

Article

Durability Properties of PVA-Strengthened Waste-Based Foam Lightweight Soil Under Freeze–Thaw Cycles and Solution Immersion Conditions

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Abstract

Traditional cement-based foamed lightweight soils suffer from high construction costs, poor durability, and low solid waste utilization efficiency, which severely restrict their engineering application. A novel polyvinyl alcohol (PVA)-reinforced solid waste-based foamed lightweight soil is fabricated using Bayer red mud, mineral powder, and fly ash. To clarify the durability evolution mechanisms, systematic freeze–thaw cycling, long-term water immersion, and sodium sulfate erosion tests were conducted on PVA-reinforced solid waste-based, unreinforced solid waste-based, and pure cement-based specimens. The results demonstrate that the PVA-reinforced specimen achieves optimal freeze–thaw resistance with only 17.10% strength loss after 50 cycles, owing to the internal three-dimensional fiber network that restrains crack propagation and enhances matrix toughness. It also exhibits excellent long-term water immersion stability, with a mild strength increment of 4.04–10.33% after 120 days. In contrast, the CN exhibited a strength increase of 43.62%, attributed to its lower initial strength caused by incomplete hydration; however, its final strength remained between those of the other two groups. In sulfate environments, unreinforced solid waste-based specimens present superior corrosion resistance, while PVA fiber-induced interconnected pores slightly weaken sulfate erosion resistance. Microscopic analysis confirms that the generation of alunite and gypsum hydration products fundamentally causes performance discrepancies among different specimens. Different from previous studies focusing on single fiber modification or single solid waste partial replacement of cement, this study innovatively adopts a composite modification strategy of “multi-solid waste alkali-activated matrix + PVA fiber toughening”, and systematically reveals the durability evolution mechanism under multiple harsh environments.

Keywords: solid waste-based foam lightweight soil; PVA reinforcement; durability; freeze–thaw cycles; sulfate erosion; water stability



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1. Introduction

Filling and foundation treatment are critical procedures in civil engineering, where uneven foundation settlement, environmental corrosion, and freeze–thaw-induced structural damage severely threaten the long-term service stability of infrastructure. Conventional foundation reinforcement strategies primarily focus on improving bearing capacity, yet differential settlement under self-weight and structural loads remains unavoidable, frequently triggering structural cracking, water leakage, and even progressive structural failure. In this context, the development of high-performance lightweight filling materials has become

an essential technical pathway to reduce permanent foundation load, mitigate uneven deformation, and enhance the environmental adaptability of engineered foundations.

Foamed lightweight soil has been widely adopted in foundation reinforcement, pit backfilling, and underground structure load reduction owing to its prominent advantages of low density, high fluidity, and low additional structural load [1–3]. Nevertheless, traditional cement-based foamed lightweight soil exhibits inherent performance defects, including high brittleness, poor crack resistance, and inferior durability under complex environmental erosion [4–6]. Moreover, its exclusive reliance on ordinary Portland cement as the sole cementitious binder leads to high material costs and excessive resource consumption, substantially limiting its large-scale promotion and engineering application in environmentally demanding scenarios.

Industrial solid wastes (e.g., red mud, mineral powder, and fly ash) are generated in massive volumes annually but suffer from low resource utilization efficiency [7,8]. Recycling these solid wastes to fabricate foamed lightweight soil can effectively realize waste resource reuse, reduce engineering costs, and conform to the low-carbon and green development concept of modern civil engineering. In addition, material modification via admixtures has become a popular research hotspot for cement-based materials. Diverse additives, including inorganic minerals (such as bentonite [9]) and organic fibers (such as polypropylene and polyvinyl alcohol fiber [10]), are adopted to optimize the mechanical performance and service properties of low-carbon filling materials. Fiber reinforcement technology has been proven to effectively compensate for the brittleness and crack-susceptibility defects of lightweight soil matrices [11,12], providing a feasible modification strategy for performance optimization of foamed lightweight materials.

This study proposes the core research hypothesis that the three-dimensional network structure formed by coupling an alkali-activated solid waste system with dispersed PVA fibers can effectively restrain crack initiation and propagation of fully solid waste-based foamed lightweight soil, thereby significantly improving the freeze–thaw resistance and long-term solution immersion stability of the matrix. Furthermore, three types of foamed lightweight soils, including PVA-reinforced solid waste-based, unreinforced solid waste-based, and pure cement-based specimens, were fabricated. A systematic comparative experimental investigation was conducted to explore the macroscopic morphological evolution, mass variation, and compressive strength degradation of the three materials under three typical harsh service environments. Combined with microscopic characterization analysis, the differential durability mechanisms of different material systems were revealed.

2. Literature Review

Durability performance constitutes a core indicator for evaluating the engineering applicability and service life of foamed lightweight soil. Existing studies have extensively explored the frost resistance, water stability, and sulfate erosion resistance of foamed lightweight materials, forming a basic theoretical system for material performance evolution.

2.1. Research Progress on Freeze–Thaw Durability

Fiber modification and solid waste replacement are two mainstream technical approaches to improve the freeze–thaw resistance of foamed lightweight soil. In terms of fiber reinforcement, organic and inorganic fibers can effectively suppress freeze–thaw damage via crack bridging and stress dispersion effects, mitigating the progressive propagation of frost heave cracks and reducing mechanical strength loss under cyclic loading. Bayraktar et al. [13] verified that polypropylene fiber incorporation optimizes the internal stress distribution of foamed soil, significantly inhibiting the expansion of freeze–thaw microcracks.

On this basis, Namsone et al. [14] further found that composite modification of silica fume and carbon fibers achieves synergistic optimization of pore structure and matrix toughness, presenting better frost resistance than single fiber modification. Li et al. [15] also confirmed that rational fiber mixing ratios can effectively improve the freeze–thaw cycle tolerance of lightweight soil.

In terms of solid waste modification, industrial solid waste substitution for cementitious materials can effectively optimize the matrix microstructure and frost resistance of lightweight soil. Bayraktar et al. [13] also demonstrated that waste marble powder and slag could improve the mechanical properties and freeze–thaw durability by modifying the matrix structure and transport characteristics. From the perspective of damage mechanism, Gencel et al. [16] reported that incorporating waste-derived materials into foamed concrete can optimize microstructure and improve resistance against freeze–thaw deterioration by reducing pore connectivity and enhancing matrix compactness.

Existing studies have confirmed that fiber modification mainly relies on bridging and toughening effects to inhibit crack propagation, while solid waste modification optimizes matrix performance by improving microstructure and pore compactness. However, most studies focus on single modification technology, and the synergistic advantages and internal mechanism of combined fiber and full solid waste modification have not been systematically clarified, leading to insufficient theoretical support for the performance upgrade of high-efficiency green lightweight materials.

2.2. Research Status of Water Immersion Stability

The long-term water immersion stability of foamed lightweight soil is primarily governed by matrix composition and internal pore structure, and differences in material formulation directly lead to differentiated water absorption and performance evolution laws. Existing studies have formed a unified consensus that matrix compactness is the core factor determining water resistance. Raj et al. [17] reported that the water absorption and durability of foamed lightweight concrete are strongly influenced by pore structure characteristics and matrix compactness. A denser hydration network and reduced interconnected porosity can significantly improve resistance against water penetration and long-term performance degradation. Peng et al. [18] investigated the performance of bauxite tailings-modified foamed mixture lightweight soil and found that tailings content significantly affected water absorption, pore structure, and mechanical properties. Appropriate tailings incorporation improved structural compactness, whereas excessive replacement increased pore connectivity and weakened water resistance. Ou et al. [19] further investigated the influence of red mud incorporation on the properties of foamed mixture lightweight soil and found that the reasonable addition of red mud could optimize the internal pore structure, improve matrix compactness, and enhance water stability by reducing water transport channels. However, excessive red mud content increased pore connectivity and weakened the long-term immersion resistance of the material.

Collectively, previous studies have mainly clarified the effects of solid waste type, replacement ratio, and pore structure on the water stability of foamed lightweight soil. However, the long-term immersion behavior and synergistic mechanism between fully solid waste-based matrices and functional fiber reinforcement remain insufficiently understood.

2.3. Research Advances in Sulfate Erosion Resistance

Current research indicates that solid waste modification has dual effects on the sulfate corrosion resistance of lightweight soil. Al-Shwaiter et al. [20] pointed out that although palm oil fuel ash and other solid wastes can optimize the basic mechanical properties of foamed soil, they will increase matrix-connected porosity, accelerate sulfate ion infiltration,

and aggravate expansion deformation and structural damage in corrosive environments. Jiang et al. [21] compared the sulfate resistance of cement-based and geopolymer-based foamed lightweight soils, and concluded that the dense geopolymer microstructure effectively blocks ion diffusion channels and presents better salt erosion resistance than traditional cement-based porous matrices. Wang et al. [22] investigated the influence of slag incorporation on the sulfate corrosion resistance of lightweight cement-treated soils and demonstrated that appropriate slag addition could improve durability by refining pore structure and modifying hydration products, thereby reducing sulfate ion penetration and corrosion-induced deterioration. Meanwhile, Que et al. [23] revealed that the engineering performance of foamed lightweight soil is closely associated with its internal pore structure and matrix composition, and the optimization of microscopic characteristics plays a critical role in improving long-term durability under complex service conditions. In addition, environmental ion characteristics also regulate the erosion degree: subsequent studies confirmed that lightweight soil presents more severe swelling degradation in sodium sulfate solution than in a magnesium sulfate environment [24].

While the superiority of geopolymer matrices over traditional cementitious systems is well-documented, the impact of solid waste incorporation remains controversial due to the trade-off between mechanical enhancement and potential porosity increase. Furthermore, current research largely focuses on macroscopic performance, with insufficient attention paid to the evolution of microscopic structure in fiber-reinforced alkali-activated lightweight soils under long-term sulfate attack.

2.4. Study Focus

In summary, the comprehensive review above of the existing literature shows that current research on the durability of foamed lightweight soil mainly focuses on traditional cement-based systems, with solid waste mostly used as auxiliary doping materials for partial performance optimization. There is a lack of systematic research on the durability evolution law of fully solid waste-based foamed lightweight soil with low cement content or a cement-free system. Meanwhile, the adaptability and synergistic modification mechanism of PVA fiber in a multi-solid waste matrix under multiple harsh environmental coupling conditions are still unclear.

Different from previous studies focusing on single fiber modification or single solid waste partial replacement of cement, this study innovatively adopts a composite modification strategy of “multi-solid waste alkali-activated matrix + PVA fiber toughening”. A systematic comparative durability test of pure cement-based, unreinforced full solid waste-based, and PVA-reinforced full solid waste-based foamed lightweight soil was carried out under three typical harsh working conditions, to clarify the environmental adaptability and superior service performance of PVA-modified solid waste-based lightweight soils. The macroscopic performance evolution law and microscopic damage mechanism of the composite material were revealed, which fills the research gap of insufficient systematic exploration on multi-working-condition durability and synergistic modification mechanism of PVA-modified full solid waste lightweight filling materials. The obtained results offer reliable experimental data for the performance optimization of low-carbon solid waste-based lightweight fillings, and provide feasible technical references for the large-scale promotion and engineering application of eco-friendly recycled filling materials in complex geological and climatic scenarios such as road subgrades and foundation treatment.

3. Experimental Materials and Protocol

3.1. Test Raw Materials

The raw materials employed in the experimental procedure encompassed Bayer red mud (RM), ground granulated blast-furnace slag (GGBS), fly ash (FA), ordinary Portland cement (OPC), foaming agent, alkali activator, and water. RM was obtained from Xinfu Group in Liaocheng, Shandong Province, China. FA was sourced from Deze Mineral Products Processing Plant in Shijiazhuang, China. Figure 1 shows the primary raw materials used in this study. As illustrated in Table 1, the primary chemical compositions of RM, GGBS, FA, and OPC are outlined. According to ISO 29581-2 [25], the chemical compositions of red mud and mineral powder were determined by a Rigaku Miniflex 600X-ray diffractometer, Tokyo, Japan, while the chemical compositions of fly ash and cement were provided by the manufacturers.



Figure 1. Test raw materials. (a) Bayer red mud; (b) ground granulated blast-furnace slag; (c) fly ash; (d) alkali activator; (e) foaming agent; (f) PVA fibers.

Table 1. Chemical composition of RM, GGBS, FA and OPC (%).

	Fe ₂ O ₃	Al ₂ O ₃	SiO ₂	Na ₂ O	TiO ₂	CaO	SO ₃	MgO	LOI
RM	46.1	22.2	14.0	10.3	5.4	0.7	0.6	0.2	0.7
GGBS	1.4	20.9	25.2	0.9	1.7	31.5	-	13.2	0.4
FA	7.6	33.8	49.7	0.5	1.4	2.9	1.4	0.6	2.1
OPC	3.2	4.7	22.6	0.23	-	62.0	2.9	3.3	1.1

The study utilized ground granulated blast-furnace slag (GGBS) with a specific surface area of 400 m²/kg as the primary binding agent. GGBS was supplied by Qiangdong Mineral Products Processing Plant in Lingshou County, Shijiazhuang, China. Portland cement (OPC) with a strength of 42.5 MPa was utilized as an additive in solid waste-based foamed lightweight soil, and as the primary binding agent in pure cement-based specimens. OPC was provided by Anyang Zoomlion Cement Co., Ltd. in Anyang, China. A mixture of sodium silicate solution and sodium hydroxide was utilized as the alkali activator. Sodium silicate solution was purchased from Jingcheng Chemical Co., Ltd. in Bengbu, China, and sodium hydroxide was obtained from Shijixing Chemical Reagent Co., Ltd. in Qingdao, China. The mixture was found to accelerate the hydration of silicoaluminates in the slag raw material, thereby producing cementitious products such as calcium silicate hydrate (C-S-H). The specifications for the alkaline activator solution provided by the manufacturer are enumerated in Table 2.

Table 2. Specifications for the alkaline activator solution.

Modulus of Sodium Silicate	SiO ₂ (%)	Na ₂ O (%)	H ₂ O (%)	Baumé Degree (B°)	Density (g/cm ³)
3.22	26.5	8.5	65	40	1.380

Further, a polymer–protein composite foaming agent, produced by Zhongsheng New Building Materials Co., Ltd. in Jinan, China, was selected; the relevant properties provided by the manufacturer are listed in Table 3. The foaming agent was diluted at a ratio of 1:40 and subsequently converted into foam by a foaming machine. The physical properties of the PVA fibers provided by the manufacturer are outlined in Table 4. The water utilized in all mixing procedures was supplied by Qingdao West Coast Public Utility Group Water Affairs Co., Ltd. in Qingdao, China.

Table 3. Properties of foaming agent.

Foam Density (kg/m ³)	Settling Distance (mm)	Water Secretion (mL)	Bubbling Times
50	4	23	20

Table 4. Physical and mechanical properties of PVA fiber.

Length (mm)	Density (g/cm ³)	Tensile Strength (MPa)	Elastic Modulus (GPa)	Fracture Elongation (%)	Diameter (μm)
12	1.31	1560	41	6.5	15

3.2. Experimental Design

In actual engineering, foamed lightweight soil is mostly used for subgrade backfill and foundation filling, and frequently suffers from freeze–thaw damage in cold regions, long-term water immersion in humid environments, and sulfate erosion in saline-alkali areas. Therefore, a comparative experimental study was performed to systematically investigate the frost resistance, long-term water stability, and sodium sulfate erosion resistance of different types of foamed lightweight soil materials. Three specimen groups with distinct formulations were set for comparative analysis, and the detailed material compositions and grouping definitions are specified as follows. The mix proportions and operating conditions for durability performance tests are shown in Table 5.

Table 5. Mix proportions and operating conditions for durability performance tests.

Sample Number	Solid Waste Ratio	Cement Mix Proportion	Fiber Content (%)	Test Condition		
				Freeze–Thaw Cycle (Cycles)	Water Stability (Days)	Sulfate Resistant (Days)
WS-N	50:40:10	-	-	1, 3, 5, 10, 15, 25, 35, 50	0, 3, 7, 14, 28, 60, 90, 120	0, 3, 7, 14, 28, 60, 90, 120
WS-P	50:40:10	-	0.3			
CN	-	100	-			

Note: -, no present.

The unreinforced solid waste-based foamed lightweight soil group (WS-N) was prepared using Bayer process red mud, mineral powder, and fly ash at a fixed mass ratio of 5:4:1, with 6% modulus–2.0 water glass incorporated as an alkali activator. The PVA-reinforced solid waste-based foamed lightweight soil group (WS-P) adopted the same solid waste matrix composition and alkali activator dosage as the WS-N group, with an additional 0.3% polyvinyl alcohol (PVA) fibers incorporated for toughening modification.

The pure cement-based foamed lightweight soil group (CN) was set as the blank control group, which was fabricated with 100% ordinary Portland cement as the sole cementitious material without any solid waste or fiber incorporation. All test specimens were designed with a constant wet density of 750 kg/m^3 and a uniform water-to-binder ratio of 0.45 to ensure controlled experimental variables.

3.3. Sample Preparation and Curing

The preparation procedure for foamed lightweight soil specimens is presented in Figure 2.



Figure 2. Preparation process of foam lightweight soil. (a) Stir the slurry mixture; (b) add foam; (c) stir the foam-based lightweight soil; (d) form the slurry into molds; (e) film-coating curing; (f) bagging care.

First, the pre-weighed red mud, mineral powder, and fly ash were dry-mixed thoroughly to form a homogeneous composite powder matrix. For the WS-P group, PVA fibers were pre-treated via 24 h water immersion to achieve full saturation, which effectively avoided fiber agglomeration and ensured uniform dispersion in the subsequent slurry. Second, saturated PVA fibers, water, and activator solution were sequentially added to the dry powder mixture, and the mixture was stirred continuously to form a uniform and stable cementitious slurry. Third, the foaming agent was diluted with water at a dilution ratio of 1:40, and uniform, stable foam was generated via a professional foaming machine. The prepared foam was slowly incorporated into the slurry in strict accordance with the designed proportion, followed by secondary stirring to guarantee the homogeneity of the foam–slurry mixture.

The well-stirred fresh composite slurry was poured into standard cubic test molds with dimensions of $100 \times 100 \times 100 \text{ mm}$. The surface of the molded specimens was covered with plastic film to prevent water evaporation and surface cracking. After initial curing for 72 h in a constant temperature and humidity curing chamber, the specimens were demolded completely. Subsequently, all demolded specimens were sealed in plastic bags and placed in a standard curing environment with a temperature of $20 \text{ }^{\circ}\text{C} \pm 2 \text{ }^{\circ}\text{C}$ and a relative humidity of $95\% \pm 3\%$ for 28 d, before being used for subsequent performance tests.

3.4. Test Methods

3.4.1. Freeze–Thaw Cycle Test

To evaluate the frost resistance of the prepared foamed lightweight soils, the variations in mass and unconfined compressive strength of specimens were tested. The test procedure was strictly implemented in accordance with the national specifications CECS 249 [26] and GB/T 43487 [27].

Prior to the freeze–thaw test, 28 d cured specimens were immersed in constant-temperature water at 20 °C for 48 h. After surface moisture was wiped dry, the initial mass and compressive strength of each specimen were measured and recorded as the baseline values (0 cycle). A programmable freeze–thaw cycle chamber, shown in Figure 3a, was adopted for the cyclic test. The test procedure for a single freeze–thaw cycle was set as follows: specimens were frozen at $-20\text{ °C} \pm 2\text{ °C}$ for 6 h, followed by full immersion in 20 °C constant-temperature water for 5 h after freezing completion. A total of 50 continuous freeze–thaw cycles were performed for all test groups.

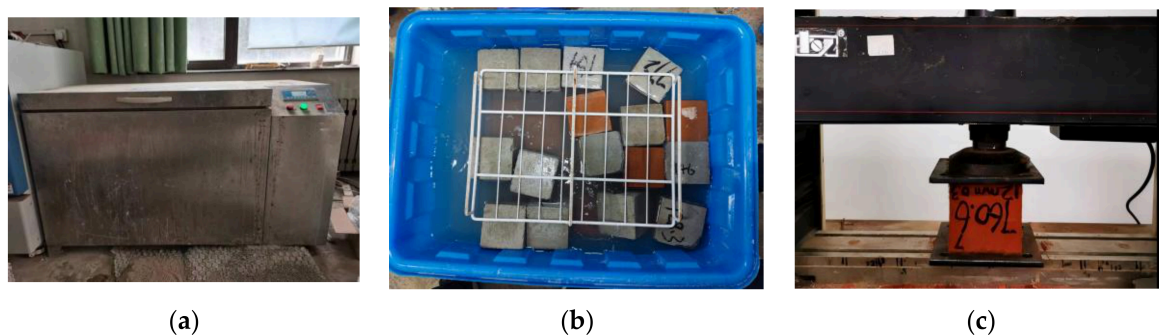


Figure 3. Test methods. (a) Freeze–thaw cycle test chamber; (b) solution immersion test; (c) compressive strength test.

To capture the dynamic evolution of frost resistance performance, three parallel specimens were randomly selected from each group for mass measurement and compressive strength testing at the 1st, 3rd, 5th, 10th, 15th, 25th, 35th, and 50th freeze–thaw cycles. The surface morphology and structural damage characteristics of specimens were comprehensively recorded for auxiliary performance analysis.

3.4.2. Long-Term Water Immersion Test

A long-term constant-temperature water immersion test was conducted to evaluate the water stability of foamed lightweight soil materials. According to the test method in GB/T 43487 [27], specimens were fully immersed in a sterile constant-temperature water tank with a fixed ambient temperature of 20 °C, and the water level was maintained at least 20 mm above the top surface of specimens to ensure complete immersion, as shown in Figure 3b. The immersion water was replaced every 30 d to keep the water environment stable and avoid the influence of water quality deterioration on test results. Three parallel specimens were selected from each group for compressive strength testing at immersion ages of 3 d, 7 d, 14 d, 28 d, 60 d, 90 d, and 120 d.

Meanwhile, dynamic mass and appearance observations were also performed. Before each test, the surface moisture of specimens was wiped dry, and the surface morphology, structural integrity and mass changes were systematically recorded.

3.4.3. Sulfate Erosion Test

A sodium sulfate immersion erosion test was carried out to investigate the sulfate erosion resistance of foamed lightweight soils, with the dynamic variations in specimen

mass and compressive strength adopted as the core evaluation indices. The test method referenced the reagent and concentration requirements specified in GB/T 50082 [28] and the experimental protocol mentioned in Ortega et al. [29]. Anhydrous sodium sulfate was used to prepare a 5% mass fraction sodium sulfate solution.

All specimens with a 28 d standard curing age were fully immersed in the prepared sulfate solution at a constant temperature of 20 °C, as shown in Figure 3b. The erosion solution was renewed every 30 d. Three parallel specimens were collected from each group at erosion ages of 0 d, 3 d, 7 d, 14 d, 28 d, 60 d, 90 d, and 120 d for compressive strength testing to characterize the strength degradation law under sulfate erosion.

Dynamic mass measurement and surface morphology observation were also conducted. The structural damage, surface corrosion and mass variation rules were recorded in detail. The final erosion damage characteristics of specimens after 120 d of sulfate immersion were analyzed comprehensively.

3.4.4. Unconfined Compressive Strength Test

In accordance with the provisions stipulated in the national standard GB/T 43487 [27], the unconfined compressive strength of foam lightweight soil specimens was measured. This was achieved by utilizing a universal testing machine (Figure 3c) for three distinct test types, with a loading rate of 2.0 ± 0.5 kN/s. The results obtained from this experimental procedure were then averaged from three parallel samples per group.

3.4.5. Microscopic Morphology Test

To reveal the intrinsic microscopic mechanism of mechanical performance degradation and erosion damage of foamed lightweight soils, the microscopic pore structure, hydration product morphology and interface characteristics of specimens after 120 d of water immersion and sulfate erosion were observed via scanning electron microscopy (SEM) following ASTM C1723-16 [30].

4. Experimental Results and Analysis

4.1. Freeze–Thaw Cycles Durability

4.1.1. Appearance Variation Characteristics

The surface morphological damage and mass evolution of cement-based (CN), unreinforced solid waste-based (WS-N), and PVA-reinforced solid waste-based (WS-P) foamed lightweight soils under cyclic freeze–thaw loading were analyzed.

Figure 4 shows the appearance changes under different freeze–thaw cycles. Obvious differential damage was observed among specimens after 10 freeze–thaw cycles. All specimens presented slight surface mortar peeling. Specifically, dense vertical microcracks appeared on the surface of WS-N specimens, while CN specimens developed a large number of interconnected surface pores. In contrast, WS-P specimens maintained intact surface morphology with only sporadic tiny pores and no crack initiation. After 25 freeze–thaw cycles, the surface deterioration of all specimens was further aggravated. The vertical microcracks of WS-N specimens continued to expand and propagate inward; CN specimens exhibited significant angular spalling and delamination, with continuous enlargement and penetration of surface pores. For WS-P specimens, only a small number of new isolated micropores were generated on the surface, without crack development or structural damage, showing excellent structural stability. After 50 freeze–thaw cycles, distinct structural failure differences were observed across groups. CN specimens suffered severe structural damage, characterized by loose internal structure and extensive surface peeling. WS-N specimens formed penetrating cross-cracks on the upper surface, which severely destroyed the structural integrity of the material. By comparison, WS-P specimens only presented

partial surface mortar shedding, with no penetrating cracks or structural deformation, which is consistent with the findings of foamed lightweight concrete reported in the literature [14,31].

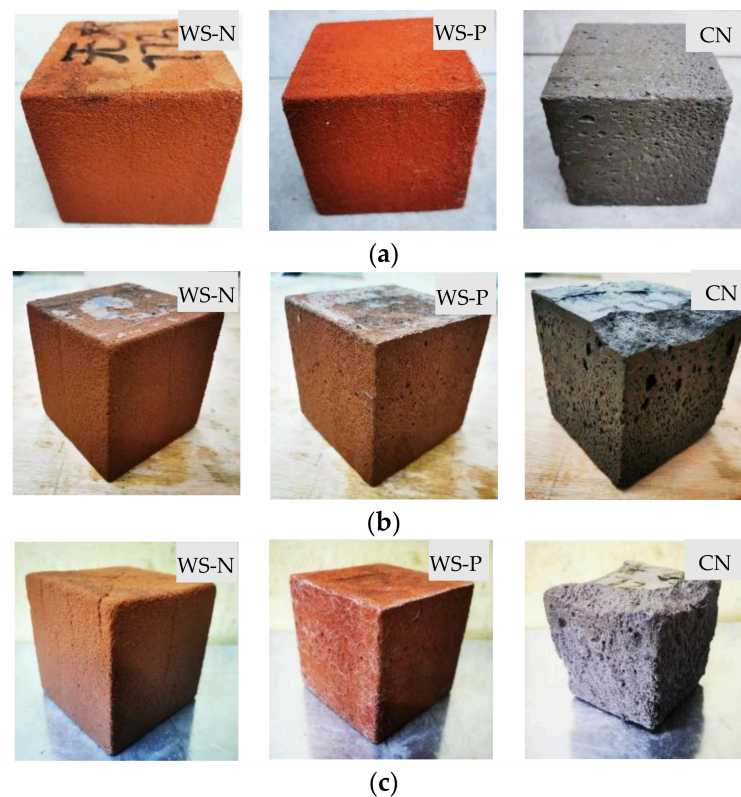


Figure 4. Appearance changes under different freeze–thaw cycles: (a) 10th cycles; (b) 25th cycles; (c) 50th cycles.

The morphological deterioration degrees of the three groups of specimens under freeze–thaw cycles followed the order $CN > WS-N > WS-P$, demonstrating that the solid waste matrix and PVA fiber modification effectively improve the freeze–thaw resistance of foamed lightweight soil.

4.1.2. Mass Variation Law

The mass variation rates of the three types of foamed lightweight soils under continuous freeze–thaw cycles were statistically analyzed. As shown in Figure 5, all specimens exhibited a consistent mass growth trend in the early stage of freeze–thaw cycles (0–10 cycles), which was attributed to the combined effects of an unsaturated initial water state and continuous water absorption during cyclic immersion, as well as the generation of new hydration products from unreacted cementitious components during thawing periods. At the 10th cycle, the mean mass growth rates of WS-N, WS-P, and CN specimens reached 13.23%, 13.30%, and 15.28%, respectively. The higher mass growth rate of CN specimens was caused by the rapid development of interconnected surface pores in the early freeze–thaw stage, which significantly enhanced water absorption capacity. During the whole test process, the maximum standard deviation of mass was 10.9 g, 8.7 g, and 12.3 g, respectively, for WS-N after 25 cycles, WS-P after 5 cycles, and CN after 35 cycles.

In the late freeze–thaw stage (10–50 cycles), the mass variation trends of the three specimens diverged significantly. Both WS-N and WS-P specimens maintained fast mass growth before 15 cycles, followed by slowed growth at the later cycles. After 50 cycles, the final mass growth rates of WS-N and WS-P specimens reached 21.41% and 22.15%,

respectively. The slightly higher mass increment of WS-P specimens compared with WS-N specimens was due to the hydrophilicity of PVA fibers and the porous microstructure of the solid waste-based matrix, which further promoted water infiltration and retention.

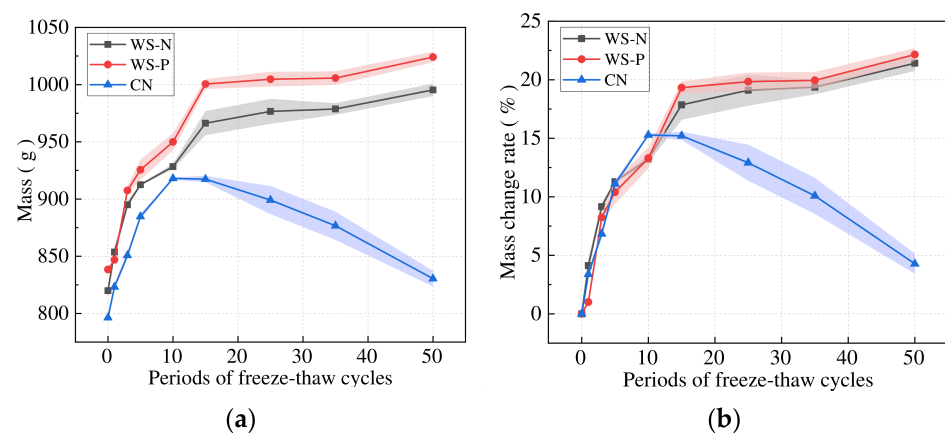


Figure 5. Mass evolution under different freeze–thaw cycles (mean $\pm$ standard deviation). (a) Mass; (b) rate of change in mass.

In contrast, the mass of CN specimens decreased continuously in this stage. This phenomenon occurred because the surface pores of CN specimens were fully saturated with water after repeated cycles; the volume expansion of pore water during freezing generated frost heave stress, leading to surface aggregate peeling and block spalling. The mass loss caused by structural peeling exceeded the mass increment from water absorption, resulting in a final mass growth rate of only 4.28% for CN specimens after 50 cycles.

Overall, the solid waste-based matrix endowed foamed lightweight soil with better freeze–thaw structural stability compared with pure cement-based materials. The incorporation of PVA fibers further optimized the structural toughness of the material, effectively resisting frost heave damage and inhibiting crack propagation.

4.1.3. Compressive Strength Evolution

The unconfined compressive strength variations in CN, WS-N, and WS-P specimens under cyclic freeze–thaw loading were quantitatively analyzed, and the strength evolution of all specimens conformed to a unified trend of initial growth followed by continuous attenuation. As shown in Figure 6, the early-stage strength enhancement was primarily attributed to water absorption during freeze–thaw immersion, which promoted secondary hydration of unreacted cementitious components and generated additional hydration gels, thereby densifying the matrix structure and improving mechanical performance. Distinct strength evolution rates and attenuation amplitudes were observed among the three specimen groups, reflecting significant differences in frost resistance.

In the early freeze–thaw stage (0–5 cycles), each specimen group reached its peak compressive strength at different cycle stages. The WS-N specimen achieved a maximum mean strength of 2.36 MPa at the first cycle, with a strength growth rate of 5.36%; the WS-P specimen peaked at 3.20 MPa at the third cycle, corresponding to a 3.23% strength increment; the CN specimen exhibited the most prominent early hydration effect, reaching a peak mean strength of 2.93 MPa at the fifth cycle with a maximum growth rate of 20.58%. Statistical analysis indicated that the early strength growth efficiency of pure cement-based materials was significantly higher than that of solid waste-based composite materials, which was closely related to the rapid hydration reaction rate of ordinary Portland cement.

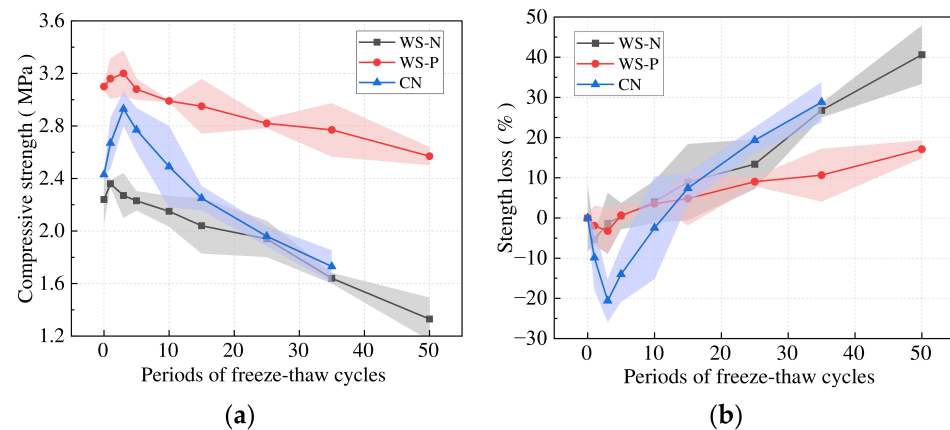


Figure 6. Compressive strength evolution under different freeze–thaw cycles (mean $\pm$ standard deviation). (a) Strength; (b) strength loss.

After reaching the peak strength, the compressive strength of all specimens decreased continuously with the increase in freeze–thaw cycles, with obvious group differences in attenuation degree. The CN specimen showed the fastest strength deterioration, with a strength loss rate of 28.81% after 35 cycles. Meanwhile, the strength loss rate of the WS-N specimen reached 26.79%, while the WS-P specimen maintained a low strength loss of 10.65%. After 50 cycles, the final strength loss rate reached 40.63% and 17.10%, respectively, for WS-N and WS-P specimens. During the whole test process, the maximum standard deviation of strength was 0.21 MPa, 0.20 MPa and 0.31 MPa, respectively, for WS-N after 15 cycles, WS-P after 35 cycles, and CN after 10 cycles.

Notably, the CN specimens after 50 cycles experienced irreversible structural failure, including matrix softening and large-area peeling, resulting in unmeasurable residual compressive strength and the absence of the last data point in Figure 6.

In freeze–thaw environments, the macroscopic frost heave pressure and microscopic pore water expansion stress are the dominant causes of crack initiation and structural degradation of foamed lightweight soil. As confirmed in the reference [13,16], the incorporation of industrial solid waste can significantly improve the matrix microstructure, and the WS-N and WS-P specimens formed a dense gel microstructure with high-strength pore walls, which effectively alleviated frost heave damage and delayed strength attenuation compared with CN specimens. Furthermore, the uniformly dispersed PVA fibers construct a continuous three-dimensional toughening network inside the fully solid waste matrix, which profoundly regulates the pore connectivity, crack propagation behavior, and interfacial stress distribution during frost damage. On the one hand, the fiber bridging effect effectively spans microcracks induced by cyclic frost heave and thawing shrinkage, restricts the opening, expansion and penetration of microcracks, and terminates the continuous propagation of damage cracks inside the matrix. On the other hand, the moderately increased interconnected pores introduced by fiber-matrix interfacial gaps provide effective pressure release channels for pore water phase transformation, avoiding concentrated expansion stress and progressive spalling damage. Furthermore, the excellent tensile toughness of PVA fibers significantly improves the overall ductility and crack resistance of the matrix, optimizes the stress distribution of the interfacial transition zone (ITZ) between hydration gel and aggregate, alleviates interfacial debonding and micro-delamination under cyclic loading, and, ultimately, inhibits the cumulative freeze–thaw damage of solid waste-based lightweight soil. Therefore, comprehensive morphological and mechanical test results verified that the frost resistance of the three foamed lightweight soils followed the order: WS-P > WS-N > CN.

4.2. Water Immersion Durability

4.2.1. Appearance Variation Characteristics

The macroscopic morphological changes were recorded during the 120 d continuous water immersion test. Figure 7 shows the appearance changes under different water immersion durations. Throughout the test, all specimen groups maintained intact overall structural morphology, without severe cracking, peeling or structural collapse. Only minor surface mortar shedding and pore water permeation were observed, showing good water immersion adaptability.

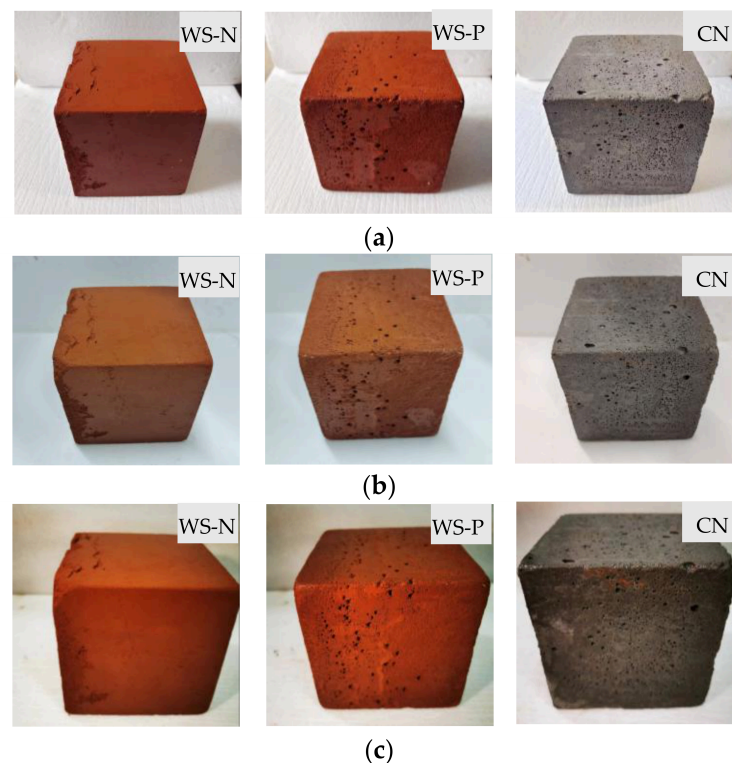


Figure 7. Appearance changes under different water immersion durations: (a) 30 days; (b) 60 days; (c) 120 days.

As illustrated in Figure 7, slight edge mortar peeling occurred in WS-N specimens after 30 days. For WS-P specimens, abundant surface pores were observed, which were attributed to the increased internal pore density induced by PVA fiber incorporation and slight non-uniform fiber dispersion during specimen preparation, forming connected pore channels between the matrix interior and the external environment. CN specimens presented a large number of fine inherent voids; the high initial pore density and relatively loose structure promoted inter-pore penetration under water pressure. With the extension of immersion time to 60 d and 120 d, no obvious aggravated damage was observed in all groups, and the structural integrity of each specimen was well maintained.

4.2.2. Mass Variation Law

Figure 8 shows the mass changes under different water immersion durations. The mass variation in all specimens exhibited a consistent evolutionary trend of rapid initial growth followed by gradually decelerated growth under long-term water immersion. After 120 d of continuous immersion, the mass growth rates of WS-P, WS-N, and CN specimens reached 27.65%, 23.89%, and 10.24%, respectively. Compared with the results of CN specimens, the standard deviations of mass for the two waste solid groups are very small,

less than 4 g during the whole test. The maximum standard deviation of mass for CN specimens is 14.7 g after 120 days of water immersion.

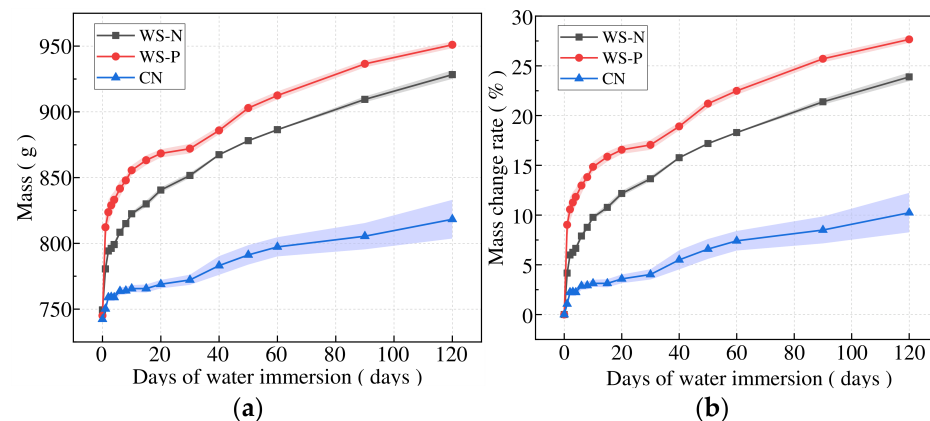


Figure 8. Mass evolution under different water immersion durations (mean $\pm$ standard deviation). (a) Mass; (b) rate of change in mass.

Statistical results verified that solid waste-based specimens exhibited significantly higher water absorption capacity than pure cement-based specimens, which is consistent with previous research findings in reference [16,17]. The fine granularity of red mud, mineral powder and fly ash endows the solid waste matrix with inherent high water absorption characteristics. Furthermore, the hydrophilic property of PVA fibers and the optimized connected pore structure further improve the water infiltration and retention capacity of WS-P specimens, resulting in the highest mass growth rate among all test groups.

4.2.3. Compressive Strength Evolution

The compressive strength of all foamed lightweight soil specimens increased to varying degrees with prolonged water immersion, and the strength growth of each group was mainly concentrated in the initial 28 d of immersion, followed by a stable state with negligible strength fluctuation. Nevertheless, significant differences in strength growth amplitude were observed among the three specimen groups, indicating distinct water stability performance.

As shown in Figure 9, CN specimens exhibited the most prominent strength enhancement under water immersion conditions. The compressive strength of CN specimens increased rapidly from 1.88 MPa to 2.73 MPa within the first 7 d of immersion, with a growth rate of 45.21%. The strength growth rate peaked within 28 d, contributing 97.1% of the total 120 d strength increment. After 120 d of immersion, the final strength growth rate of CN specimens reached 43.62%, demonstrating that the mechanical properties of pure cement-based lightweight soil are highly sensitive to long-term water immersion environments. During the whole test process, the maximum standard deviation of strength is 0.225 MPa for CN specimens after 90 days.

Overall, after the initial strength variation stage during water immersion, all three types of foamed lightweight soil exhibit favorable long-term water stability, which is consistent with the conclusions reported in the existing literature [32,33]. In comparison, solid waste-based composite specimens presented excellent mechanical stability under water immersion. The total strength growth rates of WS-N and WS-P specimens after 120 d of immersion were only 10.33% and 4.04%, respectively. The strength fluctuation amplitude of PVA-reinforced specimens was the smallest among all groups, reflecting superior long-term water immersion stability. During the whole test process, the maximum

standard deviation of strength was 0.24 MPa and 0.17 MPa, respectively, for WS-N after 7 days and WS-P after 90 days.

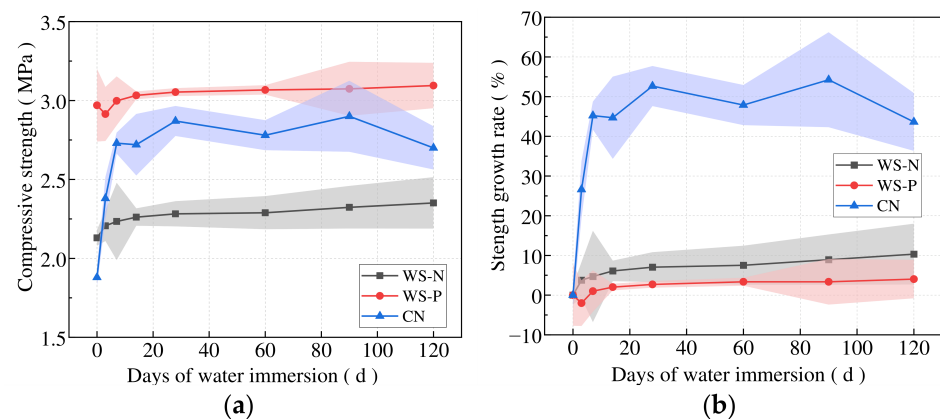


Figure 9. Compressive strength evolution under different water immersion durations (mean $\pm$ standard deviation). (a) Strength; (b) strength growth.

The differential strength variation laws are determined by the inherent hydration characteristics of different matrix materials. Pure cement-based materials retain abundant unhydrated cement clinker, and the long-term water environment continuously promotes secondary hydration reactions, thereby significantly improving matrix compactness and macroscopic strength. In contrast, the solid waste-based matrix completes sufficient alkali-activated hydration reactions during standard curing. The residual active components are limited, resulting in weak secondary hydration responses in long-term water environments and minimal mechanical performance variation. The incorporation of PVA fibers further optimizes the matrix structural stability, further reducing strength fluctuation under long-term immersion.

4.3. Sodium Sulfate Erosion Durability

4.3.1. Appearance Variation Characteristics

The macroscopic morphological damage and mass variation characteristics of CN, WS-N, and WS-P specimens under 120 d continuous sodium sulfate solution erosion were analyzed to evaluate the sulfate corrosion resistance.

As illustrated in Figure 10, slight edge and corner delamination occurred in both WS-N and WS-P specimens after 30 d of sulfate immersion, with more prominent surface peeling detected in WS-N specimens. WS-P specimens presented abundant fine surface pores, which originated from slight non-uniform fiber dispersion during specimen preparation. By comparison, CN specimens possessed more inherent interconnected pores and lower matrix compactness, showing poorer initial structural stability against sulfate erosion. With the extension of erosion duration to 60 d, no aggravated structural damage was observed in WS-N and WS-P specimens, which maintained intact macroscopic morphology. In contrast, CN specimens exhibited gradual edge delamination and structural loosening under continuous sulfate erosion. After 90 d of immersion, CN specimens suffered severe peripheral peeling and structural deterioration; the damage was further exacerbated at 120 d, forming a loose, highly porous and soft matrix with complete structural failure. Throughout the entire erosion process, WS-N and WS-P specimens only experienced minor surface peeling without structural deformation or penetrating cracks, retaining favorable structural integrity.

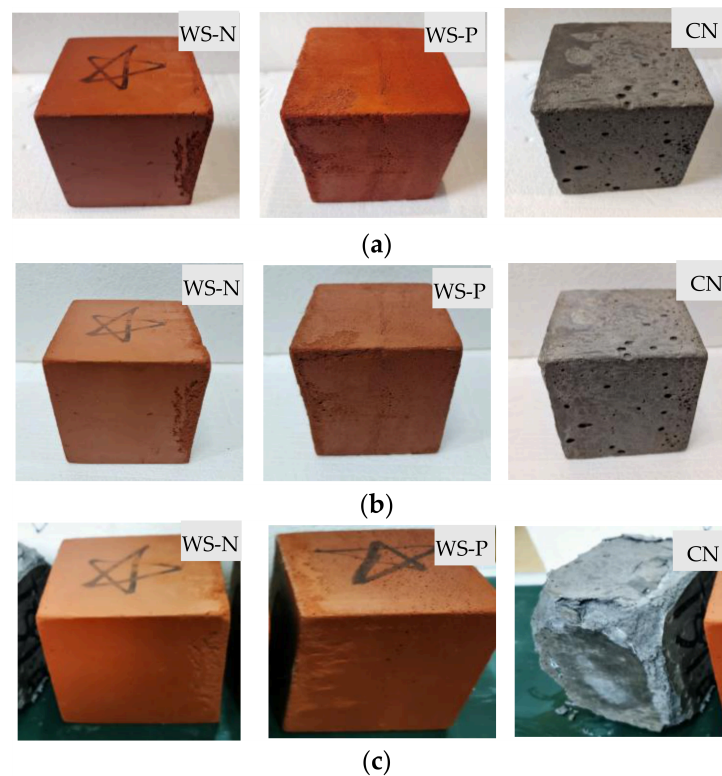


Figure 10. Appearance changes under different immersion durations of sodium sulfate solutions: (a) 30 days; (b) 60 days; (c) 120 days.

4.3.2. Mass Variation Law

All groups under sulfate erosion exhibited an overall upward trend in mass variation, just as the results found in other references [34,35]. As shown in Figure 11, for solid waste-based composite specimens, both WS-N and WS-P exhibited a unified trend of rapid initial mass growth followed by gradual stabilization. The mass growth of WS-N and WS-P specimens within the first 40 d accounted for 78.60% and 76.91% of the total 120 d mass increment, respectively. After 120 d of continuous sulfate erosion, the mass growth rate of WS-P specimens reached 28.74%, slightly higher than that of WS-N specimens (24.76%). Throughout the test, the standard deviation of mass remained relatively stable, 1~2 g for WS-N specimens, and 8~10 g for WS-P specimens. The higher water absorption of PVA fibers and the increased interconnected pores induced by fiber incorporation jointly promoted continuous solution infiltration and mass accumulation in WS-P specimens.

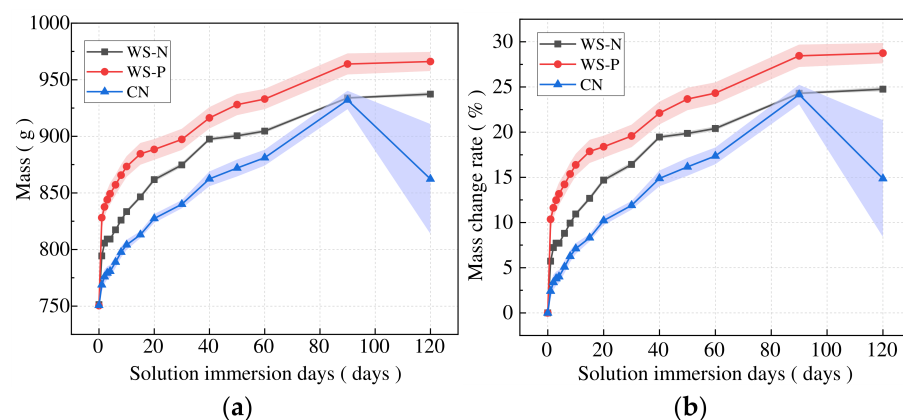


Figure 11. Mass evolution under different immersion durations of sodium sulfate solutions (mean $\pm$ standard deviation). (a) Mass; (b) rate of change in mass.

Differently, CN specimens presented a four-stage mass variation trend under sulfate erosion. A rapid mass increase was observed within 0–20 d due to intensive water absorption of the porous cement matrix. The mass growth slowed down during 20–60 d as the internal pores gradually reached water saturation. During 60–90 d, continuous sulfate erosion induced surface delamination and new pore generation, providing additional infiltration channels for the solution and triggering secondary rapid mass growth. After 90 d, large-area structural peeling and matrix collapse occurred in CN specimens. The mass loss caused by structural spalling far exceeded the mass increment from water absorption, resulting in a sharp mass decline and an abrupt rise in the standard deviation.

4.3.3. Compressive Strength Evolution

The compressive strength of WS-N and WS-P specimens exhibited a consistent trend of slight initial growth followed by long-term stability during 120 d of sulfate erosion (Figure 12). After 120 d of immersion, the mean compressive strength growth rates of WS-N and WS-P specimens reached 27.23% and 10.44%, respectively, indicating excellent mechanical performance stability under sulfate corrosion. The difference in growth ratio could be attributed to the micro-damages caused by the slight increase in pore connectivity for WS-P specimens. In contrast, CN specimens showed an opposite evolutionary trend. CN specimens reached a peak mean compressive strength of 2.63 MPa at 3 d (a growth rate of 39.89%) due to the early hydration product filling effect. Subsequently, continuous sulfate erosion induced internal expansion and microcrack propagation, leading to sustained strength degradation. After 120 d of erosion, CN specimens suffered severe matrix loosening and fragment detachment, and their residual compressive strength failed to be effectively measured, resulting in the absence of the last data point in Figure 12. During the whole test process, the maximum standard deviation of strength is 0.23 MPa, 0.26 MPa and 0.19 MPa, respectively, for WS-N after 60 days, WS-P after 90 days, and CN after 60 days.

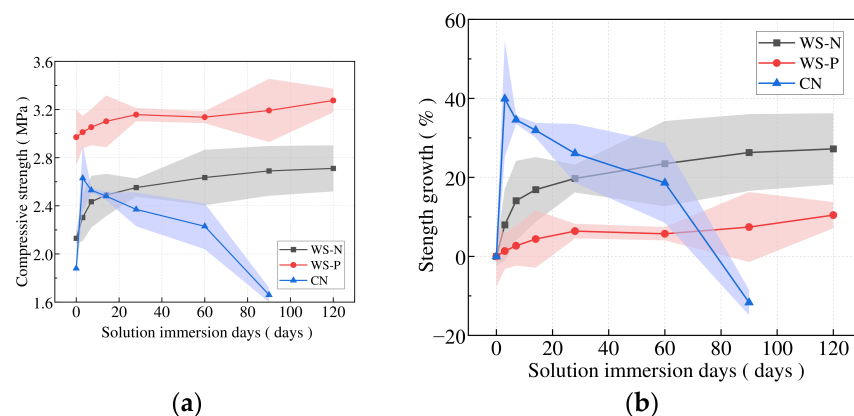


Figure 12. Compressive strength evolution under different immersion durations of sodium sulfate solutions (mean $\pm$ standard deviation). (a) Strength; (b) strength growth.

The differential performance evolution between WS and CN specimens is dominated by matrix hydration characteristics and pore structure differences. The alkali-activated solid waste matrix forms dense and stable hydration gel products in the early curing stage, with limited residual active components. The weak chemical reaction between the solid waste matrix and the sulfate solution avoids excessive expansion and cracking, thus maintaining stable mechanical performance. By contrast, pure cement-based materials undergo violent early hydration in sulfate solution, while the continuous generation of expansive erosion products induces internal structural damage, eventually leading to complete mechanical failure.

Under long-term sodium sulfate immersion, the synergistic evolution of pore structure permeability, interfacial transition zone deterioration and expansive secondary hydration products dominates the durability degradation of matrix materials. Numerous studies have revealed that sodium sulfate exposure induces typical chemical deterioration and expansion failure in cementitious and foamed lightweight materials. Hussain et al. [35] emphasized that sulfate ingress significantly alters hydration product composition and aggravates microstructural damage in porous cement-based composites, while Ranjani et al. [24] systematically clarified the sulfate erosion mechanism of foam concrete, confirming that secondary expansive products are the dominant cause of performance degradation under sulfate environments. Zhou et al. [36] found that a lower water–cement ratio contributes to better sulfate resistance of foamed concrete. Therefore, the cement-free alkali-activated solid waste matrix (WS-N and WS-P) undergoes thorough hydration during standard curing, leaving only a small quantity of unreacted active phases. This restricts the formation of expansive gypsum and alunite, effectively mitigating expansion-induced microcracking and structural deterioration.

Furthermore, the PVA fiber network can also effectively restrain the macroscopic expansion deformation caused by gypsum and alunite crystallization, block the penetration and expansion paths of erosion microcracks, and improve the integral structural toughness of the matrix. Nevertheless, the slight increase in pore connectivity introduced by fiber incorporation increases the permeability of the matrix, accelerating the inward diffusion of external sulfate ions, which promotes the generation of local micro-pores and micro-defects. This inherent competitive mechanism between fiber toughening advantage and interfacial permeability disadvantage leads to the relatively weaker sulfate resistance of PVA-reinforced (WS-P) specimens compared with unreinforced solid waste-based matrix (WS-N).

It should be noted that consistent with the results of the freeze–thaw test and water immersion test, WS-P specimens maintained the highest compressive strength and the lowest strength variation rate. This result indicates that the toughening and crack-resistance effect of the PVA fiber network is far greater than the negative impact of slight pore increase. Therefore, the overall durability of the material is significantly improved despite the increased partial porosity.

4.4. Comparison Between Water and Sulfate Immersion

4.4.1. Macroscopic Performance Comparison

To distinguish the differential effects of freshwater and sulfate corrosive environments on material performance evolution, the mass variation and compressive strength growth of all specimens under 120 d water immersion and sodium sulfate solution immersion were compared and analyzed in Figure 13.

The comparative results indicate that the mass growth amplitude of each specimen group under sulfate immersion was significantly higher than that under pure water immersion throughout the test cycle. For mechanical performance, both WS-N and WS-P specimens exhibited sustained higher compressive strength under sulfate erosion compared with freshwater immersion conditions. Similarly, CN specimens presented higher strength values in the early stage of sulfate immersion than in pure water environments. These macroscopic performance differences preliminarily verify that, apart from conventional water absorption-induced hydration reactions, additional chemical reactions occur within the foamed lightweight soil matrix in sulfate solution, generating new mineral products and further altering the physical and mechanical properties of the materials.

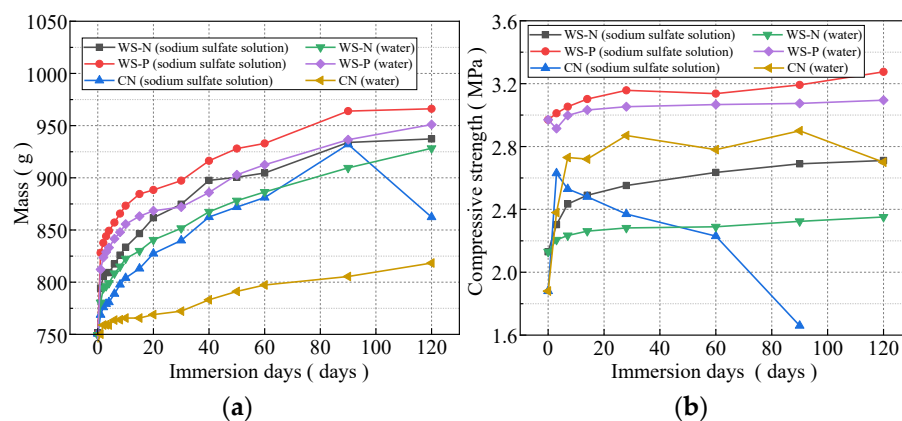


Figure 13. Comparison of mean mass and compressive strength after immersion in sodium sulfate solution versus clear water. (a) Mass; (b) strength.

4.4.2. Microscopic Morphology Analysis

Scanning electron microscopy (SEM) tests were conducted on 120 d water-immersed and sulfate-immersed specimens of CN, WS-N, and WS-P groups to reveal the microscopic mechanism causing macroscopic performance differences. As illustrated in Figure 14, obvious disparities in micro-morphology can be identified between samples soaked in pure water and those exposed to sulfate solution. All sulfate-eroded specimens produced abundant secondary crystalline hydration products dominated by gypsum and alunite, whose contents were markedly higher than those detected in freshwater-immersed counterparts.

When specimens are immersed in sodium sulfate solution, external sulfate ions react with reactive calcium and aluminum phases inside the matrix. For pure cement-based CN samples, calcium hydroxide and hydrated calcium silicate first react with SO_4^{2-} to form gypsum, which further combines with aluminate hydrates to generate expansive alunite crystals. The secondary expansive products sufficiently filled the internal matrix voids in the early immersion stage, densified the pore structure, and accounted for the rapid strength growth of cement-based lightweight soil in the early sulfate immersion stage. In contrast, WS-N and WS-P specimens generated only a small amount of secondary crystalline products after long-term sulfate immersion. The alkali-activated solid waste matrix already formed dense and stable hydration gels during curing, leaving limited reactive components for secondary chemical reactions with sulfate ions, thus avoiding expansion cracking damage.

In the late sulfate erosion stage, continuous accumulation of expansive alunite and gypsum crystals inside CN specimens induced matrix volume expansion and internal microcrack propagation, which destroyed the integrity of the pore wall structure and triggered continuous mechanical strength degradation. For WS-N and WS-P specimens, the limited generation of secondary products avoided expansion damage and structural deterioration, thereby maintaining stable strength evolution under long-term sulfate corrosive conditions. The microscopic results are highly consistent with the macroscopic mass and strength variation laws.

Overall, the macroscopic mass and strength variation laws of the three groups of specimens are essentially determined by their microscopic pore structure, interfacial transition zone characteristics, and hydration product composition. On the matrix side, the dense alkali-activated hydration gel formed by the fully solid waste system endows the material with inherent stable structural performance and fewer residual active phases, which effectively limits the accumulation of expansive secondary hydration products under erosion conditions. Furthermore, uniformly dispersed PVA fibers play a critical synergistic modification role in bridging microcracks, regulating pore structure, and improving

matrix toughness. The three-dimensional fiber network effectively spans and restricts the initiation and continuous propagation of microcracks, inhibiting macroscopic cracking and peeling. The combined effects of matrix structural optimization and PVA fiber toughening modification fundamentally account for the macroscopic performance differences and differentiated durability evolution characteristics among cement-based and fiber-reinforced solid waste-based material systems under harsh environments.

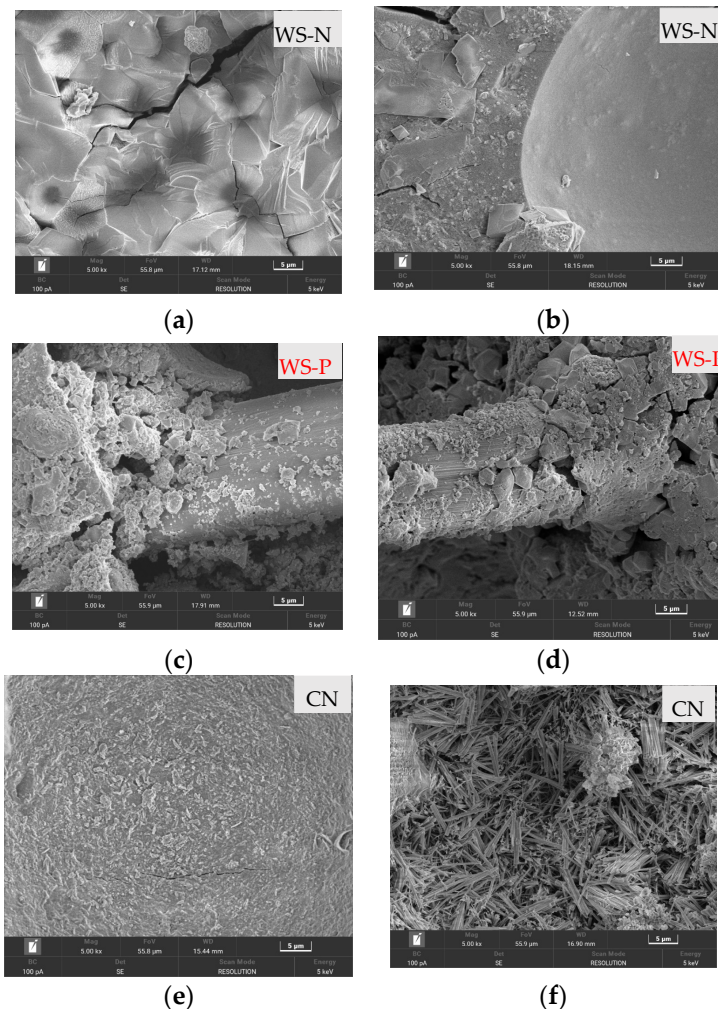


Figure 14. Microscopic morphology after immersion in clear water versus sodium sulfate solution. (a) WS-N after water immersion; (b) WS-N after sodium sulfate solution immersion; (c) WS-P after water immersion; (d) WS-P after sodium sulfate solution immersion; (e) CN after water immersion; (f) CN after sodium sulfate solution immersion.

5. Conclusions

This study adopts a high-proportion substitution strategy of ordinary Portland cement using three typical industrial solid wastes (red mud, fly ash, and slag) to prepare full solid waste-based foamed lightweight soil. This preparation technique significantly reduces cement consumption, realizes the resource recycling of bulk industrial by-products, and alleviates environmental problems caused by solid waste stacking. Meanwhile, it effectively cuts down the carbon emissions and energy consumption generated during cement production, fully conforming to the low-carbon, green and sustainable development concept of modern civil engineering. The prepared PVA-reinforced full solid waste-based composite material features low density, high structural toughness and outstanding environmental durability, which possesses broad application prospects in practical engineering. It can be

widely applied to road embankment filling, bridge approach backfill, railway subgrade reinforcement and soft foundation treatment, and can effectively reduce foundation load and mitigate uneven settlement of road and foundation structures.

In this study, the durability performance of pure cement-based, unreinforced full solid waste-based and PVA-reinforced full solid waste-based foamed lightweight soils was systematically investigated under three typical service environments, including freeze–thaw cycling, long-term water immersion, and sodium sulfate erosion. Combined with macroscopic performance tests and microscopic mechanism characterization tests, the core research findings are summarized as follows:

First, PVA fiber modification significantly improves the freeze–thaw durability of solid waste-based foamed lightweight soil. Uniformly dispersed PVA fibers construct a continuous three-dimensional toughening network inside the matrix, which exerts effective fiber bridging and crack resistance effects. The fiber network can effectively restrain the initiation and continuous propagation of frost heave-induced microcracks, relieve concentrated expansion stress inside pores, and maintain the structural integrity and mechanical stability of the matrix under cyclic freeze–thaw loading. Compared with unreinforced solid waste-based and pure cement-based specimens, PVA-reinforced composites exhibit the lowest mechanical attenuation after long-term freeze–thaw cycles.

Second, solid waste-based foamed lightweight soils possess excellent long-term water immersion stability, which far outperforms traditional cement-based materials. Benefiting from the dense alkali-activated gel microstructure formed during curing, solid waste-based matrices exhibit negligible secondary hydration response and minor mechanical fluctuation under continuous humid environments.

Third, distinct material adaptabilities to sulfate corrosive environments were identified among the tested specimens. Unreinforced solid waste-based foamed lightweight soil presents the optimal sulfate erosion resistance. Although PVA fiber incorporation effectively improves the freeze–thaw resistance and water stability of the matrix, the interfacial gaps between fibers and matrix introduce a certain number of interconnected pore channels, which increase matrix permeability and slightly weaken the sulfate erosion resistance of PVA-reinforced specimens. In contrast, cement-based lightweight soil suffers irreversible expansive damage and complete structural failure under long-term sulfate erosion, showing poor corrosion durability.

Fourth, the differential durability evolution of foamed lightweight soils is essentially governed by the generation and accumulation of secondary sulfate hydration products (gypsum and alunite). Excessive accumulation of expansive crystalline products induces expansion cracking and performance degradation of cement-based matrices, while the stable microstructure of solid waste-based materials limits secondary mineral generation and avoids erosion-induced structural deterioration. Furthermore, the incorporated PVA fibers exert prominent toughening and crack-bridging effects, effectively compensating for the inherent brittleness of the solid waste-based matrix and synergistically optimizing the multi-working-condition durability of the composite material.

Overall, this study verifies the excellent environmental durability and green engineering application value of PVA-reinforced full solid waste-based foamed lightweight soil. The research results provide a reliable experimental basis and theoretical support for the performance optimization and large-scale engineering application of low-carbon solid waste recycled filling materials in complex service environments.

Nevertheless, this study still has several limitations. First, the durability evaluation system is relatively single, and only three typical working conditions are explored. Other important durability indexes, such as chloride penetration resistance, acid erosion resistance, water absorption rate and water penetration depth, are not included in the current

research scope. Second, the microscopic mechanism analysis is limited to qualitative SEM morphological observation, lacking quantitative microscopic data support from EDS element analysis, XRD phase identification and MIP pore structure tests. Third, the test setting only contains 50 freeze–thaw cycles, which cannot clarify the ultra-long-cycle freeze–thaw damage evolution law of the material.

Future research can further supplement multiple durability tests to improve the comprehensive performance evaluation system of solid waste-based lightweight materials. Advanced microscopic characterization techniques will be adopted to quantitatively analyze the hydration product evolution and pore structure deterioration mechanism. Moreover, extended freeze–thaw cycle tests and field engineering verification tests will be carried out to optimize the optimal PVA fiber mixing ratio, clarify the long-term field service performance, and establish an accurate long-term performance degradation prediction model for the composite material.

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