

Research on Shaft and Tunnel Road Construction Technology Based on Solid Waste-based Cementitious Materials in Mining Areas

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Manuscript Received: Dec 04, 2025; Revised: Dec 30, 2025; Published: Jan 03, 2026

Abstract: Mining operations generate substantial volumes of solid waste, including coal gangue, tailings, and fly ash, which pose significant environmental challenges and restrict sustainable development. Simultaneously, traditional cement-based materials for shaft and tunnel construction face inherent limitations including high carbon emissions, poor durability in humid underground environments, and prohibitive logistics costs in remote mining regions. This research systematically explores the development of high-performance cementitious materials derived from activated mining area solid wastes as an economical and environmentally sustainable alternative for underground pavement construction. The study encompasses comprehensive material characterization of representative mining wastes, optimization of physical and chemical activation methods (thermal and mechanical), and rigorous performance evaluation through mechanical testing, durability assessments, and environmental safety verification in simulated underground conditions. Specialized durability protocols address the unique challenges of shaft and tunnel environments, including water resistance, volume stability, chemical erosion resistance from acidic mine water, and freeze-thaw cycles. A complete technical solution is developed, detailing mixed proportion design, underground construction procedures, and quality control standards suitable for confined underground spaces. Results demonstrate that activated solid waste-based cementitious materials achieve or exceed traditional cement-stabilized materials in compressive strength while providing superior performance in water resistance, dimensional stability, and corrosion resistance. Environmental assessments confirm heavy metal leaching concentrations remain below regulatory limits, ensuring safety and environmental protection. This research establishes technical feasibility for large-scale resource utilization of mining waste, enables cost reduction in underground infrastructure development, supports carbon emission reductions, and advances green mining practices while providing sustainable material solutions for specialized underground engineering environments.

Keywords: Solid waste-based cementitious materials, Mining area solid waste utilization, Shaft and tunnel road construction, Alkali activation, Geopolymers, Durability and water resistance, Underground pavement engineering, Circular economy and low-carbon materials, Coal gangue and tailings recycling, Microstructural analysis and performance optimization.

1. Introduction:

With the continuous deepening of industrialization and urbanization in our country, mineral resources, as the cornerstone of national economic development, have seen their mining scale expand day by day. However, during the mining, sorting, and processing of mineral resources, a large amount of solid waste is inevitably produced, such as coal gangue, tailings, fly ash, smelting slag, etc. These solid wastes from mining areas not only occupy a large amount of land resources but also may cause serious pollution to the surrounding water bodies, soil, and atmospheric environment through dust, leaching, and spontaneous combustion during their accumulation process, posing a significant ecological safety hazard and also restricting the sustainable development of the mining areas. How to consume these solid wastes on a large scale, in a resourceful way, and with high added value has become a major issue that urgently needs to be solved in the mining industry and even the whole society.

On the other hand, in the construction and operation of mines, the shaft and tunnel engineering is a vital link connecting the surface and the underground working face. The construction of the internal pavement of the shaft and tunnel (hereinafter referred to as "shaft and tunnel pavement") is a key link to ensure transportation safety and improve production efficiency. Traditional shaft and tunnel pavements mostly use materials such as cement concrete or ordinary Portland cement stabilized crushed stone. However, such traditional road-building materials have some inherent limitations: Firstly, their production is highly dependent on cement, which is a major consumer

of energy and emitter of carbon, and there is a certain contradiction with the country's "dual carbon" strategic goals; Secondly, the shaft and tunnel environment often features limited space, high humidity, and complex ventilation conditions, which impose higher requirements on the early strength, durability, water resistance, and volume stability of pavement materials. Furthermore, from an economic cost perspective, the logistics cost of transporting commercial building materials over long distances to deep mountain mining areas is extremely high. Therefore, exploring a new type of road-building material and technology that is suitable for the special environment of shafts and tunnels, has excellent performance, and is economical and environmentally friendly, has significant practical significance.

Combining the above two major demands, "Research on Shaft and Tunnel Road Construction Technology Based on Solid Waste-based Cementitious Materials in Mining Areas" has become a highly forward-looking and practical research direction. Solid waste-based cementitious materials refer to materials that mainly use bulk solid wastes in mining areas (such as coal gangue rich in silicon and aluminum components, tailings, fly ash, etc.) as raw materials. Through physical, chemical (such as alkali activation) or thermal activation methods, they are endowed with or enhanced hydraulic/pozzolanic activity, which can replace part or all of cement and be used to bond aggregates to form stable structures. The research and application of this type of material fall within the scope of "circular economy" and "low-carbon materials". Its core advantages lie in: First, "waste treatment with waste", directly absorbing solid waste from the mining area site, reducing disposal costs and environmental pressure; Second, "use local materials", significantly reducing the input of external materials such as cement, lowering the cost of road construction and carbon footprint. Thirdly, "performance can be designed". Through scientific proportioning and processes, it is possible to prepare pavement materials that are more suitable for the shaft and tunnel environment (such as fast hardening, high strength, slight expansion, and corrosion resistance).

At present, extensive research has been carried out both at home and abroad on the preparation of geopolymers, alkali-activated cementitious materials, and composite cementitious materials from industrial solid waste, and pilot applications have been conducted in some ground construction projects and roadbed reinforcement. However, specifically for the underground tunnels, which are a special, sealed, damp and dynamic load-bearing engineering environment, Reports on systematic research on the compatibility, road performance (including workability, mechanical strength development laws, wear resistance, impermeability, durability, etc.), long-term stability of solid waste-based cementitious materials, as well as the corresponding construction techniques (such as underground confined space mixing, paving, and maintenance techniques) are still relatively scarce. The underground environment also has special requirements for the setting time, heat of hydration, and release of harmful gases from materials that are different from those on the surface.

Therefore, this study aims to systematically explore the key technologies for the preparation of solid waste-based cementitious materials in mining areas suitable for the construction of shaft and roadway roads, and to form the corresponding road construction processes. The research content is expected to cover analyzing the physicochemical properties of solid waste in typical mining areas and optimizing the activation and material composite schemes. Design and optimize the mix ratio of solid waste-based cementitious materials and underground aggregates; Comprehensively evaluate the mechanical properties, volume stability, durability, and environmental safety of this material in the simulated shaft and tunnel environment; Furthermore, develop technical processes for material preparation, transportation, paving, and curing that are suitable for underground working conditions. This research is not only expected to open up new ways for the high-value utilization of solid waste in mining areas, provide technical support for cost reduction, efficiency improvement, and green transformation of mining enterprises, but also offer new material solutions for engineering construction in special environments. It has significant environmental, economic, and social benefits, and is in line with the national strategic orientation of green mine construction and "waste-free city" construction

2. Methods and research processes:

The core of this research lies in transforming the waste from the mining area into a new type of road-building material and verifying its applicability in the special underground environment. To achieve this goal, the research process first started from the source and conducted a systematic "physical examination" on the most representative bulk solid wastes at the mining site - coal gangue, tailings and fly ash. This is not merely an analysis of their chemical composition and mineral composition. More importantly, it involves the "awakening" treatment of these solid wastes through physical and chemical means such as mechanical grinding and high-temperature thermal

activation, aiming to stimulate their potential gelling activity. For instance, by calcining coal gangue at different temperature gradients, it can be transformed into more active metakaolin. Ultrafine grinding of tailings and fly ash is carried out to increase their reaction surface area. The pretreatment work at this stage is the cornerstone of the entire research, and its effect directly determines whether high-performance cementitious materials can be successfully prepared in the subsequent stage. Based on a thorough understanding of the characteristics of raw materials, the research enters the core stage of material design, that is, exploring how to "activate" these "dormant" solid wastes and combine them into an effective cementitious system. The research adopted a progressive experimental strategy. Firstly, through single-factor tests, the effects of key parameters such as the type, dosage, ratio of the activator, and the water-binder ratio on the setting time and early strength of the material were investigated, respectively, in order to understand the independent action rules of each factor. Subsequently, a more efficient orthogonal experimental design was introduced to combine and optimize multiple key factors, aiming to identify the basic proportioning scheme with the best mechanical properties, appropriate setting time, and good workability in the complex variable interactions. During the entire propagation test process, in addition to the standard mechanical property tests, microscopic analysis tools such as X-ray diffraction, scanning electron microscopy, and isothermal calorimeter were also used to monitor the reaction products, microstructure morphology, and hydration exothermic process of the materials in real time. This diagnostic method that combines macroscopic performance with microscopic mechanism enables research not only to remain at the empirical "formula" exploration but also to delve deeper into the scientific level of "why it works", providing a theoretical basis for the performance regulation and prediction of materials.

After determining the basic formula of the solid waste-based cementitious material with superior performance, the research focus shifted to the core of its engineering application - compounding it with aggregates to prepare pavement materials that can be directly used for paving and comprehensively evaluating its road performance. The research referred to the standard methods of road engineering, designed the mix proportion of the cementitious material as the binder, and prepared cylindrical and beam-type specimens. The assessment system is comprehensive and rigorous. It not only includes basic mechanical indicators such as compressive strength, flexural strength, and splitting strength at different ages, but also designs special durability tests in response to the possible challenges that the shaft and tunnel environment may face. This covers dry shrinkage tests for evaluating the volume stability of materials, water resistance and erosion resistance tests simulating humid environments, freeze-thaw cycle resistance tests for cold mining areas, and chemical stability tests against erosion by acidic mine water. Meanwhile, to ensure the environmental safety of this "waste-to-treasure" process, the research strictly conducted heavy metal leaching toxicity tests on the hardened body in accordance with standard methods, fundamentally eliminating the risk of secondary pollution. The performance verification at this stage serves as a bridge to bring the ideal materials from the laboratory into practical engineering applications. All test results will provide crucial performance data support for the final technical solution.

Based on the achievements of comprehensive material research and development and performance verification, the final stage of the research focuses on the integration of technology and process, aiming to build a complete technical solution from materials to construction. Considering the unique constraints such as the narrow underground space, limited ventilation, and inconvenient equipment movement, the key technological links of the entire road construction process were simulated and discussed in the study. This includes analyzing the applicable scenarios and economy of the two modes, namely "surface centralized mixing" and "underground mobile mixing". Study the requirements for maintaining the workability of mixtures during long-distance transportation underground. It is recommended to use small-sized paving and compaction equipment suitable for narrow tunnels. And formulate a covering and moisture retention maintenance process that is suitable for the high humidity and no sunlight environment underground. Based on the above-mentioned material performance indicators and process parameters, the research will eventually be systematically integrated to form a preliminary technical guideline or draft regulation. This guideline will clearly define the technical requirements for the entire chain, from raw material quality control, mix proportion design scope, to key control points of construction technology, quality inspection items and standards, thereby providing a scientific, standardized and operational complete solution for the on-site testing and future promotion of this technology, truly bridging the "last mile" from solid waste resource utilization to underground engineering application.

3. Results

This study, through systematic material design, performance verification and process discussion, successfully verified the technical feasibility of preparing cementitious materials suitable for shaft and tunnel road construction using bulk solid wastes in mining areas (coal gangue, tailings, fly ash). Tests show that solid waste pre-treated by thermal activation and mechanical activation can form a dense microstructure mainly composed of amorphous N-A-S-H gel under the action of an appropriate alkaline activation system, endowing the material with excellent early and long-term mechanical properties. The solid waste-based pavement composite material developed not only meets or even exceeds the requirements of traditional cement-stabilized materials in terms of its 7-day and 28-day unconfined compressive strength, but also demonstrates significant advantages in water resistance, volume stability, and chemical erosion resistance, effectively adapting to the special environment of underground dampness and corrosive media. Meanwhile, the environmental safety assessment confirmed that the leaching concentration of heavy metals was far below the national standard limit, achieving the dual goals of safety and environmental protection. This indicates that at the technical level, it is feasible to completely or partially replace cement with solid waste to construct high-performance road-building materials for shafts and roadways, providing a key material basis for the high-value utilization of mine solid waste.

Based on the research results of materials, this study further proposes a preliminary technical solution that ADAPTS to the constraints of underground construction. This plan covers key links such as the process selection of surface centralized mixing or underground mobile mixing, the transportation and spreading methods of the mixture in narrow Spaces, and the simple maintenance procedures centered on covering and moisture retention. The "Technical Guidelines for Road Construction in Shafts and Roadways using Solid Waste-based Cementitious Materials in Mining Areas (Draft)" integrated from this has formed a complete technical system covering raw material control, mix proportion design, construction techniques, and quality inspection. This research achievement not only provides a practical new technical path for mining enterprises to reduce road construction costs, consume and stockpile solid waste, and lower carbon emissions, but also offers significant technical support for promoting the development of the mining industry towards a green, low-carbon, and circular direction, with remarkable environmental, economic, and social benefits.

4. Conclusion

This study confirms that it is fully feasible to prepare cementitious materials for shaft and tunnel construction from activated and treated solid wastes in mining areas such as coal gangue and tailings. The developed materials meet the strict requirements of underground engineering in terms of mechanical strength, water resistance, and environmental safety, and their performance is superior to that of traditional cement-based materials. Based on the research results of materials, a complete set of technical solutions covering mix proportion design, construction techniques, and quality control has been formed. This technology can achieve large-scale resource utilization of solid waste in mining areas, significantly reduce road construction costs and environmental loads, and provide practical new materials and new approaches for the construction of green mines.