

Article

Performance of Ferronickel Slag Powder Soil Cement under Freshwater Curing Conditions

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Abstract: Ferronickel slag is the solid waste slag produced by smelting nickel–iron alloy. After grinding ferronickel slag into powder, it has potential chemical activity. It can partially replace cement and reduce the amount of cement, and is conducive to environmental protection. The mechanical properties of soil cement were investigated through the compressive strength test and inter-split tensile test of ferronickel slag powder soil cement with different dosages. To further study the mechanism of ferronickel slag powder's action on soil cement microscopically, the microstructure of soil cement was analyzed by using a scanning electron microscope and nuclear magnetic resonance equipment. The results of the study show that the incorporation of ferronickel slag powder can enhance the compressive and tensile strength of soil cement. The best performance enhancement of ferronickel slag powder was achieved when it was doped with 45% of its mass. The hydration products of soil cement increased with the increase in the doping amount, but the excessive doping of ferronickel slag powder would lead to a weakening of the hydration reaction and a decrease in the strength of the soil cement. At the same time, ferronickel slag powder plays the role of filling the void of soil cement. With the increase in ferronickel slag powder, the large pores inside the soil cement are reduced and the structure is denser.

Keywords: ferronickel slag powder; soil cement; unconfined compressive strength; splitting tensile test; microstructure



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1. Introduction

Soil cement is made by mixing substances such as earth, cement, water, and external admixtures, and then solidifying them into shape. It has improved properties such as integrity, solidity, and water stability compared to the original soil [1]. In the field of construction materials, soil cement is a common and important material widely used in building structures and foundation works [2,3]. Soil cement has the advantages of locally sourced materials, flexible construction, low environmental impact, and reduced cement usage.

In recent years, with the growing demand for sustainable development and environmentally friendly materials, researchers have extensively studied the optimization and improvement of soil cement properties [4–6]. Industrial by-products such as slag and fly-ash have gained more attention as they promote sustainability and circularity in the construction industry [7]. In this context, incorporating industrial waste slag has become a prevalent method aimed at enhancing the performance of soil cement and achieving effective resource utilization. China annually produces approximately 40 million tons of ferronickel waste slag, accounting for about 20% of the total metallurgical waste slag output, making it the fourth largest smelting waste slag in the country, following mine slag, steel slag, and red mud [8,9].

Mineral powder is a commonly used mineral admixture with good chemical activity that helps to improve the properties of cementitious materials [10]. It can also be used as a replacement material for cement, thereby reducing the amount of cement used [11]. Ferronickel slag powder is potentially chemically active [12,13]; although it is chemically weaker than mineral powder, it can also be used as a mineral admixture and can be used to improve the mechanical properties and microstructure of soil cement [14,15]. Yang and lee et al. [16,17] incorporated ferronickel slag powder into cement mortar as a partial replacement for cement and discovered that an appropriate amount of ferronickel slag powder can enhance the strength of the mortar. Kim et al. [18] studied the role of ferronickel slag powder in the hydration process of cement, finding that ferronickel slag powder participates in the hydration reaction in the later stages, producing more hydration products. Wang et al. [19] investigated the influence of ferronickel slag powder on the concrete's resistance to sulfate attack when added to the mixture. Chen et al. [20] conducted a strength test on ferronickel slag powder soil cement, noting that the strength of the soil cement decreased with an increase in the slag powder content. By 28 d, the rate of strength reduction in the soil cement gradually decreased, and the microstructure became denser, with the soil cement primarily exhibiting brittle failure. Research by Huang et al. [21] indicated that using ferronickel slag powder to replace part of the cement reduced the total Ca/Si ratio of C-S-H gel, increased the polymerization of silicate chains, and enhanced the concrete's resistance to chloride ion penetration. Kim et al. [22] examined the use of three different fine-grained ferronickel slags as partial replacements for ordinary Portland cement as a binder. The results showed that using them as a binder could reduce microcracking, thereby reducing maintenance costs, and that the shear resistance of finer ferronickel slag powder was superior to that of coarser slag powder. Lin et al. [23] demonstrated that the addition of ferronickel slag can effectively improve the mortar's flowability and porosity, but excessive addition might lead to a decline in mechanical strength. Early mechanical grinding and steam curing can effectively activate the pozzolanic materials in the slag, enhancing the mortar's compressive strength and connectivity of the pores [8]. However, research on the hydration behavior and performance of ferronickel slag powder soil cement under different curing conditions are rarely seen.

Therefore, this study aims to explore the hydration behavior and performance of ferronickel slag powder soil cement under freshwater curing conditions. Through unconfined compression tests, splitting tensile tests, and microstructural analysis, it intends to deepen understanding of the impact mechanisms of ferronickel slag powder on soil cement properties, providing theoretical and practical guidance for optimizing the performance of soil cement.

2. Materials and Methods

2.1. Materials

The soil used in the experiment was sourced from the silt of a construction pit China, and characterized by a dark gray color, a moisture content of 58.6%, a unit weight of 16.32 kN/m³, a porosity ratio of 1.53, a liquid limit of 49%, and a plastic limit of 29.3%. The cement used was ordinary Portland cement (P.O 42.5), with its chemical composition detailed in Table 1. The water was purified tap water from Fuzhou and processed through a water purifier. The composite ferronickel slag powder was a blend of blast furnace ferronickel slag powder and granulated blast furnace ore powder. All of the above raw materials are sourced from Fuzhou City, Fujian Province, China.

Table 1. Chemical composition of cement.

Component	SO ₃	MgO	CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	f-CaO	Other	LOI
Mass Percentage (%)	2.89	2.05	62.55	21.69	4.38	3.34	0.57	0.84	1.59

Note: LOI refers to loss on ignition.

The mineral powder has good chemical activity. Ferronickel slag powder is potentially chemically active and inexpensive. They are economically efficient when mixed together and used as mineral admixtures. The mass ratio of blast furnace ferronickel slag powder to mineral powder was 2:1 [20]. For ease of reference, this composite material is hereinafter referred to as ferronickel slag powder, with its chemical composition presented in Table 2. The morphology and micro-morphology of the composite ferronickel slag powder are shown in Figure 1.

Table 2. Chemical composition of ferronickel slag powder.

Component	SiO ₂	Al ₂ O ₃	CaO	MgO	TiO ₂	MnO	Fe ₂ O ₃	SO ₃	LOI
Ferronickel Slag Powder (%)	35.82	21.46	29.22	9.46	0.78	0.57	1.33	0.16	2.43
Ore Powder (%)	32.00	16.81	36.12	10.59	0.93	0.9	2.29	0.14	0.16

Note: LOI refers to loss on ignition.

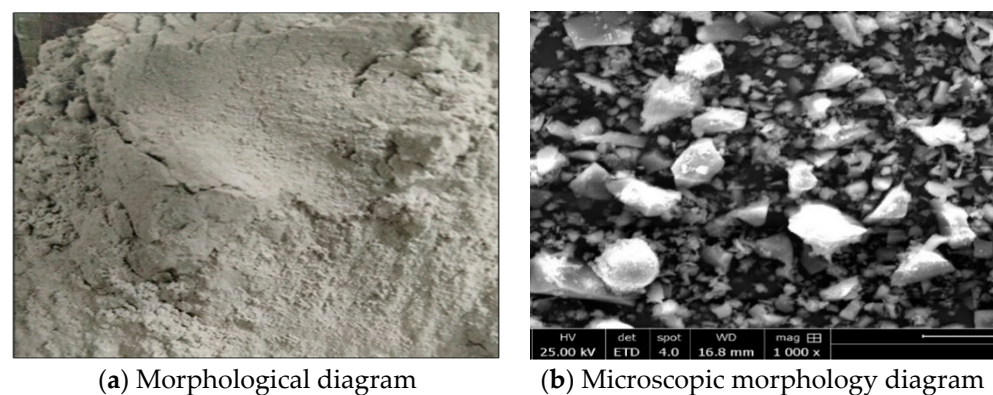


Figure 1. Morphology and microstructure of ferronickel slag powder composites.

2.2. Methods

2.2.1. Preparation of Ferronickel Slag Powder Soil Cement

The silt was first retrieved from the construction pit, air-dried, crushed, and then oven-dried for 24 h at 60 °C. Then, the dried silt chunks were milled in a ball mill for 360 s. The material was further sifted through sieves of 10 mm, 5 mm, and 2 mm, selecting the dry soil that passed through the 2 mm sieve. Non-compliant soil was stored in sealed bags for later use. Next, considering the original moisture content of 58.6%, wet soil was prepared by uniformly mixing the dry soil with a specific amount of purified water using a mortar mixer. The mixing process was divided into two stages, each lasting no less than three minutes, with manual intervention to ensure even mixing at the bottom. According to the design mix ratio, the appropriate amounts of purified water, cement, and ferronickel slag powder were weighed and blended in a clean mortar mixer to obtain a uniform cement slurry. This slurry was then combined with the wet soil and mixed thoroughly for no less than five minutes to produce the final soil cement slurry.

The test was conducted in accordance with the specific requirements of the Design Regulations for the Mix Proportion of Cement soil (JGJT233-2011) [24]. The size and number of soil cement specimens were set according to the requirements specified in the specification. The water used in the test process was purified pure water, which can effectively avoid the influence of corrosive substances such as Cl[−] in tap water on the test. The soil cement specimens were demolded after 24 h. They were soaked and maintained in pure water until the designed age. The room temperature of the standard curing room was 20 ± 3 °C.

After soaking in a freshwater environment, the surface of the ferronickel slag powder soil cement (Group A samples) appeared smooth and flat, maintaining good integrity and consistent apparent characteristics, as illustrated in Figure 2.

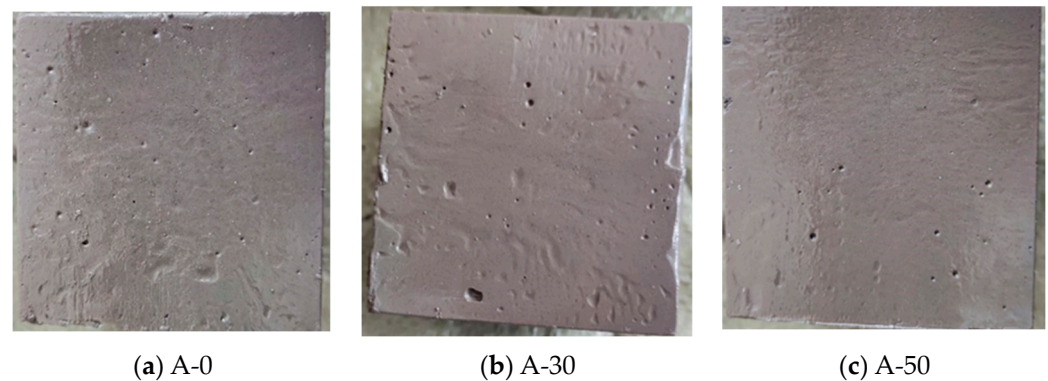


Figure 2. Erosion appearance of soil cement in a 28-day freshwater environment.

2.2.2. Unconfined Compression Test

The primary objective of the unconfined compressive test was to investigate the effect of ferronickel slag powder content and age on the compressive strength and damage state of soil cement. The water-to-cement ratio was set at 0.5, with a cement content of 15%. The experimental scheme is outlined in Table 3.

Table 3. Unconfined compression test scheme.

No.	Cement Content (%)	Water/Cement Ratio	Ferronickel Slag Powder Mass Replacement Ratio (%)	Number of Specimens	
				7 d	28 d
A-0	15	0.5	freshwater	3	3
A-10			freshwater	3	3
A-20			freshwater	3	3
A-30			freshwater	3	3
A-40			freshwater	3	3
A-50			freshwater	3	3
A-60			freshwater	3	3

Note: In the mix ratio code A-10, A refers to the freshwater soaking environment, 10 to the 10% ferronickel slag powder content.

2.2.3. Splitting Tensile Test

This experiment was conducted with a maturation period of 28 days, during which the water-to-cement ratio, cement incorporation ratio, and admixture content, as well as the curing conditions, were consistent with those in the unconfined compression test. Test samples with 0%, 30%, 45%, and 60% of nickel–iron slag powder admixture were selected for the study. The detailed test scheme for the soil cement is shown in Table 3.

2.2.4. Scanning Electron Microscope

Scanning electron microscopy (SEM) tests using a QUANTA250 multifunctional tungsten filament scanning electron microscope were performed to compare and analyze the microstructure of soil cement. This scanning electron microscope is manufactured by FEI Company of Hillsboro, OR, USA. The primary purpose of the SEM test was to study the effect of different ferronickel slag powder contents on the pore structure within the soil cement after 28 days of curing. Samples with 0%, 30%, 45%, and 60% ferronickel slag powder content were selected for this study. The detailed experimental scheme is outlined in Table 3.

2.2.5. Nuclear Magnetic Resonance

The model of the Nuclear Magnetic Resonance (NMR) analyzer used for the test was the MesoMR12-060H-I. This NMR analyzer is manufactured by Suzhou Neumay Analytical Instruments, Inc. in Suzhou, China. The NMR test aimed to explore the impact of different

ferronickel slag powder contents, the number of wet–dry cycles, and the number of load cycles on the internal pore structure of the soil cement. For the scenarios with 0%, 30%, 45%, and 60% ferronickel slag powder content, the effects on the soil cement’s pore structure were analyzed after 28 days of curing in a freshwater environment. Specifically, under the condition of a 45% ferronickel slag powder content, four levels of wet–dry cycles (0, 6, 12, and 18 times) and four levels of load cycles (0, 3000, 6000, and 9000 times) were designed. The experiment compared and analyzed the influence of the number of wet–dry cycles and load cycles on the size and quantity of pores in the ferronickel slag powder soil cement. The water-to-cement ratio, cement incorporation ratio, and admixture content in this test were kept consistent with the unconfined compression test. The specific experimental scheme is depicted in Table 4.

Table 4. NMR test scheme.

Test	Ferronickel Slag Powder Content				Number of Wet–Dry Cycles				Number of Load Cycles			
	0%	30%	45%	60%	0 Cycle	6 Cycles	12 Cycles	18 Cycles	0 Cycle	3000 Cycles	6000 Cycles	9000 Cycles
Test Variables												

3. Results and Discussion

3.1. Compressive Strength

Based on the experimental data, the relationship curve between the unconfined compressive strength of ferronickel slag powder soil cement at 7 d and 28 d, and different contents of ferronickel slag powder was plotted, as shown in Figure 3. The sequential growth rate of the soil cement’s compressive strength was calculated and is shown in Table 5.

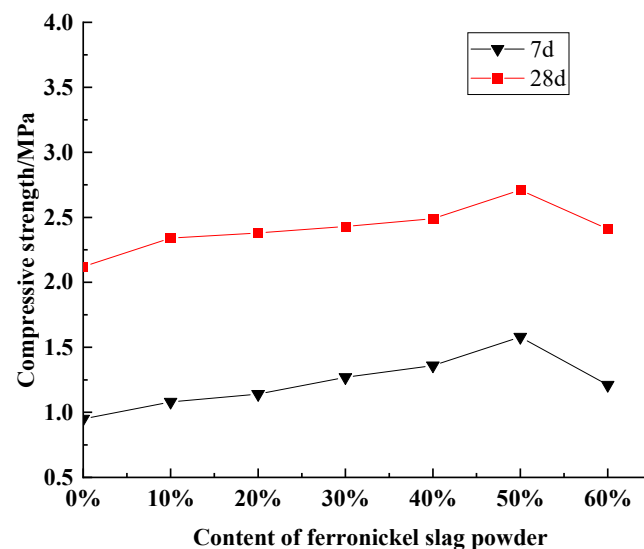


Figure 3. Relationship curve between compressive strength of soil cement and ferronickel slag powder content in freshwater environment.

Table 5. Sequential growth rate of compressive strength of ferronickel slag powder soil cement.

Sequential Growth Rate	Age	
	7 d	28 d
A-10 compared with A-0	13.68%	10.38%
A-20 compared with A-10	5.56%	1.71%
A-30 compared with A-20	11.40%	2.10%
A-40 compared with A-30	7.09%	2.47%
A-50 compared with A-40	16.18%	8.84%
A-60 compared with A-50	−23.42%	−11.07%

From the analysis of Figure 3 and Table 5, the following patterns regarding the impact of ferronickel slag powder content on the strength enhancement of soil cement were identified:

(1) As indicated in Figure 3, the compressive strength of soil cement cured in freshwater at 7 d exhibits an initial increase followed by a decrease with the rising content of ferronickel slag powder. Specifically, when the ferronickel slag powder content is less than 50%, the compressive strength of the soil cement increases with the addition of slag powder. However, beyond a 50% inclusion rate, the compressive strength begins to fall. This suggests that, while ferronickel slag powder contributes to the enhancement of compressive strength, there is a threshold beyond which additional content is counterproductive. In fact, an optimal content exists, identified as 50%. At this stage, with a relatively short curing period, the reactivity of the ferronickel slag powder is not fully activated, with only a portion exhibiting activity akin to the hydration reaction of cement [2]. That aside, excessive ferronickel slag powder would lead to a reduction in cement content and, consequently, a decrease in cement hydration products. Therefore, when the ferronickel slag powder content exceeds 50%, the compressive strength diminishes. According to the Technical Specification for Application of Slag Powder Used for Cement Products (JC/T2238-2014) [25], the maximum permissible limit for replacing cement with ferronickel slag powder in experiments is 45%. Hence, the optimal content for ferronickel slag powder soil cement is determined to be 45%, at which the 7-day compressive strength meets the 1 MPa requirement in the Technical Specifications for Highway Engineering Inorganic Binding Stabilized Materials.

(2) As depicted in Figure 3, for the 28 d curing period, the trend of the compressive strength curve of soil cement cured in a freshwater environment aligns with that observed at 7 d. The compressive strength initially increases and then decreases with the rising content of ferronickel slag powder. The strength of the soil cement increases with the addition of slag powder up to 50% content, after which it begins to decline as the content exceeds 50%. This indicates that, while the incorporation of ferronickel slag powder enhances the compressive strength of soil cement, there is a limit beyond which additional content is detrimental, possibly leading to a decrease in compressive strength or even failure to form. Hence, an optimal content value exists, identified as 50%, which is consistent with the optimal value found for the 7 d curing period.

From Table 5, under freshwater curing conditions, the sequential growth rates of compressive strength for the six 28 d groups are 10.38%, 1.71%, 2.10%, 2.47%, 8.84%, and −11.07%, respectively. Except for Group A-60, which has a negative sequential growth rate, all other groups show positive growth rates, aligning with the 28 d curing period's compressive strength curve pattern. Compared with 7 d, 28 d's compressive strength growth rates exhibit a certain pattern. Group A-10 shows the highest growth rate, indicating that the addition of ferronickel slag powder is beneficial for enhancing the compressive strength of soil cement. For Groups A-20 to A-60, the growth rates initially increase and then decrease with increasing content. The maximum growth rate at a 50% content confirms that soil cement has the highest compressive strength when the ferronickel slag powder content is 50%. This is because, after 28 days of curing, most of the cement's hydration reaction has happened, and the OH^- produced from the hydration reaction activates the reactivity of the ferronickel slag powder in the soil cement, leading to a hydration-like reaction that generates products conducive to enhancing compressive strength. Therefore, the addition of ferronickel slag powder is advantageous for improving the compressive strength of soil cement. According to regulatory requirements, the maximum permissible limit for replacing cement with ferronickel slag powder in experiments is 45%, hence selecting the optimal content for ferronickel slag powder soil cement as 45%.

3.2. Tensile Strength

Based on the experimental design, splitting tensile strength tests were conducted on three ferronickel slag powder soil cement samples with different slag contents, and the results were calculated, as shown in Table 6.

Table 6. Tensile strength of ferronickel slag powder soil cement at different ages.

No.	A-0	A-30	A-45	A-60
Tensile Strength (MPa)	0.30	0.32	0.38	0.31

Table 6 indicates that the tensile strengths of the four groups of soil cement with different ferronickel slag powder contents are 0.30 MPa, 0.32 MPa, 0.38 MPa, and 0.31 MPa, respectively. The tensile strength of A-30 is 7.25% higher than A-0, A-45 is 15.64% higher than A-30, and A-60 is 15.85% lower than A-45. This shows that incorporating ferronickel slag powder into soil cement enhances its tensile strength. This enhancement is attributed to the full hydration reaction within the 28 d ferronickel slag powder soil cement, where the activated slag powder not only improves its compressive strength but also enhances tensile strength.

However, excessive inclusion of ferronickel slag powder is detrimental to the tensile strength of soil cement. When excessive slag is added, the cement hydration reaction is weakened, and some ferronickel slag powder remains inactivated, merely serving as a micro-aggregate filler without triggering pozzolanic reactions, thus failing to enhance the tensile strength of the soil cement. Therefore, there is an optimal content of ferronickel slag powder for enhancing strength, that is 45%, aligning with the optimal value for compressive strength at 28 d.

Relationship between Tensile Strength and Compressive Strength

Based on the experimental results of the compressive and tensile strengths of ferronickel slag powder soil cement at 28 d, the relationship between the tensile strength (q_u) and compressive strength (f_u) of the samples with different contents of ferronickel slag powder is illustrated in Table 7.

Table 7. Ratio of compressive strength (q_u) to tensile strength (r_t) of ferronickel slag powder.

No.	A-0	A-30	A-45	A-60
q_u (MPa)	2.12	2.43	2.60	2.41
R_t (MPa)	0.30	0.32	0.38	0.31
q_u/R_t	7.00	7.48	6.93	7.63

Table 7 reveals a certain proportional relationship between the tensile strength (R_t) and compressive strength (q_u) of ferronickel slag powder soil cement at 28 d. Under freshwater conditions, the ratio of compressive strength (q_u) to tensile strength (R_t) for the four different slag contents ranges between 7.00, 7.48, 6.93, and 7.63, with the ratio falling within the range of 7 to 8. In marine environments, the corresponding ratios are 6.37, 7.22, 6.95, and 7.60, with the ratio ranging between 6 to 8. This indicates no major difference between the ratios of compressive strength (q_u) to tensile strength (R_t) in freshwater and marine environments, with q_u being approximately 6 to 8 times R_t .

3.3. Stress–Strain Relationship of Ferronickel Slag Powder Soil Cement

The stress–strain relationship curve includes two stages: pre-failure and post-failure. It represents the correlation between stress and strain experienced by soil cement under load. Stress and strain were obtained by compression test testing. Within the optimal range of ferronickel slag powder content, an analysis was conducted on the 28 d samples with 0%, 30%, and 45% ferronickel slag powder content, as illustrated in Figure 4.

Figure 4 reveals that, as the ferronickel slag powder content increases, the failure strain of the soil cement also rises, with A-0, A-30, and A-45 showing failure strains of 1.32%, 1.55%, and 1.98%, respectively. The failure strain for A-30 is 0.23% higher than A-0, an increase of 17.4%, and A-45 is 0.43% higher than A-30, an increase of 27%. This indicates that incorporating ferronickel slag powder into soil cement enhances its plasticity

to a certain extent. At 28 d, the slag powder does more than act as a micro-aggregate filler; its reactivity is also activated, initiating a hydration reaction similar to cement, which generates products that improve the mechanical properties of the soil cement.

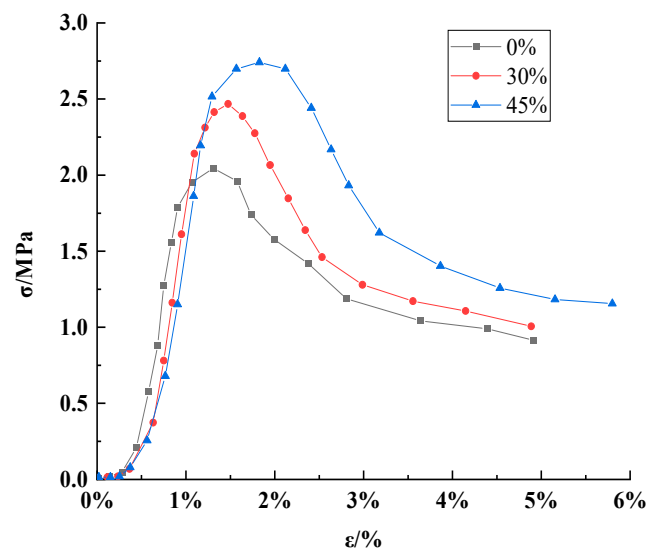


Figure 4. Stress–strain curve of ferronickel slag powder soil cement in freshwater environment.

Damage State

There are primarily two types of failure observed in ferronickel slag powder soil cement: brittle failure and plastic failure. At 7 d, ferronickel slag powder soil cement predominantly exhibits plastic failure. This is because the cement's hydration reaction is incomplete at this early age, the slag powder's reactivity is not activated, and it mainly serves as a filler, making the failure characteristics of the soil cement more akin to those of soft soil. At 28 d, with complete hydration reactions and activated slag reactivity, the failure characteristics of ferronickel slag powder soil cement are more distinctly aligned with brittle failure. The failure specimens of ferronickel slag powder soil cement at this stage are shown in Figure 5.

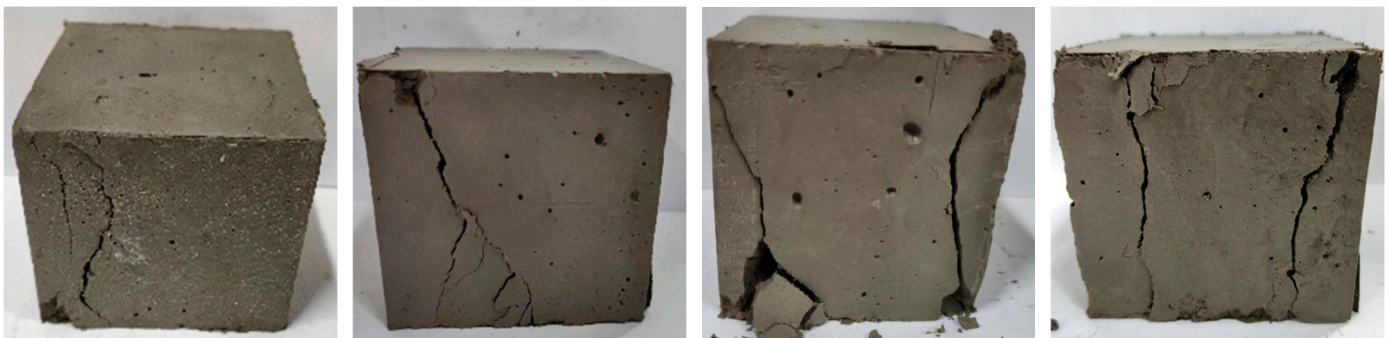


Figure 5. Failure characteristics of ferronickel slag powder soil cement at 28 d in freshwater environment.

3.4. Scanning Electron Microscopy

In this section, Scanning Electron Microscopy (SEM) was utilized to analyze the microstructure, hydration products, and internal pore structure of ferronickel slag powder soil cement in both freshwater and seawater environments. This analysis further elucidates the mechanism by which the incorporation of a certain amount of ferronickel slag powder affects the strength of soil cement. SEM images of ferronickel slag powder soil cement with different contents and under different curing conditions are presented in Figure 6.

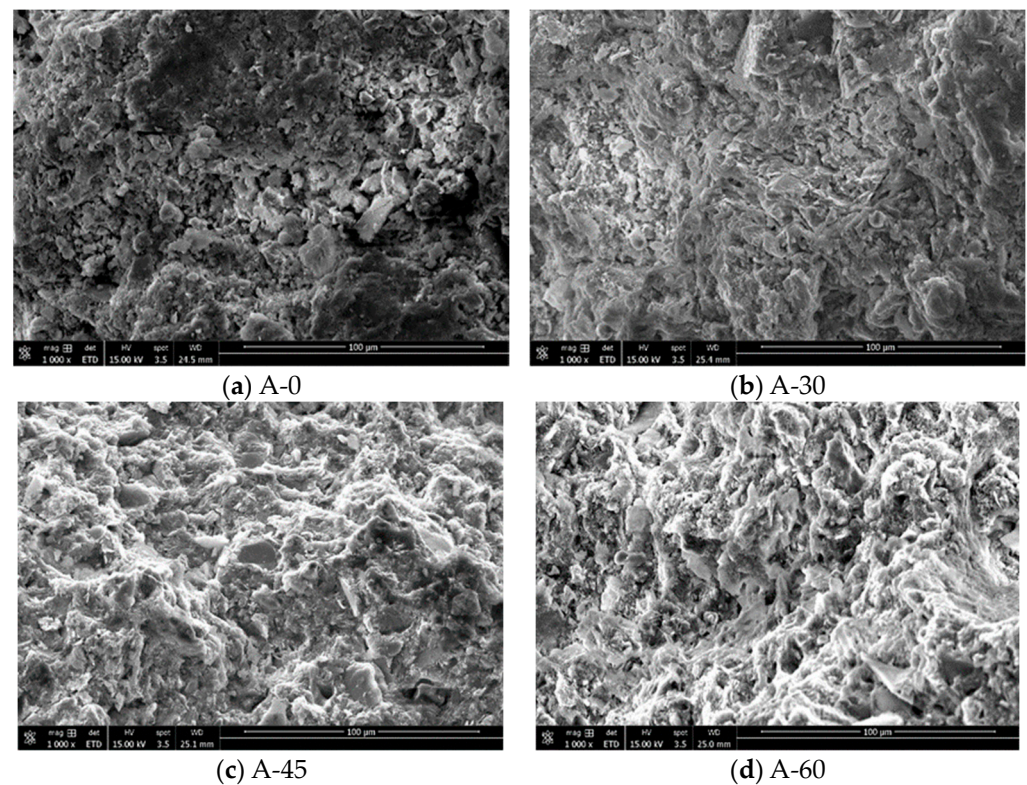
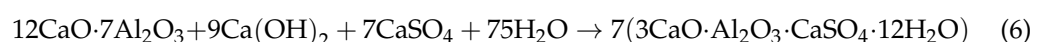
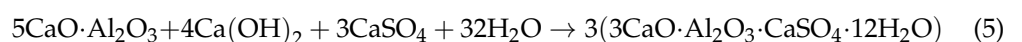
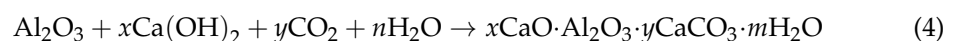
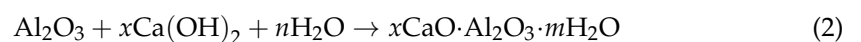


Figure 6. The 28 d morphology of soil cement in freshwater environment.

From Figure 6, at 28 d in a freshwater environment, the primary hydration product in soil cement is the C-S-H gel. The chemical composition of C-S-H gel is variable and lacks a specific morphological characteristic, making it an amorphous phase. The C-S-H gel binds the soil particles and ferronickel slag powder together, solidifying into a cohesive whole. The reference group A-0, without ferronickel slag powder, shows fewer hydration products and more inter-particle pores, resulting in lower compactness of the soil cement structure. With the addition of ferronickel slag powder, the quantity of hydration products in the soil cement increases, reducing the inter-particle porosity and making the soil cement denser. The compactness of A-45 is superior to A-35 and A-60, with minimal difference between A-35 and A-60. This is due to the complex hydration reactions occurring when the silicate cement in soil cement comes into contact with water. The main hydration products include C-S-H gel, $\text{Ca}(\text{OH})_2$ crystals (as shown in Figure 7b), and ettringite AFt (as shown in Figure 7a), which continuously fill the internal pores until the cement soil matrix sets and hardens into a stable structure [26,27]. The produced $\text{Ca}(\text{OH})_2$ dissolves, creating an alkaline environment that can activate the reactivity of the vitreous phase (SiO_2 , Al_2O_3 , Fe_2O_3 , etc.) in the ferronickel slag powder, inducing a cement-like hydration reaction. This process is referred to as the pozzolanic activity of the ferronickel slag powder [18,28], as indicated in the following reactions:



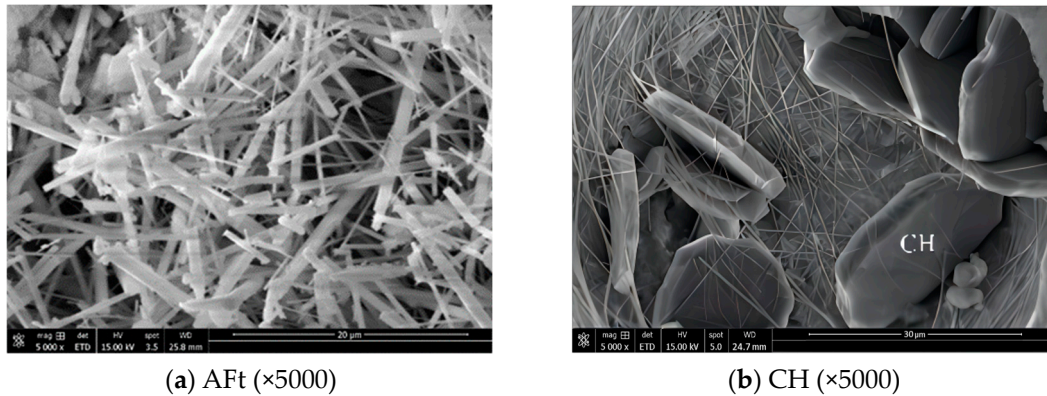


Figure 7. Morphology of different hydration products at 28 d.

From the above chemical reaction mechanisms, it is evident that the pozzolanic effect of ferronickel slag powder is similar to the hydration reaction of cement. During this process, ferronickel slag powder not only serves as a micro-aggregate filler but its hydration products also bind soil particles and ferronickel slag powder particles together, forming a cohesive whole. This effectively fills the internal structural pores of the soil cement, thereby enhancing its compactness. This also elucidates why the strength of soil cement increases with the incorporation of ferronickel slag powder. However, an excessive addition of ferronickel slag powder reduces the cement hydration products, preventing the effective activation of the vitreous phase of the slag powder. For instance, the compactness of the soil cement sample A-60 is slightly inferior to that of A-45, explaining why the strength of A-45 is superior to that of A-60.

3.5. NMR

3.5.1. Characteristic Analysis of Magnetic Resonance T_2 Curve

To study the impact of different ferronickel slag powder contents and marine environments on the internal pores of soil cement, T_2 distribution curves were measured for A-0, A-30, A-45, and A-60 in a freshwater environment, as shown in Figure 8. The characteristic values of the T_2 distribution curves are presented in Table 8.

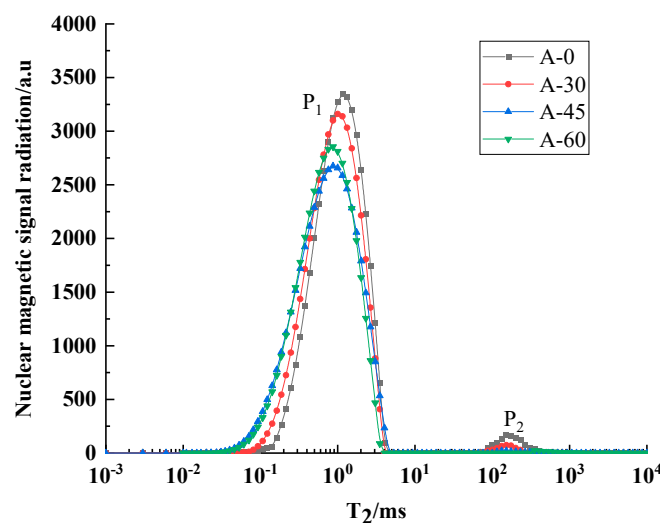


Figure 8. T_2 Distribution curves of ferronickel slag powder soil cement in freshwater environment.

Table 8. T₂ Distribution curves of ferronickel slag powder soil cement in freshwater.

No.	A-0	A-30	A-45	A-60
Peak Area	44,676	43,755	42,911	43,396
Peak T ₂ Value	1.20	1.08	0.85	0.93

In Figure 8, the T₂ distribution curve for sample A-0 exhibits a bimodal distribution with a major peak P₁ and a minor peak P₂, where the integrated area of P₁ is significantly larger than that of P₂. The T₂ value corresponding to P₂ is greater than that for P₁, indicating a less continuous internal pore distribution in A-0. With the addition of ferronickel slag powder, the T₂ distribution curves for A-30, A-45, and A-60 transition to a unimodal distribution, suggesting a more continuous pore size distribution in these samples compared with A-0.

As indicated in Table 8 and Figure 8, the peak T₂ values for A-0, A-30, and A-45 are 1.2 ms, 1.08 ms, and 0.85 ms, respectively. The starting point of T₂ progressively shifts leftward, with no significant change in the endpoint values. The peak signal amplitude decreases, suggesting that, with increasing ferronickel slag powder content, larger pores transform into smaller ones, increasing the number of small pores while reducing larger ones. The peak integral areas for A-0, A-30, and A-45 are 44676, 43755, and 42911, respectively, decreasing as the ferronickel slag content increases, indicating a reduction in the number and overall volume of pores. This reduction is attributed to the hydration reaction of cement at 28 d, where hydration products fill larger pores. The generated Ca(OH)₂ activates the ferronickel slag powder's reactivity, causing a similar hydration reaction, with the resulting substances further filling larger pores and making the soil cement structure denser. However, excessive ferronickel slag powder reduces the hydration reaction of cement, leading to fewer hydration products and incomplete activation of the slag powder's reactivity. This insufficiency in filling the pores between soil particles and ferronickel slag powder increases larger pores, as evidenced in A-60, where the peak T₂ value, peak integral area, and peak signal amplitude are all higher than in A-45, indicating poorer internal compactness in A-60 compared with A-45, consistent with their relative strength patterns.

3.5.2. Magnetic Resonance Imaging Analysis

Magnetic resonance imaging was employed to directly observe the number and size distribution of pores in ferronickel slag powder soil cement [29]. To analyze the effect of ferronickel slag powder content on the internal pores of soil cement in freshwater more intuitively, the grayscale values were processed to produce clearer pseudocolor images (as shown in Figure 9), which were then analyzed in conjunction with the soil cement's porosity (as shown in Table 9).

Table 9. Porosity of ferronickel slag powder soil cement with different contents.

No.	A-0	A-30	A-45	A-60
Porosity (%)	45.42	44.72	42.15	46.02

In the pseudocolor images, the bright rectangular area at the center represents the imaging result of the specimen, while the surrounding deep blue area denotes the non-specimen region. The pixels and bright areas in the image represent pores and cracks filled with fluid (water). The denser and brighter the pixels, the more water there is in the pores and cracks, indicating a higher number and larger volume of pores [30,31]. From Figure 9, it is apparent that A-0 contains a greater number of pixels and brighter areas, with localized clusters of dense pixels forming bright spots and poor uniformity, suggesting water accumulation in larger pores. With increased ferronickel slag powder content, the number of pixels in A-30 decreases, and the bright spots in the image also reduce compared with A-0, indicating that larger pores are being filled with hydration products. Compared with the first two groups, A-45 has fewer pixels and a relatively dimmer color but with

a more uniform distribution, indicating that the soil cement's interior is dominated by smaller pores, resulting in a uniform and dense state with better integrity. With the excessive inclusion of ferronickel slag powder, A-60 shows an increase in pixel count and clustering, with poor uniformity, indicating a rise in the number of large pores.

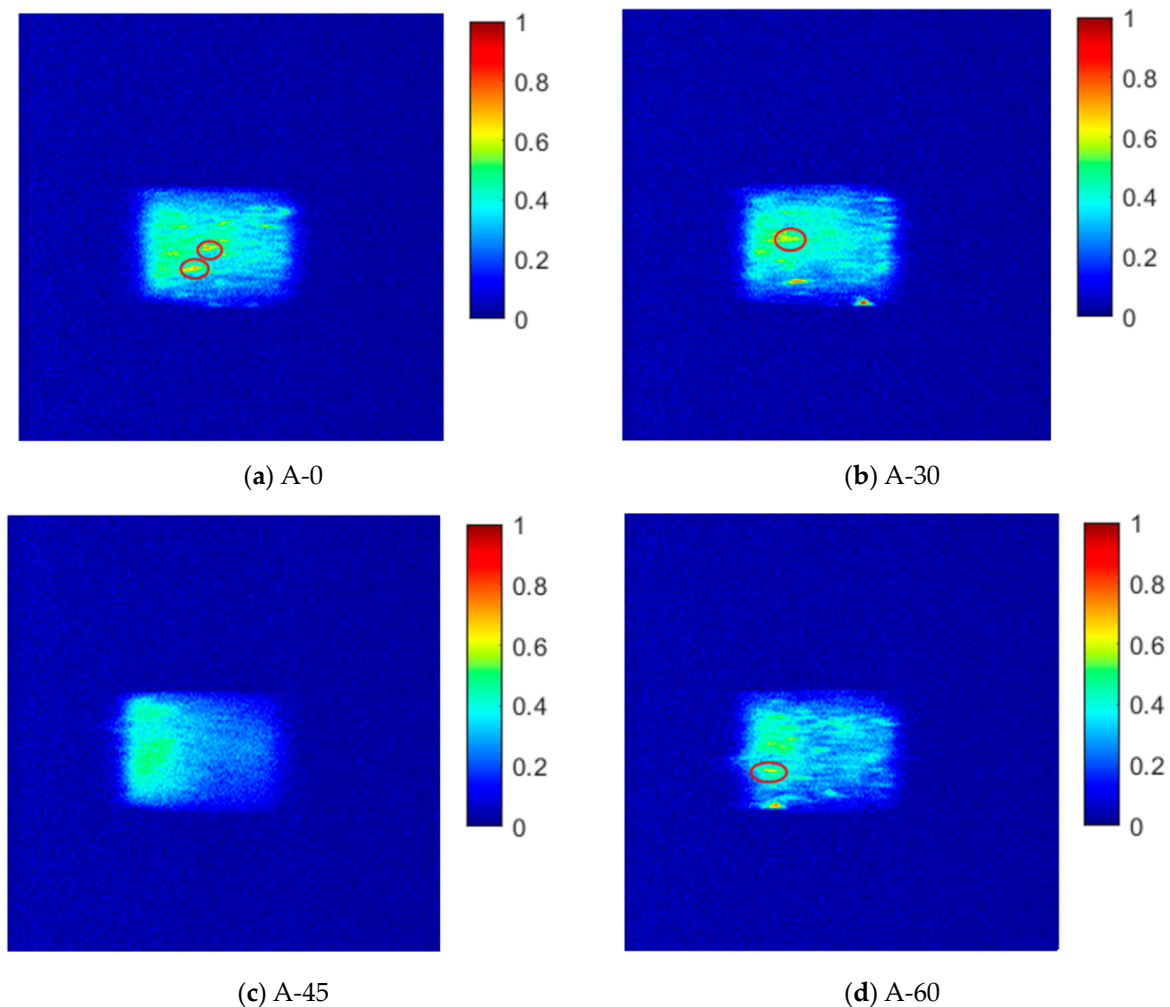


Figure 9. Pseudocolor magnetic resonance imaging of ferronickel slag powder soil cement in a freshwater environment.

According to Table 9, the porosity rates for A-0, A-30, A-45, and A-60 are 45.42%, 44.72%, 42.15%, and 46.02%, respectively, consistent with the changes observed in the pore structures in the magnetic resonance images.

4. Conclusions

This study investigated the effects of different ferronickel slag powder contents on the compressive and tensile strengths, as well as the internal pore structure of soil cement in a freshwater curing environment, through unconfined compression tests, splitting tensile tests, and microscopic examinations. The specific conclusions are as follows:

(1) The unconfined compression test indicates that the inclusion of ferronickel slag powder in soil cement enhances its compressive strength. The compressive strength first increases with the slag content up to a certain point and then decreases, reaching a maximum at a 50% inclusion rate. However, as per relevant regulations, the ferronickel slag powder content should not exceed 45%, making the optimal content 45%.

(2) The splitting tensile test indicates that the incorporation of ferronickel slag powder into soil cement enhances its tensile strength. The tensile strength increases with the slag content, peaks, and then decreases, with the optimal ferronickel slag powder content being

45%. The compressive strength is approximately six to eight times the tensile strength, primarily exhibiting brittle failure.

(3) SEM analysis reveals that the primary hydration products within soil cement are C-S-H gels, which increase with the addition of slag up to a point and then decrease. At 28 d, the ferronickel slag powder begins to exhibit its pozzolanic effect, undergoing a hydration-like reaction. The reaction products not only encapsulate and bind soil particles but also react with SO_2^{4-} and Cl^- . However, excessive inclusion of ferronickel slag powder (resulting in insufficient cement content) weakens the hydration reaction, inhibiting full activation of its reactivity and leading to a reduction in soil cement strength.

(4) Analysis of the T_2 distribution curves of soil cement with different ferronickel slag powder contents shows that, as the slag content increases, the peak amplitude of the T_2 distribution curve, the peak T_2 value, and the peak integral area progressively decrease, transitioning from a bimodal to a unimodal distribution. This indicates a transformation from larger to smaller internal pores in the soil cement, a reduction in total pore volume, and a denser structure.

(5) In the pseudocolor magnetic resonance imaging, as the ferronickel slag powder content increases, there is a gradual reduction in pixel count and pixel clustering, with brightness diminishing and pixel distribution becoming more uniform. This suggests a decrease in larger internal pores and an increase in smaller ones, enhancing the continuity in pore size distribution within the soil cement.

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