

Analysis of the performance improvement of sandy soil in roadbed by waste residue containing Ba²⁺

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Abstract: Barium slag is a solid waste generated as a by-product during the industrial production of barium carbonate. Classified as hazardous industrial waste due to its high content of barium oxide and other harmful constituents, it poses potential environmental risks. This research systematically characterized the fundamental physical and chemical properties of barium slag through an integrated approach of laboratory experiments and numerical simulation. Subsequently, a comprehensive experimental evaluation was conducted to assess its feasibility for utilization in road engineering, encompassing tests for slake durability, compaction characteristics, strength performance, deformation behavior, stability, resilient modulus, and shear strength. Furthermore, a processing technique was developed to convert barium slag into a sand-like material suitable for use as subgrade filler. The findings demonstrate that processed barium slag can effectively replace natural sandy soil as a subgrade material, meeting requisite road performance standards while offering advantages of enhanced strength and improved stability. separate 0-5 mm sized particles, control the dust content less than 1%.

Key words: barium slag; feasibility analysis; sandy soil

1 Introduction

The continuous expansion of infrastructure construction in China has led to a growing demand for subgrade filling materials in highway engineering. At the site of a specific road project, a significant amount of barium slag has been stockpiled, awaiting disposal. Conventional earthwork construction for subgrades often encounters challenges such as shortage of soil sources, rising costs, long transportation distances, land occupation, and ecological environmental damage. Concurrently, the stockpiling and disposal of large quantities of industrial solid waste pose sustained pressure on the environment. Against the backdrop of increasingly stringent environmental policies, the environmentally sound treatment and resource utilization of barium slag have become urgent issues. To address both the material shortage in engineering construction and the resource recovery of industrial solid waste, this study undertakes, for the first time in China, comprehensive research and practical application focused on utilizing barium slag as a replacement for sandy soil in subgrade filling.

2 Sources and physicochemical properties of barium slag

Barium slag is a by-product generated during the industrial production of barium carbonate, primarily derived from

the "carbonation-reduction process" in which barite serves as the raw material for barium carbonate synthesis [1]. In this process, barite (60–65%) and coke (35–40%) are mixed, crushed, and then calcined in a rotary kiln at high temperatures ranging from 900 to 1100°C to produce barium sulfide as an intermediate product [2,3]. The barium sulfide subsequently undergoes hydrolysis followed by a carbonation reaction with carbon dioxide, yielding a slurry of barium carbonate [4,5]. This slurry is then processed through washing for desulfurization, vacuum filtration, pulverization, and drying to obtain the final barium carbonate product [6]. The solid residue generated throughout these stages constitutes barium slag.

2.1 Physical and chemical properties

Barium slag appears black, brown, or dark brown in color and consists of porous granules with uneven particle sizes, having a fineness of approximately 250 mesh. Its natural moisture content generally exceeds 20%, with a density ranging from 2.35 to 2.75 g/cm³. The barium content is about 80–85% [7].

2.2 Hazardous components

Barium slag exhibits strong alkaline corrosiveness, with a pH value around 10 and a high content of soluble barium compounds. Leaching tests indicate that the Ba²⁺ leaching concentration is significantly excessive, reaching approximately 1000 mg·L⁻¹, which far exceeds the regulatory limit for landfill admission (≤ 100 mg·L⁻¹) [8]. This characteristic, along with its associated toxicity, substantially restricts the potential for resource utilization of barium slag and hinders its widespread application.

2.3 Chemical and environmental safety assessment

Leaching toxicity tests indicate that, aside from the excessive leaching concentration of barium, cyanide was not detected in the barium slag. Moreover, the leaching concentrations of heavy metals (chromium, copper, zinc, arsenic, selenium, etc.) and fluoride were extremely low, well below the corresponding regulatory limits [9]. The specific measured values are as follows: chromium < 5 mg·L⁻¹, copper and zinc < 100 mg·L⁻¹, arsenic < 5 mg·L⁻¹, and selenium < 1 mg·L⁻¹. Comprehensive analysis suggests that after appropriate innocuous treatment and with effective anti-seepage and isolation measures in place, the environmental risk associated with barium slag can be controlled [10]. Considering the findings presented in Sections 2.2 and 2.3, and in accordance with the "Standard for Pollution Control on Hazardous Waste Landfill" (GB 18598-2019) [11], the treated barium slag can be utilized in subgrade filling. However, its application is restricted to secondary and lower-grade roads (excluding high-grade highways) and it must not be used in primary load-bearing layers.

3 Feasibility analysis

Two principal methods for the detoxification of barium slag, grounded in the "co-precipitation" mechanism, are outlined as follows:

(1) Neutralization of barium slag using phosphogypsum (pH ≤ 3), wherein the phosphate ions (PO₄²⁻) induce precipitation of soluble barium ions, thereby substantially mitigating the corrosivity of the slag.

(2) Co-processing of barium slag with red mud via low-temperature roasting, during which sintering effectively immobilizes the soluble barium ions, reducing their leaching concentration to below 100 mg·L⁻¹.

3.1 Mechanism analysis

Based on the chemical properties of barium slag described in Section 2.1, the strength formation mechanism of barium slag-stabilized soil is attributed to two primary aspects. Firstly, Ba²⁺ ions activate the hydration of cement through ionic substitution, while the resulting calcium silicate hydrate gel chemically binds Ba²⁺ and forms an encapsulating layer, effectively suppressing Ba²⁺ leaching and maintaining its concentration below the regulatory limit (≤ 100 mg·L⁻¹) specified in the "Identification Standards for Hazardous Wastes—Identification for Extraction Toxicity" (GB 5085.3-2007). Secondly,

Ba²⁺ from the slag replaces Na⁺ and K⁺ in the soil matrix, promoting the aggregation of soil particles and enhancing internal frictional resistance. Concurrently, crystalline phases such as BaSiO₃, BaSO₄, and BaCO₃ within the slag interconnect to form a stabilized structure with considerable strength. These combined processes not only improve the mechanical performance of the material but also significantly reduce the leachability of barium ions, thereby achieving effective toxicity mitigation.

4 Experimental verification

Based on the mechanisms described in Sections 2.3 and 3.1, a stabilized material was prepared in the laboratory using 4% cement and detoxified barium slag (as a replacement for sandy soil). A series of performance tests were conducted on representative samples, with the key results summarized below.

4.1 Slake durability

The average slake durability index was 96.0%, with a minimum value of 93.9%. All results exceeded 90%, indicating excellent water stability and resistance to disintegration and softening upon wetting.

4.2 Compaction characteristics

The moisture content ranged from 18.0% to 26.0%, and the dry density varied between 1.50 and 1.70 g/cm³. Through engineering application validation, the optimum moisture content and maximum dry density of the cement-stabilized barium slag soil (with 4% cement) were determined to be 25.7% and 1.61 g/cm³, respectively, providing key parameters for compaction control in the field.

4.3 Strength characteristics (CBR)

The California Bearing Ratio (CBR) value reached 9.6%. The CBR values obtained for different subgrade layers (e.g., subgrade bed and embankment) significantly exceeded the design requirements for highway subgrades (for instance, the upper subgrade bed typically requires a CBR ≥ 8%), demonstrating superior load-bearing capacity.

4.4 Deformation characteristics

The compression coefficient ranged from 0.15 to 0.25 MPa⁻¹, classifying the material as a medium-compressibility soil. The free swell rate was 12%–22%, while the loaded swell rate was very low (0.0%–0.2%). This indicates that its expansion behavior can be effectively managed through appropriate construction controls.

4.5 Stability characteristics

The average autoclave disintegration rate was 4.4%, meeting the specification limit of ≤ 5%. It is recommended to strengthen the quality inspection of incoming materials during construction and reject any batches that do not comply with the requirements.

4.6 Resilient modulus

The average resilient modulus was 315 MPa, with a maximum value of 545 MPa. This is considerably higher than that of conventional fill materials (according to the Urban Road Design Specifications, the recommended resilient modulus for subgrade soils is generally greater than 20 MPa). The high resilient modulus contributes to reduced subgrade settlement and enhanced overall pavement durability.

4.7 Shear strength

The cohesion ranged from 15 to 25 kPa, and the effective internal friction angle was between 25° and 35°. These parameters are generally superior to those of natural sandy soil. The shear strength parameters (cohesion and internal friction angle) are directly related to the proportion of coarse and fine particles in the processed barium slag. The parameters obtained from triaxial compression and direct shear tests confirm that the material is conducive to the stability of subgrade slopes.

5 Numerical simulation

According to the Mohr-Coulomb failure criterion in soil mechanics, the maximum shear stress (τ) that the soil mass composed of barium slag (replacing sandy soil) can resist during shear failure is calculated as follows:

$$\tau = c + \sigma \times \tan(\varphi) \quad (1)$$

where:

τ is the shear stress (kPa);

c is the cohesion (kPa);

σ is the normal stress (kPa);

Φ is the internal friction angle ;

\tan is the tangent function.

Using the parameters obtained from tests ($c = 15 \text{ kPa}$, $\varphi = 25^\circ$) and assuming a typical normal stress $\sigma = 100 \text{ kPa}$, the calculation proceeds as follows:

$$\tau = 15 \text{ kPa} + 100 \text{ kPa} \times \tan(25^\circ) \approx 61.6 \text{ kPa}$$

The result indicates that the shear strength of the barium slag soil under the given stress condition is approximately 61.6 kPa.

6 Barium slag preparation of sandy soil process

6.1 Working principle

By the control of air flow, flow direction and gravity, the gravity classifier can realize 0-5mm material classification. The fed material and primary air enters into the classifier from the top, the direction of air flow changes 120° , and leaves the classifier with fine particles through the blades. The coarse particles falls down to the bottom of the classifier because of the gravity itself then can't be flowed with the air, and discharges from a valve. Secondary air blowing from the bottom of the blades passes the curtain of falling particles mandatorily. These coarse particles nearing the classification point enters into the eddy in the heart-shaped cavity secondary air flow which changed its director. When enter the classifier, the captured fine particles and other particles pulled by the eddy all gather into the powder collector and will be recycled at last. The air throttle of secondary air can be adjusted simply by hand. It can change the particles granularity of classification. There is no moving part in material flow area, so the maintenance requirement of this machine is the lowest. For abrasive material, wear liners are used in some area in order to guarantee the long operating life of equipment.

6.2 Process advantages

(1) The principle of separation is advanced: the product has a variety of classification systems, and the aerodynamic analysis method is used to optimize the material flow field, which makes the equipment running resistance significantly reduced, the sorting efficiency is high and the energy saving is very obvious. It is superior to the traditional production process of washed sand and gravel sorting.

(2) The V shaped scatter grading area has the advantages of simple structure, less material consumption, no electric scatter device, small pressure loss, stable operation and low power consumption.

(3) High separation accuracy, which is patented by the state, is adopted. The air flow in the rectifier only rises and does not rotate with respect to the rotor, and the material is washed repeatedly in the sorting section, and the classification accuracy is high.

(4) Simple operation. Cage rotor adopts frequency conversion stepless speed regulation. The range of adjustment is large, the adjustment is convenient, sensitive and reliable.

(5) High classification efficiency. In the "V" type scattered powder selection area, set up multilayer break and grading

plate are set up to repeatedly break up and blow off, so that there is almost no fine powder among the discharged coarse powder. In the settlement classification zone, the powder discharge port has air flow to make sure that the fine powder in the material is once again blown away, and the fine powder content in the material is greatly reduced. The baffle plate is added to Cage shaped rotor classification zone, thus making the the grading more accurate and effective.

(6) The wear resistant parts have little maintenance and long service life. The wearing parts of the main parts of the powder removing machine are made of imported wear-resistant steel plates, which effectively improves the service life. The whole machine is adjusted by dynamic balance, and it runs smoothly in the full speed range.

(7) The main shaft seal adopts new design scheme, which effectively solves two important problems of bearing ash entry and lubrication oil leakage, and effectively prolongs the service life of the bearing.

(8) In the design of the powder removal machine, the principle of mechanical vibration damping is adopted to make the vibration frequency of the sorting machine not to form an integral relationship with the natural frequency of the sorting machine, and the resonance problem of the separator is solved in the long run.

(9) Double interlocking air valves are adopted in sand pipes, middle fine sand pipes and fine sand pipes, which greatly reduces the leakage rate of the system and overcomes the defects of generating a large amount of dust during the operation of the powder removing machine. The system adopts double interlocking air valve and internal circulation air, effectively reducing the air leakage of the system and the dust pollution during operation.

7 Conclusion

(1) Given the complex chemical composition of barium slag and its potential to cause environmental pollution if improperly managed, effective treatment and utilization strategies are essential. This study focused on the feasibility of using barium slag as a replacement for sandy soil in subgrade filling. A dedicated filling and construction scheme was implemented to ensure long-term performance and eliminate environmental risks, with successful engineering outcomes achieved. This application represents the first of its kind in China.

(2) According to soil shear test specifications, under a normal stress corresponding to a shear stress of 100 kPa at a shear displacement of 4 mm, the theoretical shear strength is 61.26 kPa. The measured shear stress of the barium slag soil in this study was 61.63 kPa, exceeding this theoretical value. Combined with the performance test results presented earlier, this confirms that the fundamental mechanical properties of barium slag soil are superior to those of natural sandy soil.

(3) During project implementation, strict control over filling thickness and compaction quality resulted in a representative measured deflection value at the subgrade surface that was lower than the design acceptance value of 268.8 (0.01 mm), significantly outperforming the design standard. This demonstrates that the barium slag subgrade exhibits superior overall strength, stiffness, and stability compared to traditional sandy soil subgrades.

(4) The natural moisture content of the processed barium slag is approximately 25%, which is very close to the optimum moisture content (25.7%) for cement-stabilized barium slag soil. Additionally, its fineness modulus is about 2.50, making it highly suitable for subgrade construction. It is recommended that future similar projects conduct comprehensive testing and compatibility design studies on solid waste materials prior to implementation. During construction, special environmental protection plans must be strictly followed, including isolation and containment measures. Furthermore, a long-term performance monitoring mechanism should be established to accumulate data for broader application.

Acknowledgments

Supported by Scientific and Technological Innovation Programs of Higher Education Institutions in Shanxi.

Conflicts of interest

The author declares no conflicts of interest regarding the publication of this paper.

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