

Research Article

Impermeability Characteristics of Treated Marine Soft Soil with Ferronickel Slag Powder

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In order to study the law of evolution of erosion time on the impermeability of soil-cement in the marine environment, permeability tests, X-ray diffraction (XRD) tests, and scanning electron microscopy (SEM) tests were conducted on ferronickel slag powder (FSP) soil-cement. The changes in the permeability properties of the soil-cement under different soaking age conditions were investigated. The results show that the marine environment has little influence on the impermeability of soil-cement at an early age, and that their permeability coefficient is essentially identical to that of clear water. The impermeability of soil-cement in the marine environment decreases significantly after 28 days, and it continues to decrease with age. However, the deterioration in impermeability of soil-cement caused by the marine environment can be alleviated after FSP is added to the soil-cement, and a better mixing value of 40% is obtained. At the same time, the regression curve equation of the permeability coefficient of soil-cement with the change of age is established. FSP exerts a microaggregate effect and chemical activity in the soil-cement. It not only improves the compactness of the soil-cement matrix but also prevents the penetration of corrosive ions into the soil-cement, thereby improving the impermeability of the soil-cement.

1. Introduction

Construction projects are being implemented worldwide for urban development, and coastal areas have been used for engineering construction [1, 2]. Marine clay, which usually exists in offshore areas, has a high level of uncertainty in its properties and is considered a problematic soil [3–5]. Pakir et al. [6] showed that marine clay exhibited weak physical and mechanical properties, making it unsuitable to even bear its self-weight. Thus, the mechanical properties of marine clay should be improved for the land demands. The soft soil can be stabilized by compaction [7], chemical [8, 9], electro-kinetically applications [10], bacteria [11], and hydrological processes. Research studies indicated that the soil-cement is the effective technique to strengthen marine clay given soil characteristics and site conditions [12, 13].

Soil-cement is a composite material composed primarily of soil, cement, and water. Cement-soil is widely applied to treating soft soil foundations for roads, airports, and ports [14, 15]. It plays an irreplaceable role in soil improvement in coastal areas. However, the soluble salt content of soft sea soil in coastal areas is high. It will corrode cement soil for a long time and even reduce the durability of cement soil [16]. For example, Shihata and Baghdadi [17] and Nan et al. [18] investigated the deterioration of cement strength in the marine environment. Xing et al. [19–21] studied the effect of the content of soluble salt ions on the strength of cement soil. The results show that the Cl^- , SO_4^{2-} , and Mg^{2+} soluble salt ions have distinct adverse effects on the strength of cement soil samples. The impermeability of soil-cement is an important indicator for evaluating the durability and useful service life. Therefore, research into the impermeability of soil-cement has attracted more and more attention.

TABLE 1: The main salt content of seawater.

Salt of seawater	NaCl	MgCl ₂	MgSO ₄	CaSO ₄	K ₂ SO ₄	CaCO ₃	MgBr ₂	Total
Content (‰)	27.21	3.81	1.66	1.26	0.86	0.12	0.08	35

TABLE 2: Chemical composition of common Portland cement (P.O 42.5).

Composition	CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	SO ₃	MgO	f-CaO	Others	LOI
Portland cement (%)	62.55	21.69	4.38	3.34	2.89	2.05	0.57	0.84	1.59

TABLE 3: Chemical composition of compound admixture.

Composition	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
Granulated blast furnace slag powder (%)	32.00	16.81	36.12	10.59	0.93	0.9	2.29	0.14	0.16

TABLE 4: Permeability test of soil-cement.

No.	Cement mixing ratio (%)	Water binder ratio	Mixing ratio (%)	Environment
A-0	15	0.5	0	Fresh water
A-1	15	0.5	10	
A-2	15	0.5	20	
A-3	15	0.5	30	
A-4	15	0.5	40	
B-0	15	0.5	0	Seawater
B-1	15	0.5	10	
B-2	15	0.5	20	
B-3	15	0.5	30	
B-4	15	0.5	40	

Mixing ratio: the ratio of composite FSP to replace cement mass.

Goreham and Lake [22] examined the influence of water on the diffusion and porosity parameters of soil-cement materials. Wang et al. [23] studied the impermeability of soil-cement by adding fly ash, and the results showed that the optimal mass ratio of CMK to cement is between 1:6.5 and 1:4. Quang and Chai [24] researched the permeability (k) of lime- and cement-treated clayey soils. The results indicate that the k value decreases when the amount of cement or lime added is large enough that the cementation products formed during the pozzolanic reactions begin to fill the interaggregate pores. However, there are relatively few studies on the permeability of soil-cement eroded by seawater.

Soil-cement has good adaptability to complex environmental conditions of construction and sites [25]. The adverse effects of erosion on the soil-cement can be reduced or prevented by selecting appropriate cement types, mixing ratios, and admixtures. The addition of mineral admixtures is the most economical, effective, and environmentally friendly measure to improve the performance of soil-cement [26–28]. Lin et al. [29], Ali and Yousuf [30], and Karpisz and Jaworski [31] researched the influence of fly ash on the strength and stability of soil-cement. The use of

fly ash as an admixture in stabilizing a soft marine clay resulted in stabilized samples with improved strength, more than 75 times that of the untreated clay. Rocha et al. [32] evaluated the compressive strength characteristics of soil-cement when rice husk ash (RHA) was used as a substitute for Portland cement, and the results indicated that RHA was feasible as a substitute for cement. Li et al. [33] added a certain amount of ultrafine silica powder to cement-stabilized soil to inhibit the expansion of cement-stabilized soil in seawater. Wang et al. [34] reported that China had discharged about 40 million tons of ferronickel waste residue every year. It accounts for about 20% of the total discharge of metallurgical waste slag. Meanwhile, the chemical activity of ferronickel slag was demonstrated by Chen and Tong [35] and Yang et al. [36]. It can be used as the raw material for slag cement.

Recycled materials are a matter of global concern in recent research on soil stabilization [37]. Ferronickel slag is a metal waste product produced by smelting steel or nickel. Generally, it is dumped as sand containing fine powder, which is nonbiodegradable. In this paper, FSP refers to the regenerated ferronickel slag powder obtained by grinding



FIGURE 1: Screening marine soft soil.

ferronickel slag into powder. Dredged marine soft soil is problematic soil because of its weak engineering performance. FSP is mixed into cement soil as a mineral admixture to strengthen the marine soft soil. Treating soft soil with this ferronickel waste would be an environmentally friendly, cost-effective, and green technology. Hence, FSP is used to improve the durability of cement reinforced marine soft soil. Permeability test and X-ray diffraction (XRD) test were conducted to evaluate the applicability of FSP for treating marine soft soil. The influence of erosion time on soil-cement permeability in the marine environment was investigated.

2. Materials and Methods

2.1. Test Materials. The marine soft soil used in the test is the sludge in a subway foundation pit in the coastal area of Fujian Province, with a pH of 6.82, moisture content of 58.5%, a void ratio of 1.53, and a plasticity index of 19.8. The cement used in the test is ordinary Portland cement (P.O. 42.5). Ferronickel slag powder (FSP) is produced by Fujian Yuanxin Group Co., Ltd. (Fujian Province, China). There is no harm in corrosive, leaching toxicity, and radioactivity. Because of the weak chemical activity of FSP [35], some granulated blast furnace slag powder with strong chemical activity is mixed into the FSP to form a mineral admixture. The mass ratio of FSP to ore powder is 2:1. The water used in the test is pure water extracted from running water after purification by water purification equipment. The seawater maintenance environment is simulated by manual configuration in the laboratory. The seawater environment is manually prepared following the *Salt Manufacturing Industry Manual* [35]. The salinity of seawater is 35‰, and the main saline content is shown in Table 1. The main performance indicators of cement, FSP, and slag used are listed in Tables 2 and 3 [38].

2.2. Test Plan. The mixing ratio of cementitious material in soil-cement was 15%, and the water binder ratio was 0.5. Three influencing factors were set up in the test: the mixing ratio of FSP, the immersion environment, and the curing age. The mixing ratios of the composite FSP in the soil-cement were 0%, 10%, 20%, 30%, and 40%, respectively.



FIGURE 2: Mixing the components.



FIGURE 3: The standard penetration mold.



FIGURE 4: Mixing the components.

The mix proportion is shown in Table 4. The methods and procedures used to prepare the samples for testing followed the *Chinese Standard JGJ 233-2011 Specification for mix proportion design of soil-cement: Part B5*. The untreated marine soft soil was first over dried and passed through a

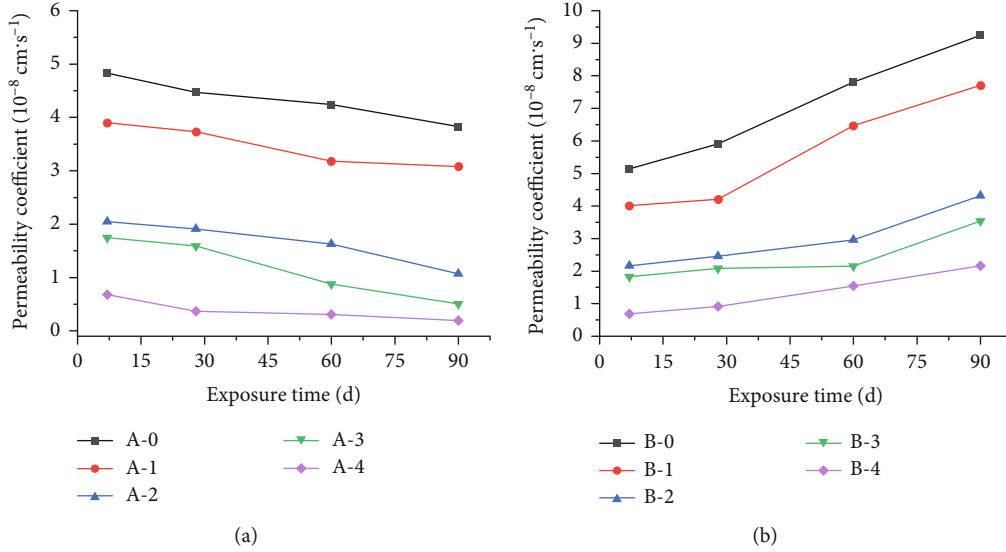


FIGURE 5: Permeability coefficient of soil-cement: (a) permeability coefficient of soil-cement in clear water; (b) permeability coefficient of soil-cement in marine environment.

2 mm mesh sieve (Figure 1). When preparing soil-cement laboratory samples, the sieved soil, FSP, and cement were first mixed for 3 min, and then, the mixture was poured into the water and thoroughly mixed for 5 min to achieve a homogeneous mixture (Figure 2). The standard penetration mold (Figure 3) was 30 mm high, and the upper mouth has an inner diameter of 70 mm and an inner diameter of 80 mm. The soil-cement slurry was placed in three equal layers inside the standard penetration mold. The vibration time of each layer of cement soil should not be less than 1 minute. The soil-cement slurry was trimmed and troweled to eliminate the extra soil-cement when the compaction process was completed. After 24 h, the prepared cement soil test block (Figure 4) was demoted and immersed in clear water and seawater. The samples were cured for 7 days, 28 days, 60 days, and 90 days.

The TJSS-25 infiltration device for soil-cement was adopted in the permeability test. In the first place, paraffin was used to seal the side wall of the cement soil. The methods and operation steps of the permeability test followed the Chinese Standard JGJT 233-2011 *Specification for mix proportion design of soil-cement*. A QUANTA 250 scanning electron microscope (SEM) and a Miniflex 300 X-ray diffractometer (XRD) were used to perform microscopic experiments on the soil-cement.

The permeability coefficient is calculated using Equation (1) and Equation (2), and the correction formula is as Equation (3).

$$k_T = \frac{V}{iAt}, \quad (1)$$

$$i = \frac{P}{100\gamma_w h}, \quad (2)$$

Where k_T is the permeability coefficient of soil-cement at $T^\circ\text{C}$ of water temperature (cm/s), accurate down to

0.01×10^{-n} cm/s; i is the hydraulic gradient, accurate down to 0.01; t is the interval time (s); V is the water seepage in time period t (ml); A is the cross-sectional area in the middle of the sample (cm^2); p is the osmotic pressure (MPa); and γ_w is the gravity of water, which is regarded as 0.0098 N/cm^3 .

$$k_{20} = k_T \times \frac{\eta_T}{\eta_{20}}, \quad (3)$$

where k_{20} is the permeability coefficient of soil-cement at 20°C of standard water temperature (cm/s), accurate down to 0.01×10^{-n} cm/s; η_T is the dynamic viscosity coefficient of water at $T^\circ\text{C}$ of water temperature (kPa·s); and η_{20} is the dynamic viscosity coefficient of water at 20°C of water temperature (kPa·s).

3. Results

3.1. Analysis of Permeability Test Results. The permeability tests of different soil-cement samples were conducted at immersion time of 7 days, 28 days, 60 days, and 90 days. The relationship between permeability coefficient and immersion time is shown in Figure 5.

It can be seen from Figure 5 that the relationship curve between the permeability system and age of the soil-cement with five admixture amounts of FSP (0%, 10%, 20%, 30%, and 40%) in clear water showed a slow downward trend with a small range of change and an overall stable coefficient of permeability of the soil-cement of each mixture proportion. In contrast, the relationship curve between the permeability coefficient and the age of the soil-cement in the marine environment showed an increasing trend. The permeability coefficients of soil-cement in the two environments were substantially the same by the age of 7 days, and the growth rate of permeability coefficient in the marine environment before the age of 28 days is slow, while the

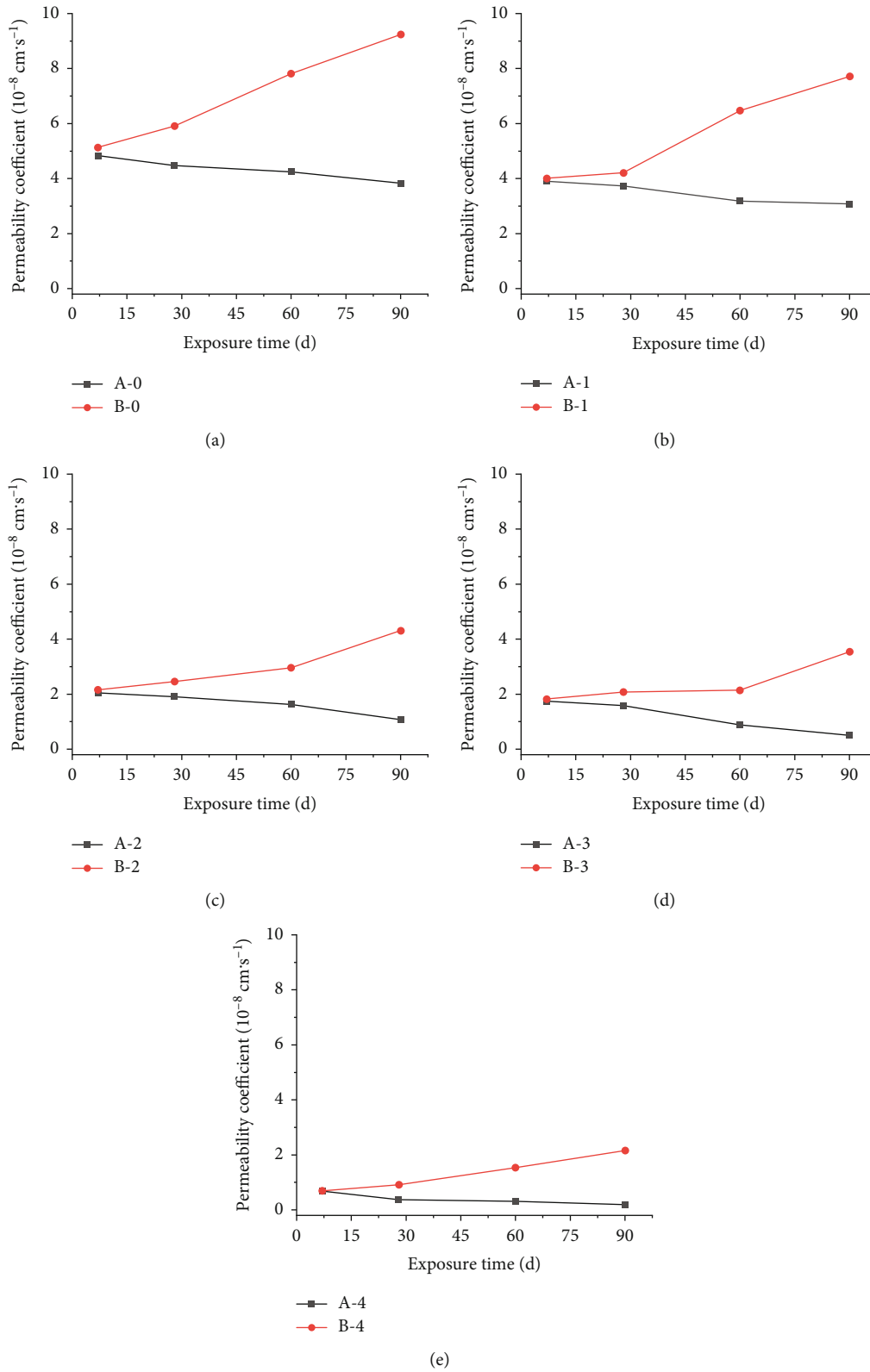


FIGURE 6: Comparison curve of soil-cement permeability coefficient and age: (a) admixture amount of ferronickel slag is 0%; (b) admixture amount of ferronickel slag is 10%; (c) admixture amount of ferronickel slag is 20%; (d) admixture amount of ferronickel slag is 30%; (e) admixture amount of ferronickel slag is 40%.

TABLE 5: Temperature and wildlife count in the three areas covered by the study.

Sample no.	Compound admixture addition	Regression curve equation	Determination coefficient
A-0	0%	$K = 0.00008725t^2 - 0.012t + 4.88$	$(R^2 = 0.979)$
A-1	10%	$K = 0.00007t^2 - 0.0176t + 4.066$	$(R^2 = 0.959)$
A-2	20%	$K = -0.000113t^2 - 0.00055t + 4.066$	$(R^2 = 0.996)$
A-3	30%	$K = -0.0000107t^2 - 0.0149t + 1.905$	$(R^2 = 0.977)$
A-4	40%	$K = 0.000074t^2 - 0.0124t + 0.730$	$(R^2 = 0.926)$
B-0	0%	$K = 0.00005t^2 + 0.046t + 4.74$	$(R^2 = 0.995)$
B-1	10%	$K = 0.0002t^2 + 0.033t + 3.58$	$(R^2 = 0.965)$
B-2	20%	$K = 0.0003t^2 - 0.004t + 2.23$	$(R^2 = 0.990)$
B-3	30%	$K = 0.0004t^2 - 0.017t + 2.03$	$(R^2 = 0.998)$
B-4	40%	$K = 0.00008t^2 - 0.011t + 0.59$	$(R^2 = 0.997)$

permeability coefficient of soil-cement increased greatly with the passage of time after 28 days of age. The results showed that if the age is less than 28 days, the marine environment has little influence on the permeability system of ferronickel slag containing soil-cement, while the negative effects of the marine environment on soil-cement increased greatly over time.

The comparison curves of permeability coefficient of soil-cement in clear water and seawater erosion environment are shown in Figure 6. According to the comparison chart in Figure 6, the curve of clear water shows an upward trend, while the one of marine environment shows a downward trend. As the immersion age progresses, the difference in permeability coefficient of the FSP containing soil-cement in the two environments becomes increasingly larger. Therefore, each group of comparison curve shows an opening shape that expands to the right, and the opening shape gradually decreases with the increase in the admixture amount. In other words, the opening shape is largest when the admixture amount of FSP is 0%, whereas the opening shape is smallest when the admixture amount of FSP is 40%. Under the designed immersion time, the permeability coefficients of the soil-cement with 40% admixture amount of FSP in seawater environment were 0.69×10^{-8} cm/s, 0.92×10^{-8} cm/s, 1.54×10^{-8} cm/s, and 2.16×10^{-8} cm/s, respectively. Compared with that in clear water, they increase by 0.01 times, 1.49 times, 3.97 times, and 10.37 times, respectively. The results show that the marine environment will deteriorate the impermeability of soil-cement, and the negative effect of this deterioration on the impermeability increases with the increase of the erosion time of seawater, while FSP can slow down the erosion of soil-cement by seawater.

In short, after analyzing the reasons, the chemical activity of FSP is weaker than that of cement [39]. The soil-cement mixed with FSP can play the role of filling voids better in the early stages and improve the workability of the soil-cement, as a result of which the soil-cement formed becomes denser [35]. Therefore, after FSP was added to the soil-cement, the permeability coefficient of the soil-cement

would be decreased while the impermeability of the soil-cement would be improved. At the age of 7 days, the solidification effect of the soil-cement was strong, and the effect of improving performance was greater than the negative influence of the marine environment on the soil-cement. Therefore, by 7 days of age, the permeability coefficient of soil-cement was essentially the same in both environments. However, after 28 days of age, the hydration of the cement in the soil-cement slowed, while the erosion of soil-cement by the marine environment continued. At this time, the deterioration of the soil-cement by the marine environment was greater than the consolidation of the soil-cement itself. Therefore, after 28 days, the permeability coefficient of soil-cement in the marine environment increased, and even the increased amplitude became larger. Although the performance enhancing effect of soil-cement after 28 days of age was weaker than the deterioration of the soil-cement by the marine environment, the activity of FSP began to play a strong role, slowing the influence of the marine environment on the soil-cement. Therefore, the opening of the curve with the large admixture amount of FSP is significantly smaller than that with the small admixture amount of FSP.

3.2. Regression Model Analysis of Permeability Coefficient and Age. The permeability coefficient of cement soil is related to the content of cementitious materials and the age of maintenance. It showed a quadratic polynomial pattern variation with age [40]. Quadratic polynomial fitting analysis was used to figure out the permeability coefficient of the FSP in the soil-cement at different ages. In both clear water and marine situations, the permeability coefficient of an FSP-cement soil varies quadratically polynomially. The regression equation is shown in Table 5, where K is the permeability coefficient of the FSP containing soil-cement, t is the immersion age, and R^2 is the coefficient of determination. The regression curve is established according to the law of change of permeability coefficient and the age of the FSP containing soil-cement, as shown in Figure 7, respectively.

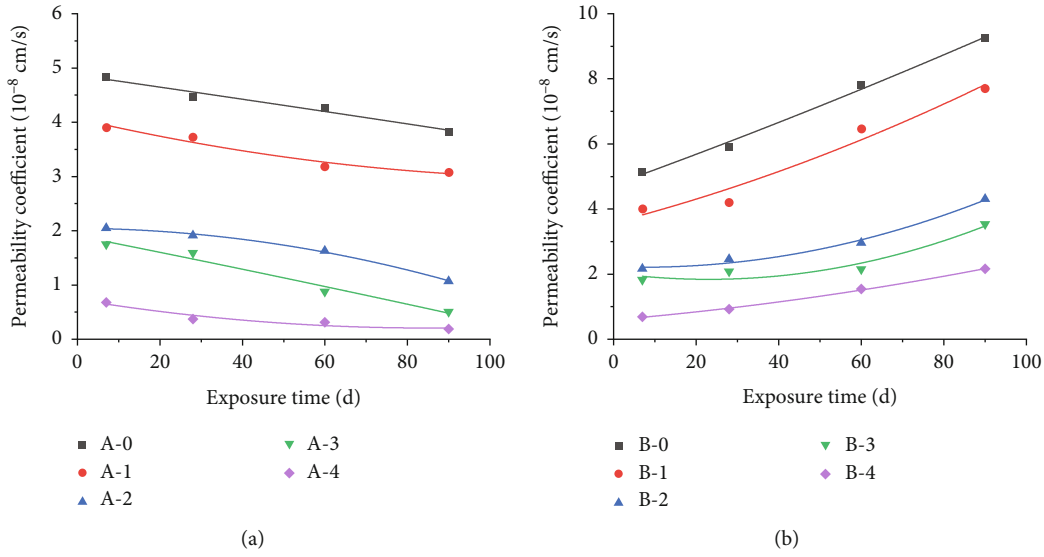


FIGURE 7: Regression curve of permeability coefficient with immersion age: (a) soil-cement soaked in clean water; (b) soil-cement soaked in seawater.

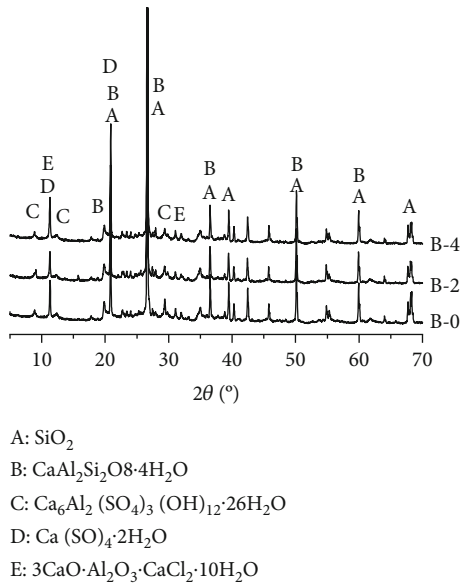


FIGURE 8: XRD energy spectrum of soil-cement at 60 d.

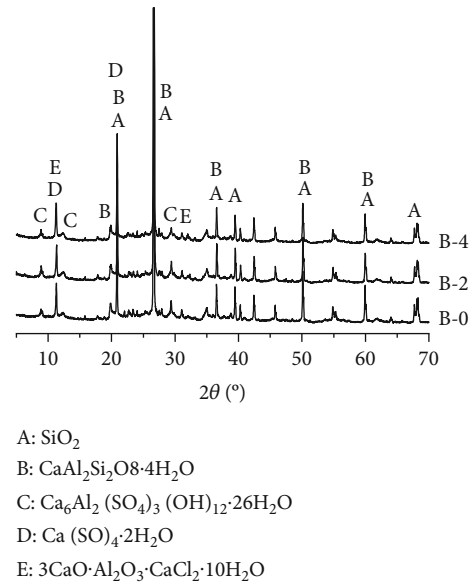


FIGURE 9: XRD energy spectrum of soil-cement at 90 d.

From Figure 7 and the corresponding fitting formulas, it can be seen that the coefficient of determination R^2 of the fitting curve of the permeability coefficient of soil-cement changing with immersion age is not less than 0.95, indicating that the fitting curve is very similar to the law of change of the permeability coefficient of soil-cement in the paper. The curing effect of soil-cement is usually completed at the age of 90 days, so the development of impermeability of soil-cement usually needs 90 days to be stable. However, in the actual engineering construction, due to reasons such as the construction period and cost, the impermeability of soil-cement can not be tested until the soil-cement reaches the age of 90 days. If the functional relationship between the early permeability coefficient of the soil-cement and

the permeability coefficient of 90 days can be established, and the early calculation of the permeability coefficient of 90 days can be achieved, it can provide references for the prediction of the impermeability of soil-cement.

3.3. Microstructure Characteristics of Soil-Cement. The FSP soil-cement is a complex multiphase system. In this paper, the main crystalline substances of the soil-cement were analyzed. The XRD pattern of the soil-cement is shown in Figures 8 and 9. The main crystalline substances of soil-cement with different admixture amounts of FSP are quartz (SiO_2), gismondine ($\text{CaAl}_2\text{Si}_2\text{O}_8 \cdot 4\text{H}_2\text{O}$), ettringite (Aft: $\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12} \cdot 26\text{H}_2\text{O}$), gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), and Friedel's salt ($3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaCl}_2 \cdot 10\text{H}_2\text{O}$). The intensity

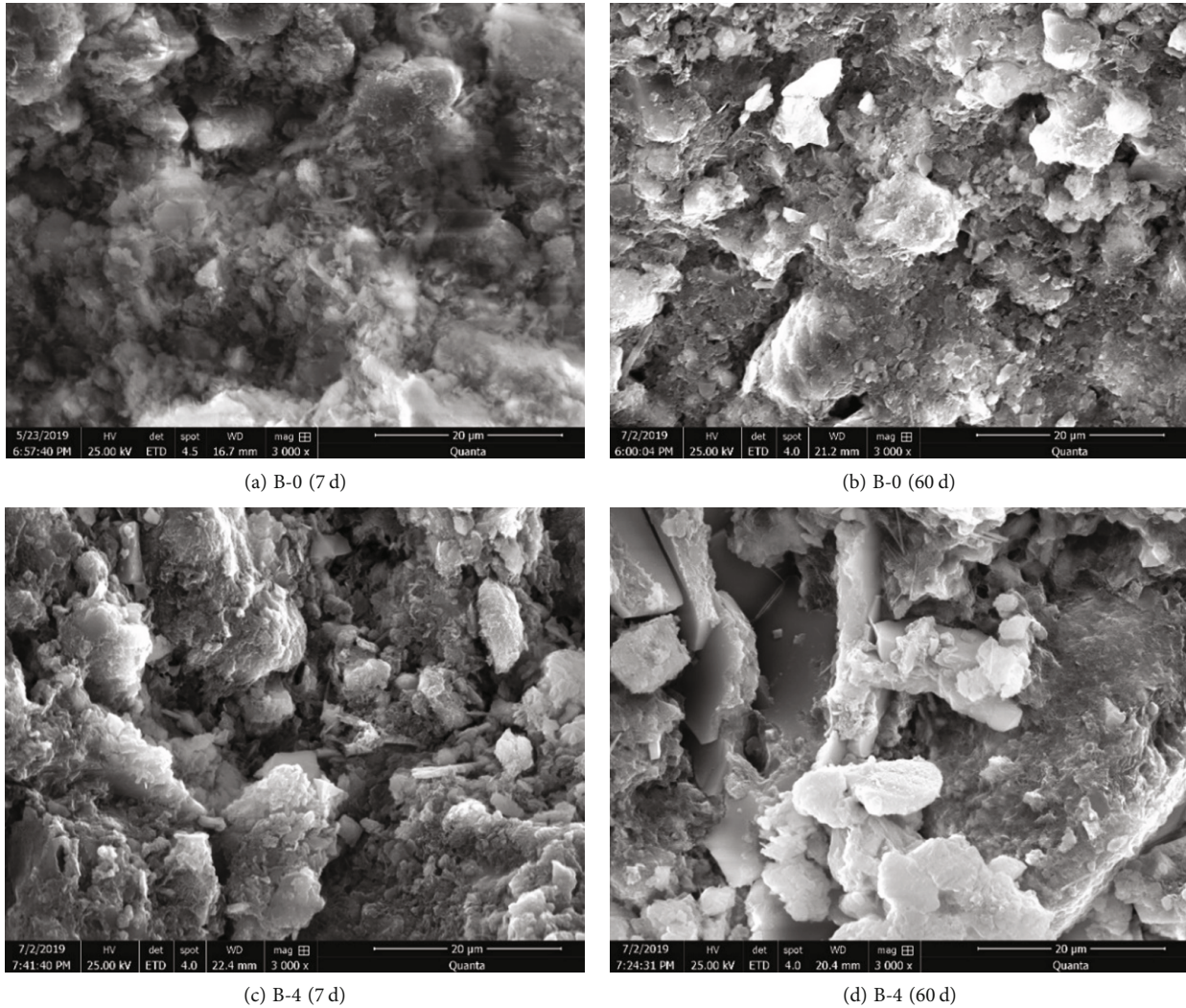


FIGURE 10: Microscopic morphology of soil-cement: (a) SEM image of B-0 at 7 days ($\times 3000$); (b) SEM image of B-0 at 60 days ($\times 3000$); (c) SEM image of B-4 at 7 days ($\times 3000$); (d) SEM image of B-4 at 60 days ($\times 3000$).

of the main diffraction peak of SiO_2 in soil-cement is very strong, so it is difficult to distinguish the difference in the diffraction peak intensity of each group. Orthorhombic scolecite and ettringite are mainly the hydration products of soil-cement, and their diffraction peak intensity increases with the passage of age.

The microstructures of the FSP soil-cement are depicted in Figure 10. The SEM images were analyzed by comparison with known crystal microstructures to discern the compositions. The soil-cement exhibits a loose microstructure, and the soft soil particles are bound by flocculating material. This flocculent is a calcium silicate hydrate (C-S-H) gel formed by the mixed hydrolysis and hydration reactions of cement and soft soil [21]. At 60 days, the cement soil's flocculation and clustered structures become more evident, while the pore structure becomes less pronounced. The flocculation and clustering phenomena are enhanced by the hydration reaction [41]. The flocculent colloid (C-S-H) is more abundant, but a trace of needle-like Aft, hexagonal prismatic CH crystals, and F salts is also visible. They

result in a reduction in the number of soil-cement pores and an increase in density.

Portland cement in soil-cement contains a large number of mineral components, such as C_3S , C_2S , C_3A , and C_4AF . So, a hydration reaction will occur after cement contacts with water. At the same time, FSP contains a large number of potentially active vitreous substances, including SiO_2 , Al_2O_3 , and Fe_2O_3 [38]. With the passage of time, vitreous substances can give better play to the chemical activity effect and produce hydration products such as C-S-H, C-A-H, $\text{CaO}\cdot\text{Fe}_2\text{O}_3\cdot m\text{H}_2\text{O}$, Aft, and AFm, which is conducive to the improvement of impermeability of soil-cement. The erosion effect of the marine environment on soil-cement is mainly a series of physical and chemical reactions between Cl^- , SO_4^{2-} , and Mg^{2+} and mineral composition or hydrated products in soil-cement [35], which can produce expansive substances such as Friedel's salt, gypsum, Aft, and M-S-H gel. When there is an excessive amount of expansive substances, spalling and softening will occur in the soil-cement. When FSP is added to soil-cement, the binding

capacity of soil-cement to Cl^- can be improved. At the same time, the low activity of FSP can make the soil-cement structure denser, which can alleviate the erosion effect of corrosive ions.

4. Conclusions

In this paper, the permeability comparison test of the FSP containing soil-cement in clear water and the marine environment was conducted with the pressurized soil-cement infiltration device. The permeability characteristics of the soil-cement with different admixtures of FSP under the erosion of seawater were studied. The following conclusions can be drawn from this research:

- (1) Prior to the age of 28 days, the difference in the permeability coefficients of cement soils in clear water and marine environments is minimal, and the values are nearly identical. After 28 days, the permeability coefficient of cement soils in a clear water environment decreased with age and remained relatively stable. In comparison, the permeability coefficient of cement soil in the marine environment tends to increase with age, and the permeability coefficient increases with age. The marine environment would then deteriorate the cement soil's permeability performance in the long run
- (2) In both clear water and marine environments, the permeability coefficients of cement soils follow a quadratic polynomial pattern with age. By increasing the amount of nickel-iron slag powder admixture in the cement soil, the permeability coefficient gradually decreases, thereby improving its permeability resistance. By increasing the amount of nickel-iron slag powder in the cement soil, the seepage resistance of the soil-cement can be slowed down by the marine environment. The soil-cement containing 40% FSP has excellent impermeability
- (3) From XRD and SEM test results, FSP has a microaggregate filling effect and can fill the pore structure of cement soil. With the hydration reaction of cement, FSP exerts a chemical activity effect and improves the quality of hydration products. FSP improves the compactness of the cement soil matrix and hinders the invasion of erosion ions, improving the impermeability and erosion resistance of cement soil

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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