

Mining Waste Materials in Road Construction

Nuha Mashaan *  and Bina Yogi

Mineral Recovery Research Centre (MRRC), School of Engineering, Edith Cowan University, 270 Joondalup Drv., Joondalup, Perth, WA 6027, Australia; byogi@our.ecu.edu.au

* Correspondence: n.mashaan@ecu.edu.au

Abstract: Resource depletion and environmental degradation have resulted from the substantial increase in the use of natural aggregates and construction materials brought on by the growing demand for infrastructure development. Road building using mining waste has become a viable substitute that reduces the buildup of industrial waste while providing ecological and economic advantages. In order to assess the appropriateness of several mining waste materials for use in road building, this study investigates their engineering characteristics. These materials include slag, fly ash, tailings, waste rock, and overburden. To ensure long-term performance in pavement applications, this study evaluates their tensile and compressive strength, resistance to abrasion, durability under freeze–thaw cycles, and chemical stability. This review highlights the potential of mining waste materials as sustainable alternatives in road construction. Waste rock and slag exhibit excellent mechanical strength and durability, making them suitable for high-traffic pavements. Although fly ash and tailings require stabilization, their pozzolanic properties enhance subgrade reinforcement and soil stabilization. Properly processed overburden materials are viable for subbase and embankment applications. By promoting the reuse of mining waste, this study supports landfill reduction, carbon emission mitigation, and circular economy principles. Overall, mining byproducts present a cost-effective and environmentally responsible alternative to conventional construction materials. To support broader implementation, further efforts are needed to improve stabilization techniques, monitor long-term field performance, and establish effective policy frameworks.

Keywords: mining waste; compressive strength; tensile strength; road construction; sustainable materials; pozzolanic reaction; waste utilization



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1. Introduction

The expansive development of infrastructure has led to the increased consumption of virgin aggregates in road construction, resulting in significant environmental impacts. High carbon emissions, habitat devastation, and resource depletion are only a few of the negative environmental effects of these materials' extraction and processing [1]. One sustainable solution to these problems is the use of waste mining materials in road construction, which has been investigated by engineers and researchers. Large volumes of waste, such as tailings, waste rock, slag, fly ash, and overburden materials, are produced by mining operations and are frequently dumped in landfills or abandoned sites, which pollutes the air, contaminates the land, and depletes water supplies [2]. Reusing mining byproducts as construction materials, rather than discarding them as waste, presents a practical and sustainable solution to the dual challenges of infrastructure development and waste management. This approach aligns with the global shift toward resource efficiency and environmental stewardship, offering significant environmental, economic, and societal

benefits. Utilizing mining waste in road construction mitigates the adverse environmental impacts typically associated with mining operations, such as land degradation and water pollution, while simultaneously reducing the reliance on virgin raw materials. This, in turn, helps conserve natural resources, lowers material extraction costs, and minimizes the energy-intensive processes involved in sourcing and processing traditional construction materials [3].

From an economic perspective, incorporating mining waste into construction practices can substantially decrease the costs related to material acquisition, transportation, and disposal. These savings can be particularly beneficial for large-scale infrastructure projects, where the volume of material required is substantial. By adopting such practices, construction activities become more cost-effective and contribute to long-term economic sustainability. Moreover, the use of locally available mining waste reduces the need for long-haul transportation, thereby further cutting costs and emissions. In terms of environmental impact, the reuse of mining byproducts contributes to lowering the overall carbon footprint of construction projects [4]. This is achieved through a reduction in emissions associated with the extraction, processing, and transportation of conventional aggregates. Furthermore, it supports the principles of the circular economy by keeping materials in use for as long as possible and extracting maximum value from them before final disposal. This closed-loop approach promotes sustainable development by emphasizing waste minimization, resource conservation, and environmental protection [5,6].

The concept of integrating mining waste into construction practices is firmly rooted in the principles of the circular economy and sustainable development, both of which advocate for reducing waste generation, enhancing resource efficiency, and minimizing environmental degradation. By aligning construction practices with these principles, the industry can play a pivotal role in addressing global environmental challenges, including climate change, resource depletion, and ecological imbalance [6].

This paper provides a comprehensive review of various types of mining waste used in road construction, examining their engineering properties, potential applications, and associated environmental and economic benefits. It also discusses the limitations and challenges that may arise in the implementation of such practices, including technical, regulatory, and public acceptance issues. By analyzing these factors, this study aims to demonstrate the technical and environmental feasibility of using mining waste as a sustainable construction material. Furthermore, it seeks to inform and guide researchers, engineers, and policymakers in developing strategies that facilitate the broader adoption of mining waste in road infrastructure projects, ultimately contributing to more resilient, cost-effective, and environmentally responsible construction practices.

2. Research Methodology

To ensure a systematic and credible review, we adopted a structured methodology for literature selection and analysis. Academic databases including Scopus, Web of Science, ScienceDirect, and Google Scholar were explored using keywords such as 'mining waste road construction', 'slag stabilization', 'pozzolanic fly ash', and 'tailings in pavement engineering'. The studies included were peer-reviewed journal articles published between 2010 and 2024, focusing on both experimental and review-based investigations. The inclusion criteria required that studies provide empirical data or comprehensive analysis relevant to road construction applications. Papers were excluded if they addressed non-engineering uses of mining waste, were not in English, or lacked methodological transparency. The data from the selected studies were synthesized comparatively, focusing on physical, mechanical, environmental, and economic performance indicators.

3. Types of Mining Waste Used in Road Construction

Many of the waste materials produced by mining activities have engineering qualities that make them appropriate for use in road construction. When appropriately stabilized and processed, these materials can be utilized in different road structural layers, lowering the need for virgin resources and lessening their negative effects on the environment. The basic types of mining waste utilized in road construction involve tailings, waste rock, slag, fly ash and bottom ash, and overburden materials. Each type has its distinct physical, chemical, and mechanical properties that influence its suitability for different road construction applications.

3.1. Tailings

When valuable minerals are extracted from ores, the finely powdered residues that remain are known as mining tailings [4]. Typically stored in tailings ponds or impoundments, these materials pose next-level environment risks due to their potential to leach heavy metals and other contaminants into surrounding ecosystems. However, tailings can be used again as subbase and base materials for roads if they are stabilized with cementitious binders or geopolymers. Because tailings are fine-grained, they can improve soil stabilization and lessen the requirement for conventional binding agents [5]. Tailings that have been appropriately handled have been shown to have great compressive strength and durability, which makes them appropriate for rural road development and low-traffic road applications [6].

3.2. Waste Rock

Waste rock consists of large fragments of rock and soil removed during mining operations to access ore deposits. This material can be used in place of natural aggregates in road construction because it is usually coarser and more durable than tailings [7]. Waste rock can be used in boarding, subbase layers, and drainage structures due to its high load-bearing capacity and resistance to weathering. Crushed and graded waste rock provides excellent mechanical linking properties, enhancing the stability and longevity of roads. Its use as a substitute for conventional aggregates helps mitigate the environmental impact of aggregate quarrying. However, the existence of sulfide minerals in some waste rock materials needs careful handling to prevent acid mine drainage, which can lead to water and soil contamination. Finally, there are significant financial advantages to employing waste rock. Construction projects can save money for contractors by reducing their reliance on pricey natural aggregates through the reuse of mining leftovers. Furthermore, using waste rock can lessen the environmental impact of conventional mining methods, supporting a circular economy in the building industry and being in line with global sustainability standards.

3.3. Slag

Slag is a byproduct of mining metallurgical processes, especially those that refine metals like copper, steel, and lithium. Slag is frequently used in road building as an alternative to crushed stone aggregates because of its great mechanical strength, longevity, and resistance to chemical weathering [8]. For example, steel slag has been effectively used in road base layers and asphalt pavements, providing better performance in terms of load-bearing capacity and skid resistance. Lithium slag, a relatively new waste material, is gaining attention for its pozzolanic properties, making it a potential binder in road construction. Indeed, it is crucial to test for leachability before utilizing slag in road infrastructure to make sure that no hazardous trace metals are released into the environment. Traces of lead, cadmium, chromium, or arsenic may be present in some types of slag, especially those that come from industrial operations like steelmaking. These metals may

be harmful to the environment and human health if they seep into the soil and water. Regulatory agencies frequently demand laboratory testing utilizing techniques such as the Synthetic Precipitation Leaching Procedure (SPLP) or the Toxicity Characteristic Leaching Procedure (TCLP) in order to evaluate leachability. These tests assist in determining if slag satisfies safety requirements for usage in construction. Slag can be altered or treated before being used in infrastructure projects if leachability is an issue.

In addition to conventional metallurgical slags, lithium slag, a byproduct of lithium refining, has recently been investigated for use in road base applications. It exhibits favorable pozzolanic reactivity and potential as a supplementary binder in stabilized layers, although field validation is still limited [9].

3.4. Fly Ash and Bottom Ash

Fly ash and bottom ash are combustion residues produced in coal-fired power plants, commonly associated with mining operations in coal-rich regions [9]. A fine, powdery substance with cementitious qualities, fly ash is frequently used to stabilize soil and partially replace Portland cement in concrete road pavements. It lowers the overall carbon footprint of road construction projects while enhancing the concrete's workability, strength, and durability. In embankments, bottom ash, a coarser material, is frequently used as a filler or subbase. These materials solve the issue of power plant ash disposal while also assisting in lowering the reliance on traditional cement and aggregates. When using fly ash in road building, it is important to closely monitor the levels of unburned carbon and heavy metals like arsenic, lead, and mercury to ensure environmental safety. Unburned carbon can degrade the material's strength and possibly contribute to unwanted emissions when it is used for roads. On the other hand, heavy metals present serious hazards of leaking into nearby ecosystems and groundwater, particularly when the material is exposed to moisture or harsh weather. To reduce these hazards, strict quality control procedures are necessary, such as routine testing for impurities and the application of binders or stabilizing agents [10].

3.5. Overburden Material

Overburden is the rock or soil layer that needs to be removed in order to access the ore being mined. Overburden is also referred to as spoil or waste. Overburdens are removed from surface mining and do not contain toxic components, unlike tailings, which are another type of underground mining waste. Interburden, a related term, refers to the material that lies between orebodies at subsurface levels [11]. Overburden, which is typically regarded as garbage, can be used for road infrastructure projects such as subgrade improvement, slope stabilization, and embankment building. When packed properly, overburden is particularly beneficial in road construction in mining regions where the transportation of conventional construction materials is costly. Indeed, geology and mining circumstances can have a substantial impact on the composition of overburden materials. Because of this heterogeneity, site-specific evaluations are essential for determining if they are suitable for road building. To guarantee stability, durability, and environmental safety, variables like moisture content, mineral composition, particle size distribution, and possible pollutants must be examined. The effectiveness of using overburden materials as subgrade, base, or fill materials in road infrastructure is determined by standard tests such as Proctor compaction, California Bearing Ratio (CBR), and permeability evaluations. A thorough assessment guarantees peak performance and reduces hazards including erosion, settling, and toxic material leakage [12].

4. Engineering Properties of Mining Waste Materials

The sustainability of mining waste materials used for road construction is determined by their engineering properties. These characteristics affect the permeability, strength, stability, durability, and environmental effect of roads constructed using these kinds of materials [13–19]. Numerous laboratory and field tests are performed to assess the physical, mechanical, and chemical properties of mining waste in order to make sure it satisfies the necessary building requirements. In this section, the main engineering properties of different types of mining waste materials are examined, along with their use in road construction.

4.1. Physical and Mechanical Properties

The physical and mechanical properties of these materials mainly include particle size distribution, density, specific gravity, shear strength, permeability, and durability. These properties are important as they evaluate the strength, stability, and acceptability of mining waste for road building [20–25]. Tables 1 and 2 present the effects of different types of mining waste on the compressive and tensile strength of concrete, respectively.

Table 1. Impact of mining waste content on compressive strength of concrete.

Types of Mining Waste	Replacement Level (%)	Compressive Strength	Major Finding	Citation
Slag	5%	6.39	Cement and slag increase compressive strength by generating dense microstructures and improving hydration. Five percent replacement produced the best results.	[6]
Fly ash	10%	22.8	Compressive strength is increased when fly ash and cement combine to create more C-S-H (calcium silicate hydrate) gel. But too much replacement might weaken the material.	[18]
Tailing	20%	32.4	Improved early strength but reduced long-term durability.	[19]
Waste rock	25%	45.2	Enhanced strength due to its rough/ angular surface.	[20]
Overburn	30	29.8	Has weak performance; thus, it needs binding agents.	[19]

Table 2. Impact of mining waste content on tensile strength of concrete.

Types of Mining Waste	Replacement Level (%)	Tensile Strength	Major Finding	Citation
Slag	10%	4.5	Improved tensile resistance due to pozzolanic reaction	[25]
Fly ash	15%	3.9	Moderate performance; requires fiber reinforcement	[26]
Tailing	20%	3.1	Weak bonding; needs stabilization	[25]
Waste rock	25%	4.8	High tensile strength due to angular particle interlock	[26]
Overburn	30%	2.7	Low performance; needs additional stabilizing agents	[25]

4.1.1. Size of Particles

The size of mining waste material particles has an effect on the compaction characteristics, permeability, and load-bearing capacity of the constructed road. When combined with cement or lime, tailings, which are mostly fine-grained particles (<0.075 mm), can act as a stabilizing agent. But, on the other hand, if they are not treated properly, the problem of excessive dust on mixing may occur, resulting in water retention [27–30]. Likewise, waste rock is suitable for replacing aggregates used as road bases as it is coarser and contains particles ranging from gravel to boulders. Steel slag aggregates have a high angle of internal friction (40° to 45°) that contributes to high stability and well-graded particle distribution; thus, they can be used in pavement construction [31–35]. Similarly, fine-grained materials like fly ash and bottom ash are frequently used to stabilize soil or to replace cement in concrete roadways. In the case of overburden materials, before being applied, they must be screened and graded since their grain sizes range from loose dirt to big rock pieces.

4.1.2. Density and Specific Gravity

Specific gravity and density affect a material's ability to withstand loads and compaction. Slag and waste rock are perfect for road base layers because of their high densities (bulk density ~ 2.8 – 3.5 g/cm³) [6]. Similarly, fly ash is appropriate for soil stabilization and lightweight embankments due to its reduced density (~ 2.1 g/cm³) [36]. Before being used in road layers, tailings must be stabilized since their densities vary according to the mineral content. Since overburden materials comprise a mixture of heavy and light particles, grading is necessary to obtain the ideal density for embankments.

4.1.3. Shear Strength

Because shear strength determines a material's resistance to deformation under stress, it is essential for road materials' stability. Waste rock and slag exhibit high shear strength; thus, they can be an excellent alternative to crushed stone, especially favorable for pavement applications [37]. Likewise, when mixed with cementitious materials, fly ash and tailings gain significant compressive and shear strengths that enable their application in stabilized subgrade layers [31]. Compaction is necessary for overburden materials to improve their bearing capacity and shear strength for subbase layers and embankments.

4.1.4. Compaction Characteristics

To ensure the suitability of mining waste materials for use in road construction, it is essential to evaluate their compaction behavior using established testing standards. The Standard Proctor Test (ASTM D698) [36] and the Modified Proctor Test (ASTM D1557) [37] are widely accepted methods used to determine the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) of construction materials. These tests simulate field compaction scenarios and provide critical parameters for material placement and structural stability. Additionally, the California Bearing Ratio (CBR) test (ASTM D1883) [38] is commonly used to evaluate the strength of subgrade and subbase layers prepared with mining waste such as overburden or tailings. The application of these standardized tests ensures consistency in compaction practices, improves load-bearing performance, and enhances the long-term durability of pavement layers [39].

4.1.5. Permeability and Drainage Properties

The drainage and water retention of road layers are impacted by permeability. When utilized in road foundations, tailings' limited permeability necessitates drainage layers. Because slag and waste rock have high permeability and strength (as shown in Table 3),

waterlogging in road construction is avoided. Additives are needed to enhance the drainage properties of fly ash.

Table 3. Summary of engineering properties of common mining waste materials used in road construction.

Waste Type	Particle Size	Bulk Density (g/cm ³)	Shear Strength	Key Remarks	Citation
Slag	Well-graded, coarse to fine	2.8–3.5	High (due to internal friction angle 40–45°)	Excellent stability; abrasion resistance; good pozzolanic reactivity	[14,31]
Fly ash	Fine (<0.075 mm)	~2.1	Low (improves with binder)	Lightweight; good cementitious properties; needs stabilization	[15,17]
Tailings	Fine-grained (<0.075 mm)	(~2.3–2.6)	Low to moderate (needs stabilization)	High moisture sensitivity; poor drainage; good for stabilization when mixed	[13]
Waste rock	Coarse (gravel to boulder)	2.6–3.2	High	Durable; angular; excellent for subbase and drainage	[6]
Overburden	Mixed (silt to rock fragments)	1.8–2.6	Low to moderate (after compaction)	Heterogeneous; needs grading and compaction; usable for embankment layers	[12,38]

4.2. Chemical and Environmental Properties

Mining waste materials possess unique chemical and environmental properties that influence their suitability for road construction. The chemical composition of mining waste materials is a major factor influencing their durability, environmental safety, and binding capacity. For road infrastructure to be free of pollutants, poisons, and instability caused by mining waste, a thorough inspection is essential.

4.2.1. Chemical Composition and Stability

Depending on the kind of ore and the mining technique, mining waste has different chemical compositions. Common components include silica, alumina, iron, calcium, and trace metals. Certain materials are perfect for stabilizing road bottoms because of their cementitious qualities, such as fly ash and slag. The presence of sulfides in some tailings, however, can result in acid mine drainage (AMD) when they encounter water and air [21]. Mining waste is frequently treated with cement or lime to increase stability, which lowers its reactivity and qualifies it for use as road subgrades and embankments [6].

4.2.2. Leachability and Environmental Impact

How quickly pollutants break down and move into soil and water is referred to as leachability. Lead, arsenic, and cadmium are among the heavy metals found in small concentrations in some mining wastes, such as coal fly ash and metal tailings, which can contaminate groundwater [22]. However, studies have also shown that leaching is reduced by compaction, encapsulation, and decreased water infiltration when mining waste is mixed into road layers under controlled settings. Many stabilizing and containment techniques are used to reduce these concerns, such as bitumen or cement encapsulation, which limits the flow of pollutants. Furthermore, neutralizing procedures using lime or other alkaline substances aid in decreasing the solubility of dangerous substances, guaranteeing environmental security [23].

4.2.3. PH and Sulfate Resistance

The chemical reactivity and long-term stability of mining waste materials are greatly influenced by their pH level. Road construction can benefit from alkaline waste products like steel slag, which can stabilize acidic soils. However, certain fly ash and tailings have extremely acidic qualities that, if left untreated, may destroy the structural integrity of roadways.

Another challenge is sulfate, which can react with cement and lead to the expansion, cracking, and premature failure of road structures.

4.2.4. Environmental Risk Assessment and Mitigation Strategies

A critical environmental consideration in the reuse of mining waste in road construction is the potential for contamination from heavy metal leaching and acid mine drainage (AMD). Tailings and fly ash, in particular, can contain trace levels of arsenic, cadmium, lead, and mercury, which, if released into the surrounding soil and water systems, pose significant ecological and public health risks. To mitigate these hazards, several strategies have been employed. The stabilization of mining waste with alkaline materials such as lime or Portland cement increases the pH and reduces the solubility of hazardous metals, thereby limiting their mobility in the environment [36]. Encapsulation methods using bituminous binders or geopolymers further prevent water infiltration and leachate formation. In AMD-prone materials like sulfide-bearing waste rock, the addition of neutralizing agents such as limestone has proven effective in reducing sulfuric acid generation and subsequent metal release [37]. Moreover, environmental assessment protocols such as the Toxicity Characteristic Leaching Procedure (TCLP) and Synthetic Precipitation Leaching Procedure (SPLP) are internationally recognized tests used to evaluate the leachability of contaminants from construction materials. These standardized methods ensure that reused mining waste meets environmental safety standards before deployment in infrastructure projects, supporting sustainable reuse practices while safeguarding ecosystems.

4.3. Durability and Weathering Resistance

The durability of mining waste materials varies, which impacts how suitable they are for road construction. Slag and waste rock are perfect for roads with heavy traffic and cold climates because of their exceptional resilience to abrasion and freeze–thaw cycles [24]. In contrast, fly ash and tailings require stabilization to prevent moisture-related degradation and improve wear resistance. The permeability and shear strength of tailings are poor, but waste rock is rough and very durable [21]. Fly ash requires a binder for structural stability; however, slag has significant pozzolanic qualities that improve binding. Before being used, overburden materials need to be graded and compacted. Natural aggregates can be substituted with slag and waste rock; however, fly ash and tailings require treatment to reduce acid production and leachability. Mining waste may improve the sustainability and performance of road construction when properly processed.

5. Applications of Mining Waste in Road Construction

Mining wastes such as those discussed before, like tailings, waste rock, slag, fly ash, and overburden, are increasingly being utilized in road construction due to their mechanical strength, cost-effectiveness, and environment benefits. Reused mining waste provides a practical substitute for traditional road construction materials, lowering the need for natural aggregates while minimizing the environmental impact considering growing concerns about resource depletion and sustainability [27]. These waste materials can be integrated into the subgrade foundation, surface layer, or other layers of a road, depending on their

engineering characteristics. The following are the key applications of mining waste in road construction.

5.1. Subgrade and Subbase Layers

The subgrade forms the foundation of a road, supporting all upper layers. If the subgrade is weak, the entire road structure may suffer from settlement, cracking, or deformation. The subbase layer, which is positioned above the subgrade, improves the road's capacity to disperse loads and withstand deformation [28]. Traditionally, natural soil, crushed stone, or gravel is used to create subgrades and subbases; however, mining waste has become a more affordable option.

In subgrade layers, weak or expansive soils can be stabilized with mining waste, such as tailings, waste rock, and overburden materials. Tailings are perfect for roads constructed on clayey or unstable terrain because they can greatly increase the soil strength and lessen shrink–swell behavior when combined with cement or lime. Compacted waste rock and overburden, which are typically coarser, can create a robust subbase layer that enhances drainage and prevents settlement. Additionally, the burden of waste storage at mining sites is lessened and land degradation is prevented by employing these materials in subgrades. For example, in Chinese road construction, clayey subgrades have been stabilized using coal tailings and lime, boosting their bearing capacity by more than 30%.

5.2. Road Base Layers

One of the most important structural elements of a pavement system is the road base. Because of its strength, stability, and load-bearing ability, it guarantees that the top layers of the road will hold up under the strain of traffic and the elements. When utilized in road base layers, mining waste materials, in particular, fly ash, slag, and waste rock, have demonstrated exceptional performance. For road bases, crushed mine waste rock can be compacted and used in place of natural gravel because it has a high shear strength and durability. Waste rock is especially useful in heavy-traffic roads, as it resists rutting and wears better than conventional aggregates. Another high-performance substance utilized in road bases is slag, which is a byproduct of metal extraction procedures. Slag's cementitious qualities can strengthen the link between particles, increasing stiffness and performance over time [31]. The economic and structural advantages of integrating mining waste into base layers were demonstrated by an Indian study that indicated that a 30% fly ash and cement mix in road bases extended the pavement lifespan by 25% [32]. Road building projects can significantly reduce costs and advance sustainable infrastructure development by substituting mining waste for natural materials.

6. Environmental and Economic Benefits

Natural resources and the environment are under a lot of strain due to the quick development of urban infrastructure and transportation systems. Traditional road building supplies, mostly natural aggregates like sand, gravel, and crushed stone, are taken out of mines and quarries, which results in the overuse of these resources and related environmental damage. Furthermore, the mining sector produces enormous volumes of trash, such as fly ash, slag, tailings, and waste rock, which are usually dumped or kept in sizable garbage piles. However, it is feasible to lessen the impact on the environment, save money, and encourage long-term sustainability by integrating mining waste into road development.

6.1. Reduction in Mining Waste Disposal Issues

Large volumes of waste are produced by mining activities, and these must be stored or disposed of somehow. Large tailing ponds, waste rock piles, or slag heaps are frequently created using traditional disposal techniques, which might present long-term environ-

mental hazards. For instance, poorly managed tailings have the potential to contaminate soil and groundwater by releasing toxic substances into the environment. Large garbage mounds can also disturb nearby ecosystems and occupy important land area.

By turning waste into a valuable resource, repurposing mining waste in road construction helps alleviate these disposal concerns. Various stages of road building, including subgrade stabilization and road base materials, can make use of tailings, slag, and waste rock that would otherwise need expensive storage or present environmental hazards. This offers a workable answer to the expanding issue of mining waste management, decreases environmental hazards, and lessens the requirement for sizable disposal sites. By using mining waste in this manner, hazardous waste accumulation is less likely to occur, and improved land use is made possible.

6.2. Cost Savings and Economic Feasibility

The financial savings that come with utilizing mining waste in road construction are among its main benefits. Traditional road construction materials, such as sand, gravel, and crushed stone, are derived from quarries and need considerable financial inputs in extraction, shipping, and processing. The long-distance transportation of these commodities can also be costly and harmful to the environment because of emissions and fuel usage. On the other hand, mining waste products like fly ash, slag, and tailings are frequently found at or close to mining sites, which lowers the need for substantial processing and transportation expenses. This offers financial incentives for road construction projects as well as the mining sector. Large waste storage spaces are not as necessary, and mining businesses save money on trash disposal. Mining waste provides a cost-effective substitute for natural aggregates in building projects without sacrificing the road's strength or longevity.

Additionally, road development projects can benefit from the use of mining waste. Road strength, load-bearing capacity, and pavement durability can all be improved by the intrinsic qualities of materials like fly ash and steel slag. This lowers the frequency of upkeep and repairs, which improves infrastructure development financially over the long run [33].

A comparative cost–benefit analysis is presented in Table 4, highlighting the differences in the material costs, transport savings, and lifecycle performance between conventional and mining-waste-based road construction materials.

Table 4. Comparative cost–benefit analysis of conventional vs. mining waste materials in road construction.

Material Type	Average Material Cost (USD/Ton)	Transport Distance (km)	Estimated Lifecycle (Years)	Notes	Citation
Natural aggregates	25–35	50–100	15–20	Require quarrying, processing, and long-distance transport	[33]
Fly ash (30% blend)	10–15	<30	18–25	Reduces cement use and improves strength and durability	[32,33]
Steel slag (20% mix)	15–20	<40	20–25	Increases load-bearing capacity, durability, and skid resistance	[31,33]
Waste rock	8–12	On site or nearby	15–22	Readily available at mines; suitable for subbase and drainage	[6,27]

6.3. Long-Term Sustainability and Environmental Benefits

By minimizing the environmental impact of extraction operations, preserving natural resources, and lowering the demand for virgin aggregates, the use of mining waste in road construction promotes long-term sustainability. In comparison to traditional quarrying, it reduces habitat destruction, water pollution, and land degradation. Additionally, by replacing Portland cement, which uses a lot of energy, with materials like fly ash and slag, road construction can have a lower carbon footprint. Additionally, roads become more durable, requiring fewer repairs and less upkeep. In general, recycling mining waste encourages ecologically conscious behavior and guarantees future infrastructure that is more durable and resilient [39].

7. Challenges and Limitations

There are financial and environmental advantages to using mining waste materials to build roads, but successful implementation requires addressing several obstacles. Environmental hazards, technical hurdles, and problems with social acceptance and regulations are the main causes of these difficulties. The possible environmental danger, especially with regard to leaching and toxicity, is a major worry when employing mining waste products. Hazardous materials like heavy metals (such as arsenic, lead, and mercury) are frequently present in mining wastes like tailings, slag, and waste rock. If these materials are not adequately stabilized, they can seep into nearby soil and water. Ecosystems and groundwater may become contaminated by this leaching process. Another environmental hazard is acid mine drainage (AMD), which occurs when sulfide minerals combine with oxygen and water to generate sulfuric acid, which then releases more hazardous metals into the environment. Stabilization procedures are required for mining waste materials in order to reduce these risks, but they increase the expense and complexity of road construction projects.

Recent developments in Artificial Intelligence (AI) and machine learning have introduced data-driven approaches for optimizing material blends and predicting the mechanical performance of stabilized mining waste. These models support better decision making in pavement design by incorporating multiple variables, improving both cost-efficiency and environmental safety [40].

Incorporating mining waste materials into roads presents substantial technological challenges. These materials, which include waste rock, fly ash, and slag, frequently differ physically from conventional construction aggregates. For instance, adding fly ash to concrete can increase its strength, but doing so requires careful handling to ensure that durability and strength requirements are met. Despite being robust and long-lasting, slag can have a high angularity, which might impact workability and compaction when combined with asphalt. Furthermore, the type of ore and the mine site can have a significant impact on the composition of mining waste, which might result in inconsistent material quality. Construction projects become more complex as a result of these variances, which call for extensive site-specific testing and quality monitoring [34]. There are two major issues with utilizing mining waste to build roads. Regulatory obstacles include stringent laws that label mining waste as dangerous and necessitate thorough testing and approval prior to usage, which can cause delays and raise expenses. Social acceptance refers to the public's worries about the safety of using mining waste, particularly in areas close to mining facilities. Concerns about environmental harm and health hazards are common. To overcome these obstacles and win support and trust for the use of mining waste in construction projects, it is necessary to communicate clearly, be transparent, and involve the local population in decision making.

8. Conclusions

Mining waste materials such as fly ash, slag, tailings, waste rock, and overburden offer a sustainable and technically sound alternative to conventional materials in road construction. When properly processed and stabilized, these industrial byproducts exhibit favorable engineering properties, including adequate compressive and tensile strength, shear resistance, durability, and chemical stability. Their reuse supports the circular economy by transforming environmental liabilities into valuable resources, reducing the dependence on virgin aggregates, and lowering the environmental footprint of infrastructure projects.

The use of mining waste in road layers—such as the subgrade, subbase, and pavement—can help mitigate greenhouse gas emissions, land degradation, and water contamination. Additionally, the economic advantages include reduced material and transportation costs and lower waste management burdens. Potential environmental risks, including heavy metal leaching and acid mine drainage, can be effectively managed through stabilization techniques, encapsulation, and adherence to international leachability standards such as the TCLP and SPLP.

Technological innovations further support this transition. Advances in AI and machine learning are enabling more precise predictions of material performance, while emerging solutions like geopolymer binders and bio-based stabilizers offer environmentally friendly alternatives to traditional additives. These developments contribute to safer, more efficient, and more consistent applications.

While challenges remain—including regulatory constraints, public perception, and material variability—collaborative research, field validation, and policy support will be key to mainstreaming mining waste use in road infrastructure. Future studies should continue to explore advanced stabilization techniques, such as bio-binders and AI-optimized mix designs, to unlock the full potential of these materials and support the global shift toward resilient, cost-effective, and sustainable construction practices.

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