

Article

Macroscopic Mechanical Properties and Mesoscopic Structure Evolution of Steel Slag–MSWIBA-Improved Soil Mixture

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Abstract

Taking municipal solid waste incineration bottom ash (MSWIBA) and natural soil as raw materials, this study incorporated steel slag to prepare MSWIBA mixed soil for pavement base courses. The modified soil was subjected to a 7-day unconfined compressive strength (UCS) test, California Bearing Ratio (CBR) test, water stability test, and freeze–thaw cycle test. The results demonstrate that the incorporation of steel slag and MSWIBA greatly boosts the modified soil's performance. The 7-day UCS and CBR first increase and then decrease with the increase in steel slag content and MSWIBA proportion. Based on this, the optimal mix ratio of MSWIBA mixed soil was determined as 50% MSWIBA + 50% natural soil (mass ratio) with an additional 15% steel slag (relative to the total mass of MSWIBA and soil). Under this optimal ratio, the 7-day UCS of the mixed soil reaches 0.82 MPa, the 5-day water stability coefficient is 0.91, and the strength retention rate after 11 freeze–thaw cycles is 65.3%, all meeting the technical requirements for pavement base course materials. A freeze–thaw resistance study based on the optimal ratio revealed that the sample with the optimal mix ratio exhibits better freeze–thaw resistance than other ratios; its strength first decreases and then tends to stabilize with increasing freeze–thaw cycles. It was found through XRD and SEM experiments that the incorporation of steel slag promoted the progress of the hydration reaction and generated gelation products. The stacking and friction between MSWIBA and soil particles enhance the structural stability. Meanwhile, in the alkaline environment produced by the hydration of steel slag, MSWIBA further promotes hydration, increasing the total amount of cementitious substances. The C-S-H and other gels generated by hydration fill the pores, resulting in fewer cracks between the matrices and a denser matrix. It should be noted that this study focuses on short-term performance and microscopic mechanisms, and discussions on long-term heavy metal leaching behavior remain hypothetical—long-term leaching experiments have not been conducted, and the long-term environmental safety of the mixture still needs to be verified by subsequent experimental data.

Keywords: steel slag; MSWIBA; optimal mix ratio; durability performance; microstructural evolution



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1. Introduction

With the rapid development of China's socioeconomic sector, highway transportation has advanced at an unprecedented rate. However, during the expansion of scale and improvement of the network in highway construction, it faces increasingly severe resource

constraints. Among these, the shortage of sand and gravel raw materials and their rising prices have become the main bottlenecks restricting project progress, directly increasing project construction costs and posing a severe challenge to the sustainability of infrastructure development [1,2]. Against this backdrop, exploring economical and environmentally friendly alternative materials to sand and gravel has become an inevitable choice to address resource constraints and promote the green development of highway construction.

The acceleration of global urbanization has led to an explosive growth in municipal solid waste (MSW) generation. Currently, the annual MSW output worldwide reaches approximately 1.9 billion tons [3], and this figure is expected to further rise, reaching 3.4 billion tons by 2025, imposing enormous pressure on solid waste management systems. Landfilling and incineration remain the dominant MSW disposal methods globally [4]. Among the residues from incineration, municipal solid waste incineration bottom ash (MSWIBA) makes up roughly 80% and is categorized as general solid waste [5,6]; the remaining 20% is composed of fly ash—designated as hazardous waste because of its enrichment in heavy metals and persistent organic pollutants—which requires specialized stabilization treatment before final disposal [7,8]. Notably, through appropriate pretreatment processes, MSWIBA can be converted into slag aggregates with acceptable strength and reasonable particle size distribution [9–11]. MSWIBA inherently contains cement clinker minerals and reactive components, endowing it with excellent pozzolanic activity [12,13]: it can not only form cementitious products through self-hydration but also undergo pozzolanic reactions with $\text{Ca}(\text{OH})_2$ produced from cement hydration to generate calcium silicate hydrate (C-S-H) and calcium aluminate silicate hydrate (C-A-S-H), thereby boosting the overall cohesion of composite materials [14]. Nevertheless, the leaching risk of heavy metals and soluble salts in MSWIBA may contaminate surrounding soil and groundwater systems [15–17], greatly limiting its direct engineering application.

To address this limitation, numerous studies have been carried out on the secondary application of MSWIBA in the academic community [18–20]. For example, Liu et al. [21] proposed an innovative method to prepare cold-bonded fiber-based aggregates (CBFAs) using MSWIBA and further apply them in environmentally sustainable concrete; the results showed that concrete incorporating CBFAs exhibited significantly enhanced chloride ion diffusion resistance and improved durability. Shi et al. [22] confirmed the technical feasibility of using cement-stabilized MSWIBA for pavement base courses—under a cement content of 5%, the performance of mixtures with different MSWIBA contents all met the requirements of relevant specifications. Vaitkus [23] developed an optimization algorithm based on the physicochemical properties of MSWIBA to guide its application in road base and subbase layers; the study found that pretreated MSWIBA could replace 100% of natural aggregates, and adjusting the particle gradation with a small quantity of cement significantly enhanced the shear strength and durability of pavement structures. Zhao et al. [24] conducted a 120-day long-term simulation test on MSWIBA with different particle sizes, revealing the mechanism by which pretreatment methods affect slag strength development from the perspectives of micromorphology, crystal structure, and mineral composition, thus providing theoretical basis for the precise utilization of MSWIBA in road engineering. Sormunen et al. [25] compared the mechanical performance evolution of MSWIBA-based and natural aggregate-based structural layers through field tests, confirming that the long-term performance of the middle and lower parts of MSWIBA layers was comparable to that of natural aggregate layers, thereby verifying the applicability of MSWIBA in the lower structural layers of roadways and sites.

At the same time, steel slag, a by-product produced from the iron and steel industry, also faces the predicament of “substantial output but low utilization efficiency.” However, due to its abundant active mineral constituents (CaO , SiO_2 , Al_2O_3) and chemical reactivity,

steel slag demonstrates considerable application potential in the field of construction materials [26,27]. In terms of soil improvement, steel slag can optimize the physical, mechanical, and chemical properties of soil by adjusting particle gradation and pH value [28–30]; Wu et al. [31] developed a new cementitious modifier through steel slag activation and applied it to the treatment of expansive soil; the results showed that the engineering properties (e.g., compressibility, shear strength) of the expansive soil were notably improved, fully meeting the standards for highway subgrades. Xu et al. [32] studied the mechanical properties of steel slag–clay mixtures and found that when the steel slag content was 40%, the shear strength, damping ratio, and shear stiffness of the mixture reached the optimal level. In road construction, steel slag is widely used as an aggregate in asphalt mixtures, subgrade fill, and pavement base materials [33,34]; Aziz et al. [35] indicated that the hydrophobicity of steel slag enhances its interfacial adhesion with asphalt binders, effectively inhibiting pavement stripping and extending the service life.

Despite the promising mechanical performance of MSWIBA and steel slag reported in previous studies, their large-scale engineering application remains limited, with global utilization rates for MSWIBA still below 30% [36,37]. This gap between research and practice stems from persistent concerns regarding environmental safety and long-term performance, which must be addressed to enable responsible deployment. Key among these are the long-term leaching risk of heavy metals (e.g., Pb, Cr, Cu) from MSWIBA, which can be exacerbated by field conditions such as carbonation—lowering the system’s pH—and prolonged rainfall infiltration [16,38]. Concurrently, the high free lime (f-CaO) content in steel slag poses a threat of volumetric instability upon hydration and carbonation, potentially compromising durability [39]. Furthermore, the carbonation of steel slag hydration products can alter the microstructure and pore chemistry, thereby influencing the leaching behavior of the entire composite system [40].

A truly sustainable evaluation also necessitates a perspective beyond laboratory mechanics. Life Cycle Assessment (LCA) studies consistently show that utilizing these by-products can significantly reduce greenhouse gas emissions and non-renewable resource consumption compared to conventional materials [41]. Therefore, integrating environmental safety and a lifecycle mindset is crucial for transitioning these waste valorization strategies from concept to practice. This is particularly urgent given the dual pressure of abundant solid waste stockpiles and the shortage of natural sand and gravel in many regions. The inherent deficiencies of traditional base materials (e.g., low strength, poor durability) further underscore the need for viable alternatives [42,43].

To bridge this gap, this study adopts a “waste-treating-waste” approach, combining typical eastern China soil with MSWIBA and steel slag. Through an integrated methodology of macroscopic tests—including unconfined compressive strength (UCS), California Bearing Ratio (CBR), water stability, and freeze–thaw cycles—and microscopic analyses (XRD, SEM), this research comprehensively evaluates the mechanical properties and solidification mechanism of the novel mixture. By correlating macro-performance with microstructural evolution and incorporating a preliminary environmental risk assessment, this work aims to provide a robust technical and scientific basis for the feasible application of steel slag–MSWIBA-improved soil as a sustainable highway base course material.

2. Materials and Methods

2.1. Experimental Materials

The experimental soil was gathered from an excavation site of a highway construction project in Ma’anshan City (Anhui Province, China), from a depth of 2–3 m beneath the ground surface (with low organic matter content). Before use, the soil was crushed and dried. The physical and mechanical characteristics of this soil are as follows: a liquid limit

of 37.6%, a plastic limit of 20.9%, a plasticity index $I_p = 16.7$; an optimal moisture content of 18.2%, and a maximum dry density of 1.85 g/cm³.

MSWIBA was obtained from a waste incineration facility located in Ma'anshan City (Anhui Province, China), predominantly comprising silico—aluminous particles (such as quartz, feldspar) and vitreous phases. The chemical makeup of MSWIBA is displayed in Table 1—SiO₂ and CaO make up the largest proportions, reaching 39.96% and 31.55%, respectively, whereas Fe₂O₃ and Al₂O₃ constitute 4.45% and 10.02%, respectively. Toxicity leaching experiments were carried out following the Solid Waste Leaching Toxicity Leaching Method (TCLP), and the outcomes are listed in Table 2: the leaching concentrations of six main heavy metals (Ba, Cd, Cr, Cu, Pb, Zn) were all beneath the national standard thresholds, which suggests that this MSWIBA is classified as general solid waste. To further assess the environmental feasibility of using MSWIBA in field applications such as pavement bases, the leaching results were compared with international regulatory limits, including the U.S. EPA TCLP criteria and the EU Landfill Directive (1999/31/EC [44]). As indicated in Table 2, all detected heavy metal concentrations are not only below the Chinese national standards but also well under the more stringent international limits (e.g., Cd < 1 mg/L, Pb < 5 mg/L). This demonstrates that the MSWIBA used in this study poses a low leaching risk under typical environmental conditions, supporting its suitability for large-scale civil engineering applications. Nevertheless, long-term field monitoring and encapsulation strategies (e.g., compaction, sealing layers) are recommended to further mitigate any potential leaching under extreme pH or rainfall scenarios.

Table 1. Chemical Constituents of MSWIBA.

Component	SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	MgO	CaO	K ₂ O	Na ₂ O	P ₂ O ₅	Other
Content/%	39.96	4.45	10.02	3.75	31.55	2.05	2.79	2.88	2.55

Table 2. Toxicity Leaching Results of MSWIBA (Unit: mg/L).

Control Index	Ba	Cd	Cr	Cu	Pb	Zn
Measured Value	0.459	0.021	0.4328	1.0035	0.034	8.5893
Chinese Standard Limit (GB)	100	1	5	100	5	100
U.S. EPA TCLP Regulatory Limit	100	1	5	-	5	-
EU Landfill Directive (1999/31/EC) for Inert Waste	20	0.04	0.5	2	0.5	4

Note: “-” indicates that the parameter is not regulated under the specific standard. The leaching concentration of Zinc (Zn) exceeds the limit for Inert Waste but is significantly below the limit for Non-Hazardous Waste and all other applicable standards. This is a common characteristic of MSWIBA and does not preclude its safe use in engineering applications.

In this test, the particle size of MSWIBA was controlled below 2 mm, and the particle gradation curve of MSWIBA and natural soil is shown in Figure 1.

The steel slag for testing was acquired from Ma'anshan Iron and Steel Group Holdings Co., Ltd. (Ma'anshan, Anhui Province, China), which had been aged for over 2 years. It has an apparent density of 3400 kg/m³ and a bulk density of 1670 kg/m³. Its chemical makeup resembles that of Portland cement, including reactive phases like C₃S and C₂S, while the primary components are oxides of Ca, Si, Fe, Mg, Al, and Mn (see Table 3). Among these oxides, CaO and Fe₂O₃ hold the largest shares, making up 58.85% and 14.39%, respectively. Prior to the experiment, the steel slag was pulverized and passed through a 0.075 mm sieve, and the steel slag micro-powder that passed through the sieve was utilized in the test. The testing materials are depicted in Figure 2.

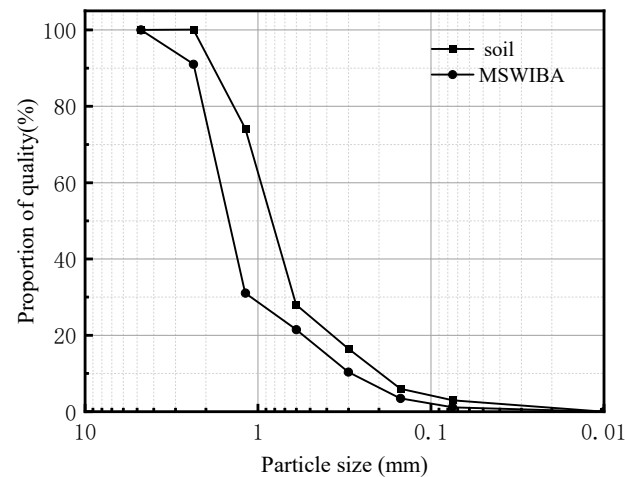


Figure 1. The gradation curve of soil and MSWIBA.

Table 3. Chemical Constituents of Steel Slag.

Component	CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	MnO	P ₂ O ₅	TiO ₂	SO ₃
Content/%	58.85	12.80	5.21	14.39	2.63	2.20	1.51	0.92	0.31

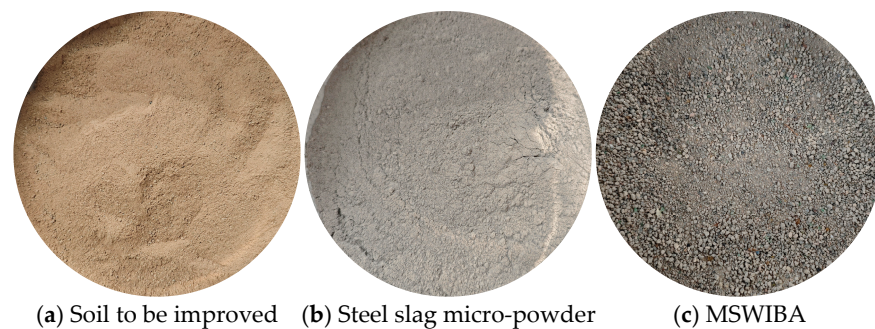


Figure 2. Test materials.

2.2. Test Methods

2.2.1. Sample Preparation

In accordance with the test method outlined in JTG E51-2019 Specification for Test Methods of Inorganic Binder Stabilized Materials for Highway Engineering [45], the requisite quantities of soil, MSWIBA, and steel slag were precisely weighed in line with the mix proportions given in Table 4 and blended homogeneously. Deionized water was introduced into the mixed soil based on the optimal moisture content derived from compaction experiments, and stirring was sustained for 20 min to finish the mixing process. Subsequently, the mixture was put into a sealed bag and left to rest for 12 h, so as to guarantee uniform moisture distribution within the mixed soil. After that, the mixed soil was statically compacted into cylindrical specimens ($\Phi 50$ mm $\times$ $H 50$ mm) via a jack and mold, with the compaction degree reaching 96% of the maximum dry density. These specimens were wrapped with plastic film and cured in a standard curing chamber (with a temperature of 23 ± 1 °C and a relative humidity of 98%) until they reached the designated curing age. All tests were conducted with three parallel specimens. Results are expressed as mean $\pm$ standard deviation (SD). Statistical significance was evaluated using one-way analysis of variance (ANOVA) with a 95% confidence level (significance threshold: $\alpha = 0.05$). Specific p -values for pairwise comparisons (e.g., optimal mix ratio vs. other groups) are reported in corresponding tables, figure captions, and text to clarify the magnitude of statistical differences.

Table 4. Mix Ratio of Test Materials.

MSWIBA-to-Soil Mass Ratio (%)	Steel Slag Content ¹ (%)
30, 40, 50, 60, 70	0, 5, 10, 15, 20

¹ Steel slag content refers to the mass percentage of steel slag relative to the total mass of MSWIBA and soil.

2.2.2. Unconfined Compressive Strength Test

The experiment was performed with an STLQ-3 pavement material strength tester (produced by Zhejiang Geotechnical Instrument Co., Ltd., Shaoxing City, China), and the loading rate was set at around 1 mm/min. When the specimen failed, the maximum load P was documented, and the unconfined compressive strength R_C of the specimen was computed via the formula below:

$$R_C = \frac{P}{A} = 0.51P \text{ (kPa)}$$

In the formula, P represents the maximum load at the specimen's failure (in Newtons, N) and A denotes the cross-sectional area of the specimen (in square millimeters, mm²).

2.2.3. Water Stability Test

To assess the water stability of the modified soil, the water stability coefficient was introduced. This coefficient was determined by following the specifications of CJ/T 486-2015 Soil Stabilization Admixtures [46]. Specimens for the water stability test were cured for 28 days. Upon reaching the curing age, these specimens were submerged in water at $(20 \pm 2)^\circ\text{C}$ for 1, 3 and 5 days, respectively. The compressive strength of the specimens was measured, and the water stability coefficient was defined as the ratio of the compressive strength of the immersed specimens to that of the non-immersed ones.

2.2.4. California Bearing Ratio (CBR) Test

Cylindrical specimens ($\Phi 152 \text{ mm} \times H120 \text{ mm}$) were fabricated through static pressure, with three parallel specimens in each group. The specimens were soaked in water for a 4-day curing process, and the expansion rate was documented. After draining for 15 min, a CBR tester was employed to carry out the test.

2.2.5. Freeze–Thaw Cycle Test

Prior to the freeze–thaw cycle test, each specimen was sealed in a plastic bag to avoid moisture loss and then put into a test chamber. The freeze–thaw cycle procedure was set as follows: freezing at -10°C in a low-temperature test chamber for 12 h $\rightarrow$ thawing at 10°C in a constant-temperature chamber for 12 h (preliminary tests verified that this procedure enables the specimens to thaw completely, with no ice residue detected after cutting). A total of 11 freeze–thaw cycles were performed (preliminary tests indicated that the physical and mechanical properties of the specimens tend to become stable after 10 cycles). The strength retention rate k was defined as the ratio of the strength of the modified soil after undergoing freeze–thaw cycles to its strength before the cycles.

2.2.6. Microscopic Analysis

X-ray Diffraction (XRD): A D8 ADVANCE X-ray diffractometer (produced by Bruker, Bremen, Germany) was utilized to analyze the mineral composition of the specimens after the reaction, with a 2θ scanning range from 10° to 80° .

Scanning Electron Microscopy (SEM): A JSM-6490LV scanning electron microscope (manufactured by JEOL, Tokyo, Japan) was adopted to observe the microstructure of

particles. Prior to scanning, the test specimens were subjected to vacuum gold-plating as per the specified requirements.

3. Results and Analysis of Macroscopic Performance Tests

3.1. UCS

3.1.1. Influence of MSWIBA Content

Figure 3 illustrates the changing trend of the 7-day UCS of the modified soil with the proportion of MSWIBA under varying steel slag contents. It is observed that when the MSWIBA proportion ranges from 30% to 50%, the strength rises continuously as the MSWIBA proportion increases, and the strength peak for all groups with different steel slag contents corresponds to a 50% MSWIBA proportion. Taking the group with 15% steel slag content as an instance, when the MSWIBA proportion goes up from 30% to 50%, the 7-day UCS grows by 24.2%. The strength difference between the 50% MSWIBA group and the 30%/70% MSWIBA groups is statistically significant (50% vs. 30%: $p = 0.015$; 50% vs. 70%: $p = 0.023 < 0.05$), confirming that 50% is the optimal MSWIBA proportion.

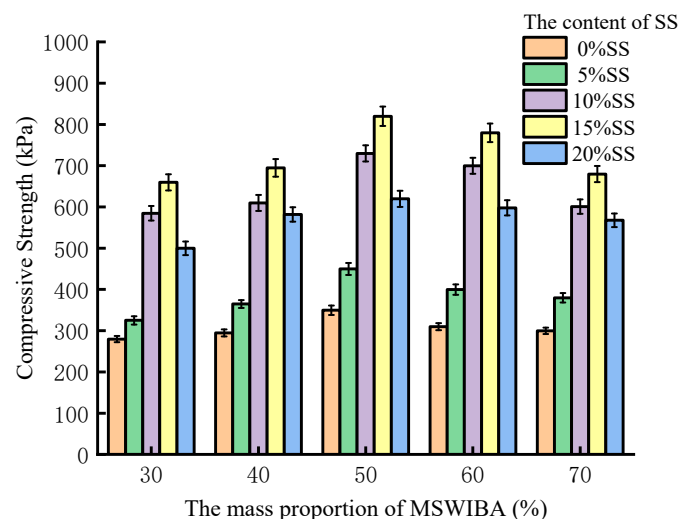


Figure 3. The variation trend of 7-day UCS of the modified soil with MSWIBA proportion under different steel slag contents. (error bars represent standard deviation of $n = 3$).

From the perspective of mechanical mechanism: in the low MSWIBA content stage (high natural soil proportion), the strength of the modified soil mainly depends on the stacking interlock and surface friction of soil particles, with insufficient cementitious substances and weak structural stability. As the MSWIBA proportion increases, the silico-aluminous particles (quartz, feldspar) and vitreous phases in MSWIBA not only enhance the structural skeleton stability through particle stacking but also have their reactive SiO_2 and Al_2O_3 activated within the alkaline environment generated by steel slag hydration. The Ca^{2+} and OH^- released by steel slag synergize with reactive SiO_2 and Al_2O_3 in MSWIBA and soil to generate a large amount of cementitious products such as C-S-H gel. These cementitious products bond with soil particle aggregates, not only strengthening particle adhesion but also filling internal pores, further enhancing the soil structure.

When the proportion of MSWIBA goes beyond 50% (ranging from 50% to 70%), the strength declines continuously as the MSWIBA proportion rises. In the group with 15% steel slag content, the strength at a 70% MSWIBA proportion is 17.2% lower than that at a 50% MSWIBA proportion, and the difference is statistically significant ($p = 0.023 < 0.05$). This occurs because an overly high MSWIBA content causes an increased average void ratio among MSWIBA particles, which results in reduced compactness. At the same time,

excessive MSWIBA lowers the clay content in the modified soil, thereby weakening the overall cohesion.

In addition, comparing groups with different MSWIBA contents: under 10% and 15% steel slag contents, the strength at 60% MSWIBA proportion is 14.75% and 12.23% higher than that at 40% MSWIBA proportion, respectively; the strength at 70% MSWIBA proportion is still 2.7% and 3% higher than that at 30% MSWIBA proportion. This confirms that MSWIBA can effectively replace natural soil as aggregate and improve strength within a reasonable content range.

3.1.2. Influence of Steel Slag Content

Figure 4 illustrates the change in 7-day unconfined compressive strength (UCS) of the modified soil as the content of steel slag varies under 13 distinct MSWIBA proportions. As depicted in the figure, when the content of steel slag ranges from 0% to 15%, the strength of the modified soil rises remarkably with the increase in steel slag content; once the content surpasses 15%, the strength of specimens across all MSWIBA proportion groups exhibits a declining tendency.

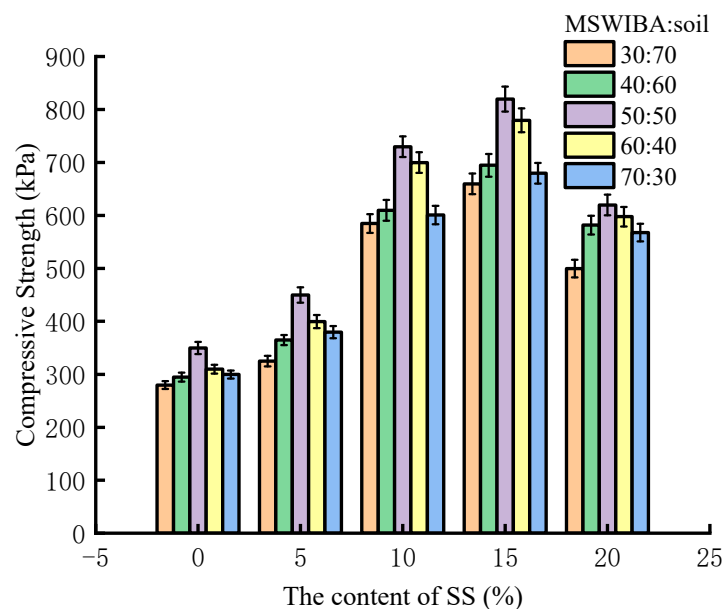


Figure 4. The 7-day UCS of improved soil under different dosages of steel slag (error bars represent standard deviation of $n = 3$).

In detail: taking the mass ratio of MSWIBA to soil at 5:5 as an instance, the strength of the group with 5% steel slag is 28.57% greater than that of the control group (which contains no steel slag), and this difference is statistically significant ($p = 0.042 < 0.05$). The strength of the group with 15% steel slag is 134.28% higher than that of the 5% steel slag ($p = 0.015 < 0.05$) group and 82.22% higher than that of the control group ($p = 0.008 < 0.05$). This occurs because when the content of steel slag is low, the substances involved in hydration are inadequate, leading to a small quantity of hydration products, and the strength is mainly produced through particle stacking and friction. As the content of steel slag increases, the hydration reaction becomes more thorough, the quantity of hydration products increases, and the matrix becomes more compact. However, when the content of steel slag exceeds 15%, the strength of specimens in all mix ratios decreases. The cause is that an excessively high content of steel slag results in incomplete reaction; the unreacted steel slag accumulates to form a framework structure, which reduces the compactness of the matrix. Additionally, the free calcium oxide (f-CaO) in the steel slag with a high

content reacts to generate expansion stress, causing microcracks inside the matrix and further structural damage, thus leading to a reduction in strength.

To sum up, the strength of specimens across all mix ratios rises rapidly as the steel slag content falls within the range of 5–10%; the rate of strength increase decelerates when the content hits 15%; and the strength declines once the content goes beyond 15% ($p < 0.05$). Hence, the content of steel slag can be further refined by taking cost considerations into account in actual engineering practices.

3.2. California Bearing Ratio (CBR)

To explore the influence of MSWIBA and steel slag contents on the CBR and expansion rate of the modified soil, six types of specimens were prepared: natural soil (without steel slag and MSWIBA); MSWIBA: soil = 50:50 + 10% steel slag (Sample A); MSWIBA: soil = 50:50 + 15% steel slag (Sample B); MSWIBA: soil = 50:50 + 20% steel slag (Sample C); MSWIBA: soil = 30:70 + 15% steel slag (Sample D); MSWIBA: soil = 70:30 + 15% steel slag (Sample E).

As depicted in Figure 5, the CBR and expansion rate of the modified soil are tightly correlated with the mix proportion. The natural soil exhibits a low CBR of merely 6% and a high expansion rate of 12.3%. When the mass ratio of MSWIBA to soil is 50:50 and the steel slag content is 15%, the CBR reaches a peak of 47.1%, which is roughly 7 times greater than that of natural soil; at the same time, the expansion rate declines notably to 1.06%. ANOVA confirms these improvements are extremely significant: CBR: Sample B vs. natural soil, $p = 0.003 < 0.01$; Sample B vs. Sample A (50:50 + 10% steel slag), $p = 0.011 < 0.05$; Sample B vs. Sample D (30:70 + 15% steel slag), $p = 0.009 < 0.01$; Expansion rate: Sample B vs. natural soil, $p = 0.004 < 0.01$; Sample B vs. Sample C (50:50 + 20% steel slag), $p = 0.018 < 0.05$.

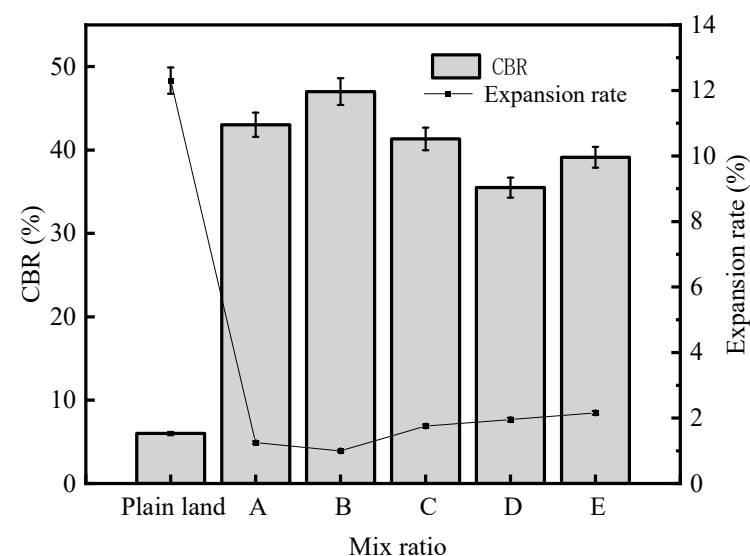


Figure 5. California Bearing Ratio of Modified Soil with Different Steel Slag and MSWIBA Contents. (error bars represent standard deviation of $n = 3$).

Under the MSWIBA-to-soil mass ratios of 30:70 and 70:30, the CBR values are lower than the peak yet still far higher than that of natural soil ($p < 0.05$), and all satisfy the technical criterion of $\text{CBR} \geq 8\%$ for subgrade fill of expressways and first-class highways stipulated in JTG D30-2015 Code for Design of Highway Subgrades [47]. This shows that adding steel slag and MSWIBA can remarkably enhance the bearing capacity of soil and restrain its expansion tendency.

From the perspective of physical mechanism: the particles in natural soil form a structure that mainly depends on their own stacking and surface friction, lacking the filling

and bonding of cementitious substances, which leads to poor overall stability, low CBR, and high expansion rate. From the perspective of chemical mechanism: steel slag has hydraulic properties similar to cement and can produce a large quantity of cementitious products during hydration. As the MSWIBA content increases, its activity is gradually activated in the alkaline environment supplied by steel slag, further facilitating the hydration reaction and generating more hydration products. These products fill the voids between soil particles and strengthen the cementation effect, thus improving the overall strength and compactness of the modified soil, raising the CBR value, and reducing the expansion rate. Additionally, the calcium oxide abundant in steel slag contributes to enhancing the water erosion resistance of the modified soil, thereby suppressing its expansion properties.

3.3. Water Stability

Table 5 shows the water stability coefficients of modified soil with different mix ratios (after immersion for 1, 3, and 5 days). As indicated in Table 5, natural soil disintegrates after 1 day of immersion; by contrast, the modified soil produced by incorporating steel slag and MSWIBA possesses outstanding water stability coefficients. Even though the water stability coefficient reduces gradually as immersion time increases, it still retains a certain level of strength after 5 days of immersion. Among all groups, the one with a 5:5 MSWIBA-to-soil mass ratio and 15% steel slag content exhibits the best water stability, with a water stability coefficient of 0.91 after 5 days of immersion. statistical analysis shows this is significantly higher than other groups: vs. 50:50 + 10% steel slag group (0.89), $p = 0.028 < 0.05$; vs. 50:50 + 20% steel slag group (0.88), $p = 0.021 < 0.05$; vs. 30:70 + 15% steel slag group (0.90), $p = 0.019 < 0.05$; vs. 30:70 + 15% steel slag group (0.90), $p = 0.019 < 0.05$.

Table 5. Water Stability Coefficients of Modified Soil with Different Mix Ratios (error bars represent standard deviation of $n = 3$).

MSWIBA-to- Soil Mass Ratio	Steel Slag Content (%)	Soaking Days (d) Value (Mean $\pm$ SD)		
		1	3	5
50:50	10	0.94 (± 0.02)	0.91 (± 0.01)	0.89 (± 0.01)
	15	0.96 (± 0.01)	0.94 (± 0.02)	0.91 (± 0.01)
	20	0.93 (± 0.02)	0.91 (± 0.02)	0.88 (± 0.01)
30:70	10	0.92 (± 0.01)	0.89 (± 0.01)	0.87 (± 0.02)
	15	0.94 (± 0.01)	0.92 (± 0.01)	0.90 (± 0.02)
	20	0.92 (± 0.02)	0.90 (± 0.01)	0.87 (± 0.01)
70:30	10	0.93 (± 0.03)	0.90 (± 0.02)	0.88 (± 0.02)
	15	0.95 (± 0.02)	0.92 (± 0.01)	0.91 (± 0.01)
	20	0.94 (± 0.01)	0.91 (± 0.02)	0.89 (± 0.01)
0:100		Disintegration		

Note: All p -values are derived from one-way ANOVA (95% confidence level, $\alpha = 0.05$); $p < 0.05$ indicates significant difference from the optimal group.

The key mechanism behind the enhanced water stability is as follows: Steel slag contains substantial amounts of free CaO, reactive SiO₂, and Al₂O₃, which undergo a series of hydration reactions when in contact with water. Free CaO reacts with water to form Ca(OH)₂, creating an alkaline environment for the system. Reactive SiO₂ and Al₂O₃ undergo pozzolanic reactions under alkaline conditions to produce cementitious substances like C-S-H and calcium aluminate hydrate (C-A-H). Simultaneously, the vitreous phases (amorphous SiO₂, Al₂O₃) in MSWIBA have pozzolanic activity and further react to form C-S-H and C-A-H gels in the alkaline environment of Ca(OH)₂ generated from steel slag hydration, thus increasing the total quantity of cementitious substances. These gels not only fill the pores between soil particles but also bind dispersed soil particles into a unified mass, lessening the damage caused by water to the interparticle bonding force. In addition,

steel slag can fill the micro-pores between MSWIBA and original soil particles, lowering the overall porosity. The reduction in porosity decreases the space available for water retention and penetration, thereby further mitigating the softening effect of water on soil particles.

Based on the aforementioned test results, the optimal mix ratio is identified as 50% MSWIBA + 50% natural soil, with an extra 15% steel slag (relative to the total mass of MSWIBA and soil). Under this mix ratio, the 7-day unconfined compressive strength (UCS) is around 0.82 MPa, the California Bearing Ratio (CBR) is 47.1%, and the 5-day water stability coefficient is 0.91, all satisfying the relevant requirements specified in JTG/T F20-2015 Technical Specifications for Construction of Highway Pavement Base Courses [48].

3.4. Freeze–Thaw Resistance

Based on the aforementioned optimal mix ratio (50:50 MSWIBA-to-soil mass ratio + 15% steel slag), specimens with different mix ratios were selected for freeze–thaw cycle tests, and the results are shown in Figure 6. As can be seen from the figure, natural soil has extremely poor freeze–thaw resistance, losing all strength after only 5 freeze–thaw cycles; in contrast, the modified soil incorporating MSWIBA and steel slag shows significantly improved freeze–thaw resistance. Among them, the specimen with the optimal mix ratio (50:50 MSWIBA-to-soil mass ratio + 15% steel slag) performs the best, with a strength retention rate of 65.3% after 11 freeze–thaw cycles; while the group with 50:50 MSWIBA-to-soil mass ratio + 20% steel slag has poor freeze–thaw resistance, with a strength retention rate of only 58.7% after 11 cycles. ANOVA confirms that the difference between the two groups is statistically significant ($p = 0.037 < 0.05$). The 30:70 + 15% steel slag group has a retention rate of 59.2% ($p = 0.029 < 0.05$ vs. optimal group), and the 70:30 + 15% group is 60.5% ($p = 0.033 < 0.05$ vs. optimal group). Notably, natural soil loses all strength after only 5 freeze–thaw cycles, showing an extremely significant difference from the optimal group ($p = 0.002 < 0.01$)—this highlights the critical role of steel slag and MSWIBA in improving freeze–thaw resistance.

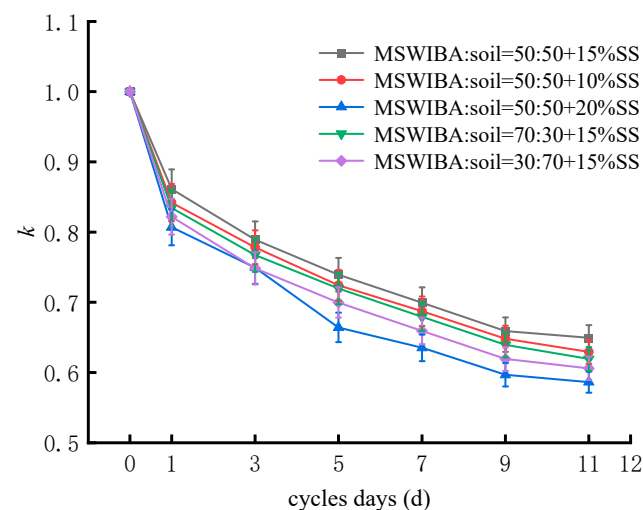


Figure 6. Strength retention rate of improved soil after freeze–thaw cycles under different mix ratios (error bars represent standard deviation of $n = 3$).

The reasons for the enhanced freeze–thaw resistance of the modified soil are as follows: the tight packing of MSWIBA and soil particles, coupled with the cementitious products formed via steel slag hydration, decreases the pores within the matrix and lessens the space for water expansion during freezing. In the initial phase of freeze–thaw cycles, the expansion stress triggered by water phase transition causes microcracks to initiate. However, the reactive components in steel slag and MSWIBA keep undergoing hydration,

and the generated C-S-H gel can fill these microcracks—creating a dynamic balance of “early microcrack initiation–late cementitious product repair” and restraining damage propagation. The inferior freeze–thaw resistance of the group with 20% steel slag content stems from the incomplete reaction of excessive steel slag; the expansion stress from the hydration of free CaO aggravates matrix cracking during freeze–thaw cycles, resulting in rapid strength degradation.

In addition, the strength evolution of the modified soil exhibits a two-stage characteristic of “significant attenuation in the early stage—gradual stabilization in the later stage”: the strength decreases rapidly in the first 3 cycles (the strength retention rate of the optimal mix ratio decreases from 100% to 82.5%), and then the decrease rate slows down, tending to stabilize after 10 cycles. This is because in the early cycles, there are many connected pores inside the matrix, and water freezing and expansion easily cause through cracks; after the cracks develop to a certain extent, the ice expansion pressure weakens, and the cementitious products continue to repair the damage, so the strength tends to stabilize.

3.5. Comparative Analysis with Traditional Base Materials

To contextualize the performance of the steel slag–MSWIBA-improved soil mixture, a comparative analysis with traditional base course materials such as natural gravel and cement-stabilized soil was conducted. The key engineering properties and characteristics are summarized in Table 6.

Table 6. Performance Comparison between the Proposed Mixture and Traditional Base Materials.

Material Type	UCS (7-Day)	(CBR) %	Key Advantages	Key Limitations
Natural Gravel	0.5–1.0 MPa	20–30	Excellent drainage; Readily available.	High cost; Resource depletion.
Cement-Stabilized Soil	1.0–2.0 MPa (with 5–10% cement)	50–100	High strength; Established practice.	High carbon footprint; Shrinkage cracks.
Proposed Mixture (Optimum)	0.82 MPa	47.1	Waste utilization; Low cost; Eco-friendly.	Lower strength than cement-based materials.

As indicated in Table 6, the optimal mixture proposed in this study (50% MSWIBA + 50% soil + 15% steel slag) exhibits a UCS of 0.82 MPa and a CBR of 47.1%. Its mechanical performance is comparable to that of mid-to-high-quality natural gravel and, while lower than that of cement-stabilized soil, it still meets or exceeds the technical requirements for pavement base courses as stipulated in JTG/T F20-2015.

The primary advantage of the proposed mixture lies not in outperforming traditional high-end materials, but in providing a technically viable, cost-effective, and environmentally sustainable alternative. It achieves this by transforming two industrial by-products—MSWIBA and steel slag—into valuable construction resources. This approach directly addresses the dual challenges of solid waste management and the shortage of natural aggregates, particularly suitable for low-volume roads, secondary highways, and resource-constrained regions. Furthermore, the use of this mixture can significantly reduce the carbon emissions and economic costs associated with cement production and gravel mining.

4. Microscopic Mechanism Analysis

4.1. XRD

To explore the solidification mechanism of MSWIBA and steel slag on soil, four types of specimens were prepared based on the optimal mix ratio of MSWIBA mixed soil (50% MSWIBA + 50% soil, with an additional 15% steel slag relative to the total mass of MSWIBA

and soil): 100% soil (Sample A); 50% pure MSWIBA + 50% soil (Sample B); 100% pure soil + 15% steel slag (Sample C); 50% MSWIBA + 50% soil + 15% steel slag (Sample D). After standard curing for 28 days, X-ray diffraction (XRD) tests were conducted on the specimens, and the results are shown in Figure 7. As can be seen from Figure 7, the positions and numbers of diffraction peaks of the four types of specimens are roughly the same, but there are differences in diffraction peak intensity, indicating that their mineral compositions are similar but crystallinity differs.

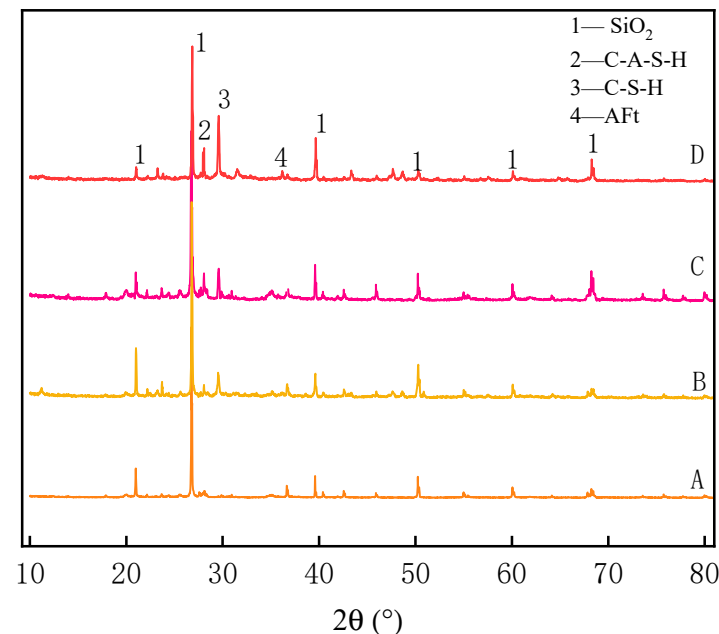


Figure 7. XRD patterns of improved soil at different ratios.

Peak 1 in the figure represents the diffraction peak of silicon dioxide (quartz); Peak 2 corresponds to that of calcium aluminate silicate hydrate (C-A-S-H); Peak 3 stands for that of calcium silicate hydrate (C-S-H); and Peak 4 denotes that of ettringite (AFt). When comparing Sample A and Sample B, the introduction of MSWIBA results in the emergence of a new diffraction peak of C-S-H gel in the specimen. This suggests that MSWIBA can facilitate the formation of hydration products, and this phenomenon is closely associated with the active components like CaO in MSWIBA.

When comparing Sample D and Sample B, after steel slag is added, the intensities of the diffraction peaks of C-A-S-H and C-S-H gel are notably heightened, and a new diffraction peak of AFt is produced. The reason for this is that components in steel slag, such as tricalcium silicate (C_3S), dicalcium silicate (C_2S), and tricalcium aluminate (C_3A), undergo hydration reactions with water to generate cementitious products including C-S-H and AFt. This makes the matrix structure more compact and further enhances the strength, which aligns with the macroscopic test results.

A further comparison between Sample D and Sample C reveals that the addition of MSWIBA intensifies the diffraction peaks of C-S-H, C-A-S-H, and AFt. This indicates that the activity of MSWIBA is gradually activated in the alkaline environment created by steel slag, further boosting the hydration reaction and increasing the quantity of cementitious substances.

4.2. SEM

To investigate the microstructure variations in soil blended with municipal solid waste incineration bottom ash (MSWIBA) under diverse MSWIBA-to-soil ratios, improved soil samples (with 15% steel slag and varying ratio proportions) underwent standard curing for 7 days, then were subjected to scanning electron microscopy (SEM) tests. The results are

illustrated in Figure 8. As observed from the figure, when the MSWIBA: soil ratio is 30:70, the primary basic units are aggregates of soil particles. Between these aggregates, wide and interconnected pores form, and penetrating cracks are visible. Only scattered flocculent C-S-H gels exist on the surface. The aggregates mainly exhibit “point-to-surface contact”, and the bonding interface is loose—leading to relatively low strength of the improved soil at this ratio. When the ratio is 50:50, the basic units show a synergistic packing pattern of “soil particles—MSWIBA particles”. The silicon-aluminum hard particles of MSWIBA fill gaps among soil aggregates, resulting in a structure with few pores and no microcracks. The surface is coated with a C-S-H gel film, and the aggregates are predominantly in “surface-to-surface contact” with a dense bonding interface, making the matrix the most compact. Hence, the improved soil achieves the highest strength at the MSWIBA: soil ratio of 50:50. When the ratio reaches 70:30, as MSWIBA becomes more dominant than soil, the basic units are mainly formed by MSWIBA particles’ agglomeration and stacking. Due to insufficient soil particles to fill inter-particle pores, cracks between particles widen, and density decreases—causing a certain reduction in the improved soil’s performance.

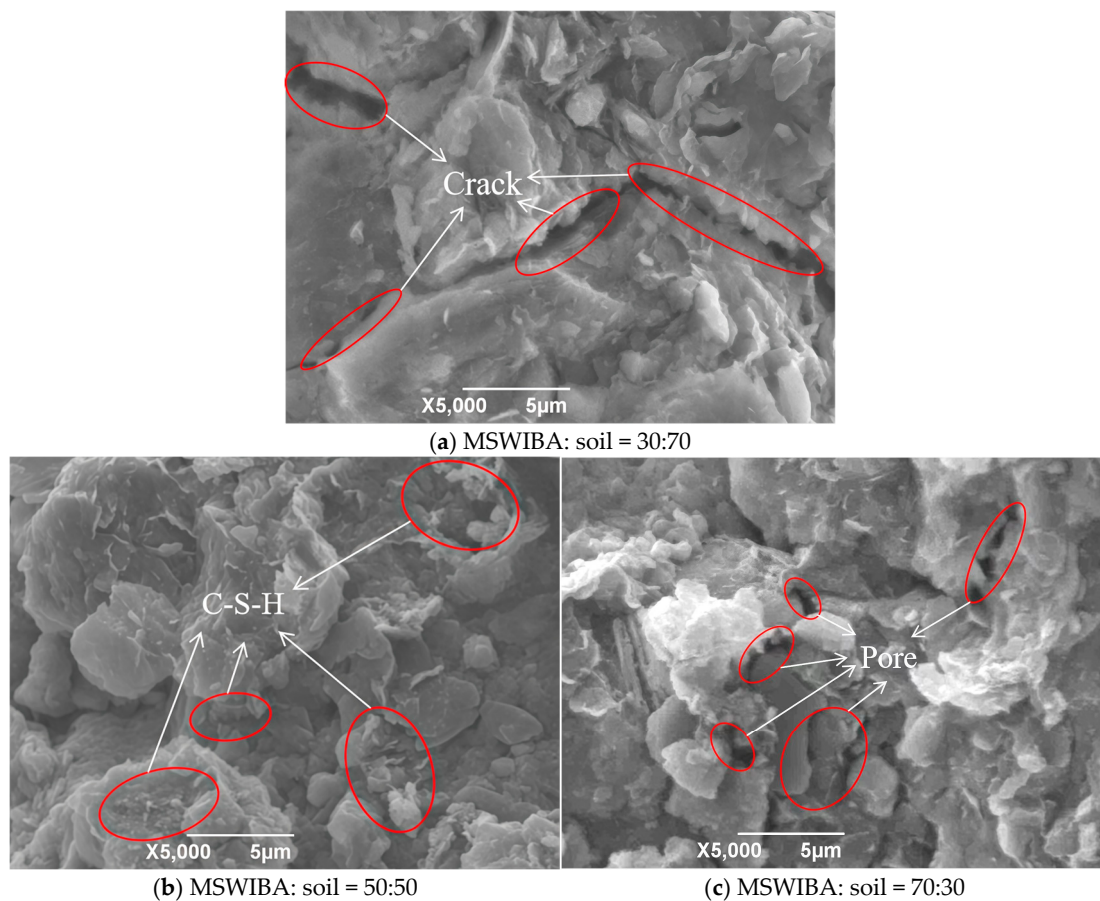


Figure 8. SEM Images of Modified Soil with Different MSWIBA-to-Soil Mass Ratios under 15% Steel Slag Content.

To examine the influence of steel slag dosage on mixed soil strength, mixed soil samples (MSWIBA: soil = 50:50, with different steel slag contents) were cured under standard conditions for 7 days, then subjected to SEM tests. The results are displayed in Figure 9. From the SEM image of pure MSWIBA mixed soil (5000× magnification), when no steel slag is added, particles mainly show “point-to-surface contact”, creating numerous suspended pores. MSWIBA’s activity fails to activate, and only a limited amount of hydration products cannot fill pores or bond particles—resulting in the lowest macroscopic strength. Additionally, plain soil tends to disintegrate. Nevertheless, with steel slag addition, the

main microstructural characteristics include reduced pore volume, decreased pore size, and lowered connectivity. C_3S and C_2S in steel slag start hydrating, forming cementitious substances that cover particle surfaces. In some regions, short fibrous C-S-H fills micropores. The particle contact mode shifts from “point-to-surface” to “surface-to-surface”, though local unfilled pores still exist. When steel slag content is 15%, the overall structure is dense and blocky, with no obvious macroscopic pores. Particles are continuously enveloped by gel, and only a few closed microcracks (with no penetrating damage) exist. Steel slag addition enables full participation in hydration: steel slag hydration generates sufficient C-S-H/AfT, and after MSWIBA activity is thoroughly activated, cementitious products are further supplemented. The gel not only fills pores but also forms a “bonding film” on particle surfaces, inhibiting water penetration and freeze–thaw expansion—matching macroscopically optimal performance. When steel slag content exceeds 15%, the main microstructural features involve increased structural cracks, a looser matrix, and reticular cementitious products on the surface. However, excess unreacted steel slag causes slag agglomeration, leading to uneven structural distribution and relatively low structural strength.

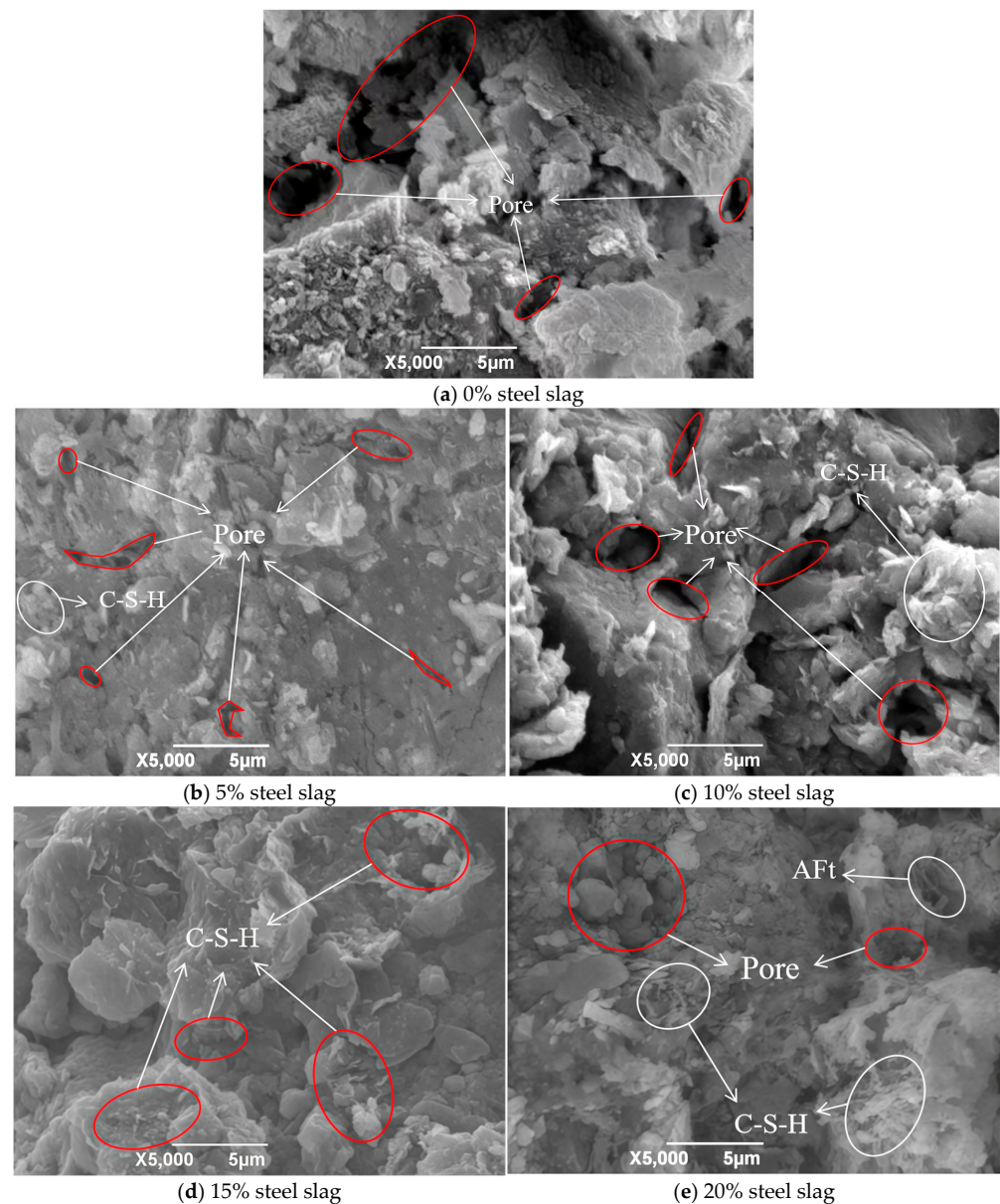


Figure 9. SEM Images of Modified Soil with Different Steel Slag Contents under 50:50 MSWIBA-to-Soil Mass Ratio.

5. Discussion

5.1. Practical Viability and Regional Implementation Strategy

The experimental results confirm that the steel slag–MSWIBA-improved soil meets the fundamental technical requirements for pavement base courses. For its application in resource-limited regions, an analysis of economic and logistical feasibility is crucial. The most significant advantage of the proposed mixture is its potential for substantial cost reduction. By utilizing MSWIBA and steel slag, which are often low-cost or negative-cost (waste) materials, the raw material expense can be drastically lowered. A preliminary estimate suggests production costs could be as low as 30–50% of those for conventional cement-stabilized materials. Logistically, successful implementation relies on geographic synergy—proximity between waste sources (incineration plants, steel mills) and construction sites—to minimize transportation costs and establish a stable supply chain. The compatibility of the mixing and compaction processes with conventional earthwork practices further lowers the barrier for adoption, making this mixture a pragmatic and sustainable alternative for regions facing both solid waste management and natural aggregate shortage challenges.

5.2. Limitations and Future Research Directions

It is important to acknowledge the limitations of this study to properly contextualize the findings. The primary limitation lies in the relatively short-term nature of the performance tests. The 7-day UCS and 11 freeze–thaw cycles, while providing valuable early-age and comparative durability indicators, are insufficient to fully characterize the material's long-term performance under decades of service. To address these limitations and validate the material for widespread use, future research should focus on (1) long-term mechanical performance (e.g., 28, 90-day UCS) and durability under more extensive freeze–thaw and wet–dry cycles; (2) field-scale pilot trials to monitor in situ behavior under real environmental and traffic conditions; and (3) long-term leaching studies to comprehensively assess the environmental impact over time.

6. Conclusions

In this research, MSWIBA mixed soil for pavement base courses was prepared by utilizing municipal solid waste incineration bottom ash (MSWIBA) and natural soil as raw materials, with steel slag being added. Via a series of performance tests and microscopic analyses, the subsequent conclusions were obtained:

- (1) Adding steel slag and MSWIBA can notably enhance the engineering properties of natural soil. As the steel slag content and MSWIBA proportion increase, the 7-day unconfined compressive strength (UCS) and California Bearing Ratio (CBR) of the mixed soil first rise and then decline, while the modified soil shows remarkable water stability.
- (2) The optimal mix proportion of steel slag–MSWIBA mixed soil is a 50:50 mass ratio of MSWIBA to natural soil, with an extra 15% steel slag relative to the total mass of MSWIBA and soil. Under this proportion, the 7-day UCS of the mixed soil reaches 0.82 MPa, the 5-day water stability coefficient is 0.91, the strength retention rate after 11 freeze–thaw cycles is 65.3%, the CBR value is 47.1%, and the expansion rate is 1.06%—all satisfying the technical criteria for subgrade fill stipulated in JTG/T F20-2015 Technical Specifications for Construction of Highway Pavement Base Courses and JTG D30-2015 Code for Design of Highway Subgrades.
- (3) The mechanism behind the improved performance of the modified soil was uncovered using microscopic testing techniques (XRD and SEM): $\text{Ca}(\text{OH})_2$ produced by steel slag hydration activates the pozzolanic activity of vitreous components in MSWIBA,

facilitating the secondary formation of C-S-H, C-A-S-H gels, and AFt crystals. The total quantity of cementitious substances is considerably higher than that of soil modified solely with steel slag; the 50:50 MSWIBA-to-soil mass ratio allows for the most compact packing of MSWIBA and soil particles; the hydration products fill the pores and bind the particles together, reducing the expansion stress induced by water phase transition during freeze–thaw cycles, and establishing a dynamic balance of “early microcrack initiation–late cementitious product repair” to guarantee structural stability.

- (4) The findings of this study demonstrate the short-term viability of the steel slag–MSWIBA mixture. However, it is acknowledged that the conclusions have two key limitations: first, they are based on a specific material source and limited testing duration (e.g., 7-day UCS, 11 freeze–thaw cycles), and second, discussions on the long-term leaching behavior of heavy metals (a critical aspect of environmental impact) are only hypothetical and theoretical—in this study, long-term leaching experiments were not conducted, and relevant environmental risk assessments rely primarily on short-term TCLP data. This limitation must be addressed by subsequent long-term leaching monitoring experiments to fully validate the long-term environmental safety of the mixture. Beyond this, the long-term mechanical performance and in situ behavior under field traffic and environmental conditions also require further investigation through the research directions outlined in the discussion.

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