most road paving materials. The reviewed literature on using MW as a road construction material can be classified into four categories: (i) MW that was used directly without treatment; (ii) stabilized MW with a hydraulic binder (cement/lime) in the presence/absence of soil/clay; (iii) MW stabilized through geopolymerization process; and iv) MW that was used with asphalt.

2.1. Aggregates Used without Ttreatment

Table 2 summarizes the untreated MW used as road construction material. Sultan [24] investigated the feasibility of recycling MW and reported that whether untreated, cement-stabilized, or asphalt-stabilized, MW exhibits good enough engineering properties to be exploited as road construction material. Coarse coal wastes (1–16 mm) were adapted to be used as gravels to produce pipeline ditch refill, gravel surfaces for parking lots, etc. Screened tailings (sandy 1–4 mm) were employed as aggregates for cobbling, while fine tailings (<1 mm) were used as fillers in the cement industry [24].

Collings [25] presents an inventory of MW and their potential reuse for dam construction, as railroad ballast, and as coarse aggregates in concrete and asphalt mixtures depending on particle size. For the finer grain-sized wastes, recommended uses include recycling as sand, as an additive to concrete and asphalt mixtures, in bricks and thermal insulation blocks, for the recovery of valuable minerals, and as mineral fillers. For example, the limitation of leaching was studied and modelled in the case of roads using MW rich in heavy metals by adjusting the geometry of the structure (dam or dike) [26]. That research presented four alternatives for the reconstruction of a road on an old mining site in Sweden. Their results are an illustration of the analytical decisions of investment costs with uncertainty about environmental effects. Costs of alternative actions, potential environmental losses associated with alternative options, and hydrogeological uncertainty were among the inputs. The amount of leached metals was predicted using stochastic simulations (zinc). The study claimed that the removal of MT was never economically effective, i.e., high investment requirements and a considerable risk of metal leaching [26].

Table 2. Mine wastes used in road construction—Untreated.

Mine	Provenance	Main Characteristics and Use	Conducted Tests	Properties	Ref.
Phosphate	Egypt, Sebaeya	WR was tested to be used as a subbase aggregate in road construction. The specific density was ~2.65 g/cm^3.	Compaction tests, California bearing ratio (CBR), Los Angeles abrasion tests, slake durability tests, and crushing strength tests.	A good dry density of 1.95 g/cm^3 was achieved.	[27]
	Egypt	Aggregates of Ø20 mm and a density of 2.42 g/cm^3 were tested for the potential use as a road subbase and base.	Compaction characteristics and CBR.	2.02 g/cm^3 dry density with an optimum moisture content of 12% was achieved.	[28]
	Morocco, Benguerir	MT were characterized in the laboratory and valorized as a material for embankment applications following both wet and dry compaction processes.	Major, minor, and trace elements, CBR, geotechnical properties, collapsible behaviour, microstructure studies: tomography, MIP (mercury intrusion porosimetry).	With specific density > 26 kN/m^3, LA of 45%–58%, and a PI < 20%, this WR could be used in an embankment at dry moisture content under total overburden stress < 200 kPa.	[29,30]
Coal	Algeria, Bechar	Coal MT was mixed with different ratios of tuff.	Geotechnical properties, leaching tests, CBR, in situ tests; density.	Results suggested an incorporation rate of up to 25% completed by local tuff.	[31]
	Australia, New South Wales	MT mainly consist of fine sand particles (85%) with an average density varied from 1.83 to 2.19 g/cm^3, used as compacted soil.	Compaction characteristics, permeability, CBR, consolidation and collapse potential analysis, shear strength, and triaxial test.	A maximum dry density > 15 kN/m^3 at a moisture content of ~12% (porosity of 22%).	[32]
	Morocco	Coal MW can be used as aggregates for road embankment applications.	The compressibility properties, geotechnical properties, swelling behaviour, environmental behaviour, and mechanical properties.	The density of 2.65 g/cm^3, specific surface area (BET) (m^2/g) of ~14 and pH 7.1. CBR was 9%. Liquid limit of 41%, a plastic limit of 25% and a PI of 17%.	[33]

Table 2. *Cont.*

Mine	Provenance	Main Characteristics and Use	Conducted Tests	Properties	Ref.
Copper	USA, Utah	41.7% < 0.075 mm with a density of 2.71 g/cm^3. A total of 100% of MT is used for highway constructions as coarse and medium aggregates.	Compaction properties, compressive, tensile, and shear strengths, compressibility and swelling characteristics, permeability, and rain erodibility.	Compressive strength of 281 kPa with 10.8% moisture content.	[24]
	Spain, Galicia	As aggregate on rural roads, no structural issues on the road. No toxicity problem is noted for the environment.	Toxicity test.	The values are below the limits established by the European Council.	[34]
Iron, copper	China	Specific gravity of 2.76–3.23 g/cm^3, grain size of 0.06–0.12 mm. An intensive laboratory test procedure was conducted on the geotechnical behaviours of the tailings.	Consolidation test, hydraulic conductivity, triaxial test, liquefaction susceptibility, cyclic resistance ratio, pore water pressure, shear modulus, and damping ratio.	Compression index of both tailings, fine and coarse, ranged from 0.025–0.26.	[35]
Marble	Turkey, Bilecik Province	Marble MT-rich $CaCO_3$ mineral was evaluated to be used as base material for road construction.	Physical, geotechnical properties, a dry/wet CBR test, MIP analysis, and freeze-thaw test.	Modified proctor revealed a density of ~22 kN/m^3 with a moisture content of ~5%.	[36]

2.2. Aggregates Used with Hydraulic Treatment

Table 3 summarizes MW used as a road construction material treated with a hydraulic binder. In the case of traditional tailings management, hydraulic binders (cement, fly ash (FA), slags, or smelters) were used to overcome the lack of real cohesiveness of hydraulic backfill. It was reported that 75% of the cost of backfill tailings storage is attributed to binders (purchase and transportation) [37]. So, binders compatible with tailings were studied and developed. Cemented paste tailings stabilized with industrial wastes have been studied [38]. Binders with lime present interesting pozzolanic properties from the C–S–H structure, even if this is a slow phenomenon. The C–S–H gel decreases the porosity and thus increases the strength. Tested industrial by-products can replace a part of the cement (30%–50% for FA, 20%–60% for slag, or 15%–35% for glass waste). Alternative sources of calcium (e.g., cement dust) can be exploited to improve the strength [38]. The same conclusions for tailings stabilization on the surface or backfilling were reported [39].

The use of a hydraulic binder also provides chemical stability with the immobilization of problematic elements in a cementitious matrix and thus limits the leachate potential (sulfides, heavy metals, or potential swelling minerals). With ordinary Portland cement (OPC), possible problems of setting and hardening may occur in association with MT and WR materials (i.e., high pH, heavy metals, soluble elements). Alkaline binders (hydraulic) are used with reactive MT, which provides encapsulation along with chemical fixation of potential mobile elements [58–60]. However, when specific strength is required (e.g., for concretes), the mechanisms of hydration can be poisoned by the heavy soluble metal contents [51,61,62]. Sultan [24] investigated the feasibility of using stabilized copper MT in highway construction. Coal residues in West Virginia were used as a subbase material for unpaved roads in the 1970s, even though the material exhibited some particle degradation under compaction. Laboratory treatment tests were conducted with OPC and concluded that 10 wt.% of cement provided excellent results as a construction material. The U.S.

Environmental Protection Agency used coal wastes as base course material on parking lots with three different mixes (untreated, treated with FA, and mixed with hydrated lime) and a drainage collection system to control the chemical composition of each base course mixture leaching. They concluded that "leachate from FA treated mixtures were neutral with much lower concentrations of heavy metals than untreated coal refuses mixture" and so "the addition of FA (with or without lime) tends to neutralize acidity and cut heavy metal concentrations from the pyritic discharge of coal refuse" [63]. As such, the co-management of different kinds of coal residues has been applied as an effective method against acid-generating tailings. By lowering metal mobilization, boosting water holding capacity, encouraging pore structure refinement, reducing hydraulic conductivity, and enhancing strength and stiffness, the co-placement of MT and FA can improve the physio-chemical characteristics of tailings [60].

In the southwest of the USA, some soils present a high concentration of sulfate due to mining activities or natural origins (evaporite formed in arid conditions), and usually, structure degradations are observed (with or without treatment). Future road projects consider these "soils" (coal residues) as materials for infrastructure. Jung and Santagata [44] presented a specific study on the expansive behaviour of coal mine spoils treated with 1%–9% hydraulic stabilizers, by dry mass. After one month, mineralogical and swelling tests were not correlated with ettringite formation, which was responsible for the observed expansion. Several implementation techniques were tested: pre-compaction, maturation, and double lime treatment. The pre-compaction period of 2–3 days resulted in a swelling strain comparable to that of the untreated spoils [44]. In Texas, synthetic aggregates composed of FA class C off-ASTM specification (coal combustion residues stockpiled or manufactured) were tested with significant benefits in flexible characteristics for base applications. Despite the lime and sulphate content and the irregular shape, no sulphate attack and swelling caused by ettringite formation were observed in aggregate blends with or without lime. On treated mixtures, neutral leachates were obtained with lower heavy-metal concentrations compared to the untreated coal waste mixture. The pyrite contained in coal wastes seemed to stabilize with FA addition. Land occupied by coal waste piles has been restored by surface preparation and additions of FA to neutralize acidic spoil materials to promote the support and growth of vegetation [64].

Teredesai [53] conducted a laboratory investigation to assess the potential of pile run chat (i.e., lead-zinc MT) without cohesion and rich in lead and zinc as a roadway base material. The pile was stabilized with 10% FA or cement kiln dust. The results showed that the unconfined uniaxial compressive strength (UCS) of the pile run chat increased significantly due to the use of stabilizing agents while the elastic modulus also exhibited an increase due to the process [53]. To regulate the strength of Italian MT rich in Pb and Zn, several kinds of additions (silica fume, sulfur polymer, $CaCl_2$, quick lime, Na_2SO_4, and K_2SO_4) were tested to achieve the minimum Italian Standard for mortar [52]. Treatment with cement or lime raises the alkaline conditions determining the metal's release. Physical trapping and formation of stable compounds were observed (hydroxy-pyromorphite: $Pb_5[PO_4]_3OH$) with a combined treatment of potassium dihydrogen phosphate and ferric chloride hexahydrate. Despite the strong alkaline conditions, the S/S of the wastes met the legal limits for groundwater and surface water [52]. In Morocco, for decades the tailings from a Pb-Zn mine with high concentrations of As, Cu, Cd, Pb, and Zn were used locally as a fine aggregate mortar. Argane et al. [51] revealed that the use of these materials in mortars presents some technical difficulties in terms of water demand (significant presence of fine <63 μm). Environmental laboratory tests showed stabilization of Pb and Zn in the cement matrix (very limited dissolution), encouraging this method. The storage and management of phosphogypsum (PG) are the main challenges facing the phosphoric acid production industry. Recently, novel alternatives to recycle this by-product in pavement structures have been suggested [45], where the performance of several formulations for the stabilization of PG with clayey soil, FA, lime, calcareous material, and a special hydraulic road binder (HRB) was reported and discussed.

Table 3. Mine wastes used in road construction—treated with a hydraulic Binder.

Mine	Provenance	Utilization	Conducted Tests	Main Properties	Ref.
Diamond	India	MT has a density of 2.42 g/cm^3, with 96% particles <20 mm, was stabilized with 3 and 5% OPC for the granular subbase.	Compaction characteristics, CBR, unconfined compressive strength (UCS).	UCS of 1.33 MPa (7-d) and 2.05 MPa (28-d).	[40]
Granite	China	The granite mill tailings were stabilized with 3%–6% cement as a pavement subbase. A total of 100% of the grains were <9.5 mm.	UCS, static and dynamic moduli, split tensile strength, thermal and drying shrinkage.	The highest UCS was achieved with 5% OPC: 6.39 and 7.17 MPa at 28 and 90-d.	[41]
Gold	India, Kolar	10%–90% of gold tailings, composed of 70% silt, with a density of 2.78 g/cm^3, were mixed with clay and 1%–6% of lime.	Compaction characteristics and UCS.	Highest UCS achieved by the mix of 10% MT and 3% lime: 840 kPa at 30-d.	[42]
	Canada	71% of the tailings were <75 µm, stabilized by 3%–7% of cement and compacted.	UCS, pulse velocity test and durability test.	UCS of 1.8 MPa was achieved for the mix with 7% OPC.	[43]
Coal	Morocco	Wastes were stabilized using 15%–25% FA and 1%–5% hydraulic road binder (HRB). The wastes have a density of 2.65 g/cm^3 rich of SiO_2.	Compressibility and geotechnical properties, swelling behaviour, environmental behaviour, and mechanical properties.	The M7 (80:20:5 = MT: FA: binder) achieved the highest UCS of 5.28 MPa at 90-d.	[33]
	USA, Indiana	MT was stabilized using 3 and 7% of quick lime, hydrated lime, and OPC.	Swelling test.	Pre-compaction mellowing was found to be an effective mitigation approach.	[44]
Phosphate	Morocco	Several formulations for recycling phosphogypsum (PG) as pavement material were tested.	USC, elastic modulus, and diametric compression strength.	The compatibility of the mix (CM:PG:SM):HRB = (10:25:65):7 for the capping and pavement layers use was confirmed. Where: CM: calcareous material, SM: clayey soil.	[45]
Iron	China	Different combinations of cement: MT was tested up to 17:100.	UCS and economic analysis.	Stabilized iron MT with 15% cement can be used for the base/subbase of low-grade highways.	[46]
	Brazil, Minas Gerais	85% of the grain <75 µm, with a high density of 3.55 g/cm^3, stabilized with 1%–10% of cement-lime as road material	CBR, UCS, and expansion	The mixtures stabilized with cement have a UCS of 1.32 MPa; those with lime reached 0.89 MPa.	[47]
	Nigeria	A laboratory study on the stabilization of black cotton soil with up to 8% lime admixed with up to 10% iron ore MT by dry weight of soil compacted.	Compaction characteristics, UCS, CBR, durability and microanalysis.	UCS of 1.1, 1.8 and 2.1 MPa (8% MT and 8% lime) reached at 7, 14 and 28 days, respectively.	[48]
	India (Goa)	Road constructions (base and subbase), particles in the range of 12.5–20 mm.	UCS, toxicity characteristic leaching procedure.	UCS of ~22 MPa at 28-d.	[1]
	China, Kogi State	0%–50% of iron tailings were stabilized with lateritic soil and 0%–10% cement-lime.	CBR, UCS, and leaching analysis.	UCS of 0.42, 0.47 and 0.55 (8% OPC-lime) for 7, 15 and 30 days were achieved, respectively	[49]
	Nigeria, Gombe State	The MT was finer than 75 µm with a density of 2.44 g/cm^3 was admixed with 0%–10% soil-cement mixtures.	Compaction characteristics, shear strength parameters, cation exchange capacity and microanalysis.	An optimal blend of 4% cement/6% tailings for microanalysis and workability.	[50]

Table 3. *Cont.*

Mine	Provenance	Utilization	Conducted Tests	Main Properties	Ref.
Lead-Zinc	Morocco	Traditional use of MT as rendering mortar aggregates.	Mineralogical and porosity study.	Higher water demand and so higher porosity; cement matrix limited Pb and Zn dissolution.	[51]
	Italy, Sardaigna	Tailings stabilized by different compositions of lime, $FeCl_3$, and KH_2PO_4 to improve strength.	Stability of heavy metal.	Cement alone does not permit the acquisition of a product complying with legal limits.	[52]
	USA, Miami	MT as roadway base treated by 10% of CFA or CKD in laboratory tests and in a 0.6-mile-long test road.	UCS, modulus of elasticity, and seismic modulus.	UCS and elastic modulus significantly increased due to use of stabilizing agents.	[53]
Copper	USA, Utah	Copper MT was treated with 2–12% of OPC for highway constructions as coarse and medium aggregates.	Compaction characteristics, UCS, tensile, and flexural strengths, durability losses, permeability, and rain erodibility.	UCS ranged from 1.55 MPa at 7-d (2% OPC) to 10 MPa at 90-d (12% OPC).	[24]
	Canada, different locations	With a density range from 2.8–3.4 g/cm^3, and a d_{50} of 0.2–0.8 mm, the MT was used for an unpaved road base construction.	UCS.	UCS reached 9.5 MPa with a water-to-cement ratio of ~0.35.	[54]
Copper and Garnet	USA, Arizona	Synthetic MT: 86% <75 µm; copper MT: 55% sand content; garnet MT (SP), treated with FA and OPC (0%–20%).	Standard Proctor compaction and UCS.	UCS reached ~2.2 MPa with 10% OPC treatment.	[55]
Copper /Gold	Philippines, Benguet	Almost 100% of the grain <2.5 mm treated with 200–500 kg/m^3 of cement and used in roller-compacted concrete.	UCS and durability.	Increasing the dosage of cement increased the UCS up to 28 MPa at 28-d.	[56]
Gold; Iron; Copper; Lead	Canada	Several treatment types (OPC, slag, FA, Calsifrit).	UCS, mortar strength, leaching and durability correlated with numerical simulations.	Tailings binder matrix passed the freezing/thawing, durability, and TCLP tests, and sustained high compression loads.	[57]

2.3. Aggregates Used with Geopolymer Treatment

Table 4 summarizes the studies on mine by-products treated by geopolymerization used as road construction materials. Geopolymerization is a reaction of aluminosilicates in highly concentrated alkali hydroxide or silicate solution, leading to a stable geopolymer composed of amorphous polymeric structures with interconnected Si–O–Al–O–Si bonds [65]. Few studies have been conducted on the geopolymerization of MT for road structures [66–69]. Indeed, this kind of activation usually requires temperatures higher than 20 °C, more appropriate for concrete prefabrication or cement paste backfill.

Ahmari et al. [66] presented preliminary research on Arizona's sterile copper compacted with NaOH and FA. They adjusted the large Si/Al ratio of MT with FA ratio (i.e., lower) and used NaOH as an alkaline agent (2%–2.5% to maintain the stability of the C–S–H gel). Their study focused on evaluating UCS, microstructure analysis by scanning electron microscope (SEM), and mineralogical composition. The presence of ash increased compactness, and the resistance was improved with adequate mechanical properties developed during the first 7-d (80% in 2-d). Sterile copper MT is a promising material for road technology [66,68]. Pacheco-Torgal et al. [67] presented the properties of dehydroxylated tungsten MW treated with a geopolymeric binder (portlandite and/or hydroxide and/or waste glass powder). Traditional mortars showed setting and compaction difficulties: too viscous to measure the workability, flash-setting time phenomenon, and non-measurable shrinkage. Yet, the first results showed successful water absorption tests. The very compact structures obtained are advantageous against aggression, but some porosity analyses are missing.

Table 4. Mine wastes used in road construction—geopolymerization treatment.

Mine	Provenance	Main Characterization and Use	Conducted Tests	Main Properties	Ref.
Lead-Zinc	Italy, Sardaigna	Tailings stabilized by different compositions of lime, $FeCl_3$, and KH_2PO_4 to improve strength.	Stability of heavy metal.	The combined use of $FeCl_3$—KH_2PO_4 decreases the leachability of Pb, As, and P.	[52]
Tungsten	Portugal	Geopolymeric concretes with MW mud.	UCS.	More durable than traditional concrete but fresh properties are difficult to define.	[67]
Copper	USA, Arizona	36% of copper MT are less than 75 µm. They were treated with 0%–6% NaOH and FA and used as a road base material.	UCS and SEM.	UCS reached 2.5 MPa with 2% NaOH.	[66]
	USA	Tailings were mixed with 0 to 11 mol of NaOH to be used as a road base construction material through geopolymerization.	UCS and SEM.	UCS of 5.32 MPa for the mix with 11 mol of NaOH.	[70]

2.4. Aggregates Used with Bituminous Treatment

Numerous WR and coarse tailings have been used in the bituminous pavement because of their availability or their skid-resistant qualities. Table 5 summarizes the MW employed as road construction materials in an asphalt matrix. In the USA, several uses of tailings have been applied in road asphalt layers, e.g., in 1974 in Riverside County (California) where iron coarse tailings were used as aggregate for bituminous paving for a new county road and in a local concrete structure. Iron mine residues are also used in Missouri and Illinois. Several hundred thousand tons of WR from a closed iron mine was crushed and sold as gravel for bituminous paving (skid-resistant aggregate). In Missouri, for many years WR from an abandoned lead mining operation was used for bituminous paving in St François County and St Louis City. Coarse tailings from lead-zinc ores from the tri-state mine have been employed as aggregate material in bituminous base courses and wearing surfaces for highway construction (Kansas, Missouri, and Oklahoma) and in OPC concrete. In New Mexico State, molybdenum MW was used in bituminous road structures [63].

In Minnesota, the skid resistance quality of taconite tailings (iron ore) has been noted since the 1970s. Recently in Texas, the use of taconite in asphalt layers led to better results when compared to granite and limestone aggregates in terms of semicircular bending, indirect tensile, dynamic modulus, and restrained specimen thermal stress tests [63,75]. In Malaysia, electric arc furnace steel slag and copper MT were tested as a substitute for conventional granite gravels used in pavements. The essential laboratory parameters were studied (Marshall's stability, moisture susceptibility, indirect tensile resilient modulus, and dynamic creep tests). The maximum portion of copper MT is 20% as fine aggregates due to its gradation (generally < 1 mm). The performance of asphalt mixtures for road construction can be improved with an alternative source of aggregate. Optimum results have been observed for the mix of 20% tailings and 80% furnace steel compared to 100% granite aggregate while respecting the target water content (max 2% water absorption). All tested properties satisfied the Malaysian road work standard specification and moisture susceptibility test results do not appear to be a problem [73]. Amrani et al. [76] have studied the feasibility of using phosphate-MW for improving the rheological characteristics of asphalt binders. In this work, the potential valorization of PG, phosphate sludge, and FA wastes as mineral fillers were investigated. The results showed that the viscous flow behaviour and mechanical properties of an asphalt binder containing PG by-products were substantially improved compared with bitumen reinforced by the other additives.

Table 5. Mine wastes used in road construction—asphalt.

Mine	Provenance	Utilization	Conducted Test	Properties	Ref.
Copper	Malaysia	Copper MT, with a specific gravity of 3.58, was mixed with a grade bitumen binder to produce stone mastic asphalt.	Binder drain-down test, resilient modulus test, and Marshall's stability test, rutting deformability.	Indirect tensile resilient modulus was higher in the mixtures containing MT at the low and elevated temperatures.	[71,72]
	Malaysia	Up to 20% of copper MT (85% <75 µm) used for asphalt mixtures utilized in pavements.	Marshall's stability, moisture susceptibility, indirect tensile resilient modulus, dynamic creep test, rutting test, toxicity characteristic leaching procedure.	Mix that contained 20% copper MT displayed sufficient resistance to permanent deformation.	[73,74]
	USA, Utah	Copper MT as aggregates mixed with 0 to 20% asphalt emulsion.	Compressive and tensile strengths, permeability, rain erodibility, and resilient modulus.	Highest compressive strength reached 1992 kPa at 28-d and 4% of cement.	[24]
Taconite	USA, Minnesota	Asphalt mixtures prepared with conventional gravels, taconite gravels, or combinations of both. A total of 90% of the taconite grain <10 mm.	Indirect tensile test, creep stiffness and strength, semicircular bending, thermal stress restrained specimen test, acoustic emissions monitoring, and dynamic modulus.	Taconite gravels and mineral filler (T + MF)—mixture has the highest strength with 8.5 MPa at −36 °C.	[75]
Phosphate	Morocco	PG, phosphate sludge, and FA wastes were used as mineral fillers for improving rheological characteristics of asphalt binder.	Chemical and mineralogical properties, viscous flow, frequency sweep, and temperature sweep tests dynamic shear rheometers.	Extra 5 wt.% of PG improved high service temperature properties of asphalt binder. The complex shear modulus of the PG sample was the best at all test temperatures.	[76]

2.5. Example of Usages

In the USA, for decades several examples of using tailings in road construction were reported, such as the historical "Million Dollar Highway" (Colorado, 1930) built with gold MW. In 1974, ASTM E38.06 formed an MW in the construction task group to define mine waste classification and determine the potential construction use following existing ASTM specifications. They elected to exclude mill tailings as aggregate (too fine) but considered WR depending on its location and characteristics (uniform composition, inexpensive, iron content) [25]. In the late 1970s, an inventory of mining and mineral waste use across the USA was conducted [63,77]. In southeastern Illinois, 90 k tons of fluorspar WR was used as gravel. A considerable amount of "poor rock" from copper MT in Michigan has been used as a base and sub-base material. Aggregates made of crushed WR from two slate producers were employed as subbase material in Virginia with a careful control of the shape factor (flat and elongated index). In Utah, more than 5 Mt of copper MT has been used for highway construction, thanks to the separation facility constructed by Kennecott Copper Corporation, which allows the selection of 50% of tailings from the concentrator. In California, in numerous instances, aggregates from historic gold MT have been used successfully in highways and construction projects, such as the Oroville Dam in Butte County. Two aggregate producers in the Sacramento area have commercialized gold mill tailings. Despite the numerous practical cases, no state has yet defined a general methodology to facilitate this kind of reuse. In 2009, the European Commission produced a reference document on the best available techniques for the management of tailings and WR in mining activities [78]. This document reports and discusses several projects using tailings as road construction material. For example, in the German barite mining industry, crushed WR and coarse MT (<4–16 mm) are currently used as subbase or as backfill material; medium MT (1–4 mm) are used as aggregate in shotcrete mixtures to replace sand. At Siilinjärvi, a phosphate mine in Finland, a portion of WR was crushed and used as a structural material for earthworks. At Aitifk, Sweden, copper MT was subjected to an extensive testing program, including material characterization, field-scale transport modelling, and hydrogeological tracer tests. They concluded that 65% of WR does not produce acid drainage and has the characteristics to be used as ballast (road and railways) and in asphalt applications. They used the 35% of WR that presents the potential of acid drainage as cover material. In Europe, coal MT (coarse and fine) are used in multiple ways as base material on for constructions such as dams or dikes (e.g., filling material), road embankments, noise protection walls, and ground improvement with hydraulic binders, also including the brick or ceramic industries. The improvement of industrial processes has also allowed the re-exploitation of a part of coal MT as a coal source since the middle of the 20th century.

3. Guidelines on the Selection and Use of Road Construction Materials

The Transport Research Laboratory (UK) has published guidelines for selecting road materials [79]. The guidance for the road materials selection as a base or subbase layer is summarized in Figure 3. The framework is built to help select appropriate solutions to design requirements by evaluating the available options, identifying potential problems, and assessing their impacts. For this, the recognition of intrinsic parameters, such as material nature and properties, and external effects are important (i.e., use condition, environmental risks, project social impact, and economic constraints). Table 6 presents some of the required specifications. The selection framework identifies four principal scenarios:

(i) The material is recommended; it meets all criteria for the targeted use and has an acceptable performance record in similar geotechnical and climatic environments. Its use should be promoted.
(ii) The material meets all criteria for the aimed use and has a satisfactory performance record but in significantly diverse geotechnical and climatic environments. An assessment of the impacts of the various conditions on the material must be conducted (i.e., traffic, climate, hydrology, and topography), with engineering context, construction method, and road maintenance program. Finally, special measures can be taken such as limiting its incorporation rates, or treatment with a hydraulic binder, or both.
(iii) When the material meets the selection criteria, but has not previously been used successfully, a review of potential problems identified by standard tests and criteria is required. Then, the material is to be considered as-is or after treatment.
(iv) If the material fails the selection criteria, for the targeted use after cross-checking that test methods are appropriate, review implications of environmental impacts and geotechnical characteristics are required. If modifying the material or the design will not lead to improved performance, it is recommended to downgrade it from the base to the subbase, or from filling to capping [79].

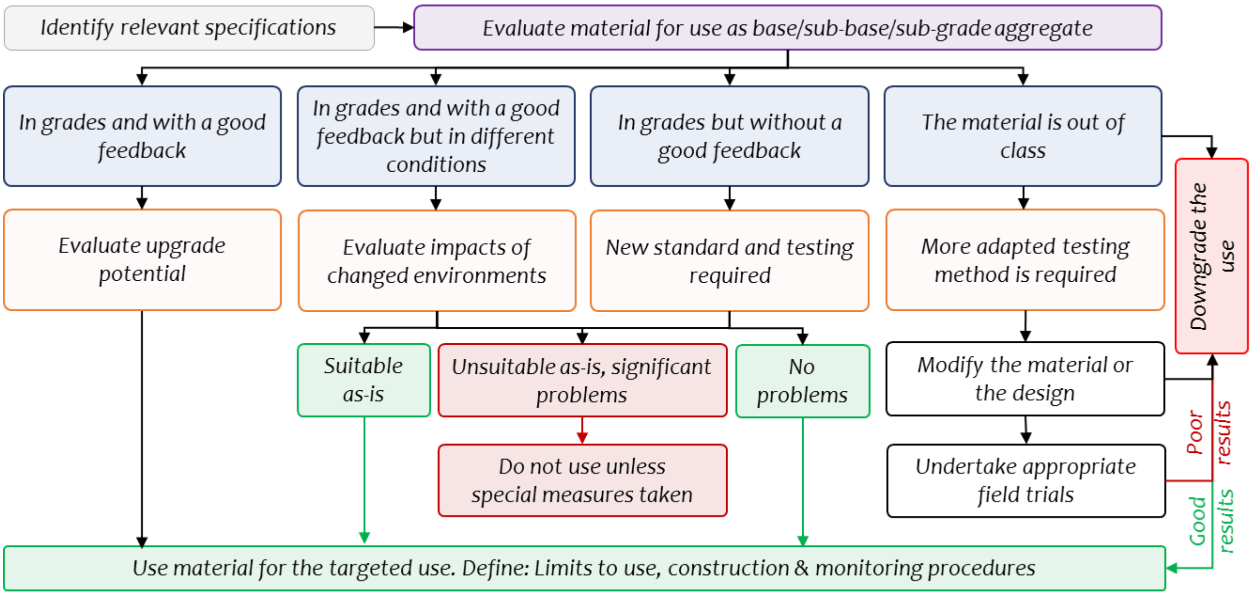

Figure 3. Aggregate selection assessment framework for use as a base or subbase adapted [79].

Table 6. Specifications for materials used for the base, subbase, subgrade, and asphalt surface.

Layer		**Gravel**	**Sand**	**Fine**	**Standards**
Criteria		**Surface/Base/Subbase**	**Surface/Base/Subbase**	**Surface/Stabilized Soil**	
d/D	mm	112/5	5 or 2/0	0.315	BNQ 2560-114; Setra, 1994; NF P 18-545
		56/0.315	0/6.3	0.8	
Passing 80 µm	%	7	8–10	>15% 90 µm	CSA-A23.2-5A; NF P 15 108
VBS	%	≤0.2	≤0.2	≤8	LC 31-255
MD	%	≤15–45	–	–	LC 21-070; EN 1097-1; Setra, 1994
LA	%	≤20–50	–	–	LC 21-400; EN 1097-2; NF P 18-545
MD + LA	–	≤35–85	–	–	BNQ 2560 -114; NF P 18-545
Fragmentation	%	100–50	–	–	LC-21-100
Flakiness	%	15–35	–	–	NF P 18-545
Property	%	0.5–2	<2	3	NF P 18-545; CSA-A23.2-5A
Plasticity	–	–	LL < 30 and IP < 10	LL < 30 and IP < 10	NF P94-051
Sand equivalent		–	>35	–	UNE EN 933-8
UCS	MPa	–	–	≥1 at 3-d	NF P 15-108; CFTR [80]
Tensile strength	MPa	–	–	≥0.2	NF P 94-100
Reversible Modulus	MPa	200–600	400–600	90–15	NQ 2560-114; Setra, 1994; AASHTO Ware Pavement ME Design
Gelivity	–	Cf. passing 80 µm	Cf. passing 80 µm	UCS ≥ 0.25 MPa	CSA-A23.2-5A; NF P 98-234.2; CFTR [80]
MO	%	≤0.8	<1	<1	LC 31-228
Sulfur content	%		0.2		MDDEP (2002)
Leaching potential	–		Cf. local non-hazardous waste classification		1999/31/CE; MDDEP (2002)

4. Conclusions

This paper reports and reviews the mine by-products used directly or with treatment as geomaterials for road construction. Most of the studies found were conducted using copper MT. Many examples show that the use of mine by-products is an interesting alternative to new materials as aggregates with a treatment. The mining industry can progress in many areas to be eco-friendly (exploration, extraction, treatment, transport, and closing) and to ensure the sustainable development of exploited regions. Management of MW is a major issue: secure solutions and valorization techniques are required. MW can be considered a new resource of aggregate for road construction, building materials, and clay for brick manufacturing. The sustainability of road structures depends in part on a judicious choice of granular materials. At the same time, forecasts of the aggregate market indicate an important increase in demand. Developing methods to promote the use of alternative materials from by-product recovery or recycling as new reliable sources will be essential to conserve nonrenewable resources in accordance with the principles of sustainable development. The similarities between tailings and aggregates, and between road engineering and some non-hazardous waste management should be exploited. The recovery methodology must maintain the same level of road material standards and integrity despite repeated loading and environmental modification (wetting and drying, freezing and thawing). Depending on the distance of the mines and the aggregate needs, these issues can be coupled to ensure an eco-responsible expansion of nearby territory. Some processing of the mine residues will be required at the mine site (i.e., characterization, selection, and sorting) to facilitate their valorization as valuable aggregate products. An awareness of the necessity of sustainable development in modern society grows in the collective consciousness. To encourage initial investment and develop sustainable practices, legal incentives are necessary for the form of specific legal texts or taxation of landfilled waste.

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