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Research Article

Study on Grouted Body Deterioration Mechanism of Sand Layer in Seawater Environment

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Water-rich sand is a common stratum in marine underground engineering. Grouting is the most common method for solving geological disasters in water-rich sand. However, the marine environment differs greatly from the land environment. The erosion and seepage of seawater ion cause significant deterioration of grouted body, which reduces the physical and mechanical properties of grouted body. The maintenance of grouted body performance is the guarantee of long-term safe operation of the tunnel in the marine environment. In order to solve the problem of long-life grouting design for sand layer in seawater environment, an accelerated test of grouted body erosion under seawater erosion environment is designed to study the mesomorphological characteristics of seawater erosion on grouted body erosion and to reveal the mechanism of seawater erosion and solids. The evolution law of grouting plus solid strength under different slurry water-cement ratios and different seawater erosion time conditions is analyzed. The results show that the grouting plus solid effective time for water-cement ratios of 0.8 : 1, 1 : 1, 1.4 : 1, and 2 : 1 is 75a, 60a, 30a, and 15a; the index of strength degradation ratio of seawater environment to grouting plus solids is proposed, and the quantitative relationship between seawater erosion time and grouting plus solids strength is established, which provides theoretical basis for sand layer grouting reinforcement in seawater environment. We hope to provide some reference for the design and construction of sand grouting in seawater environment.

1. Introduction

Marine underground engineering entered a period of large-scale construction. The construction and operation of underground engineering in marine environments such as subsea tunnels and offshore subways are booming. Poor geology is one of the important threats to engineering construction and operation. The water-rich sand layer becomes one of the important geological disaster sources affecting the safety of the subsea tunnel during construction due to its low cementing strength and poor self-stabilizing ability. Grouting is the most commonly used method to resolve geological disasters in water-rich sand layers, but the marine environment is greatly different from the land area environment. Seawater ion erosion causes significant deterioration of grouting plus solids, reducing the physical and mechanical properties of grouting plus solids and threatening long-term safe operation of the tunnel.

At present, domestic and foreign scholars made some progress in the research of grouting reinforcement in seawater environment. Terashi [1] studied the relationship between the depth of cement soil degradation and the logarithm of time and found that they are basically linear. Ning et al. [2–7] studied the mechanical effects and erosion mechanism of cement soil under different concentrations and different pH values for aggressive ions including SO_4^{2-}, Cl^-, and HCO_3^-, and it was proved that among the factors such as pH value and concentration, pH value has the greatest influence on the mechanical properties of cement soil, and the strength of natural soil is high in alkaline environment. Han et al. [8] proposed a time model of the strength of cement soil based on the change law of magnesium ions and sulfate ions. Liu et al. [9] conducted a lot of experiments with different mix ratios to establish the relationship between the strength of cement soil and grouting parameters. Bai et al. [10] studied the change law of the properties of cement soil under different erosion environments and obtained the strength-time relationship of cement soil. Chen et al. [11] experimentally studied the mechanical properties and failure mechanism of cement soil under different erosion ion solutions. Huang et al. [12], Huang et al. [13], and Huang et al. [14] studied the influence of different factors on the performance of cement soil in engineering practice and put forward research studies that guide engineering design. Chu et al. [15] studied the mechanism of chloride ion erosion on cement soil and based on the research results put forward measures to prevent chloride ion erosion on cement soil. Zhang et al. [16] used early strength cement to configure cement test blocks with different water-cement ratios and found that the interior of the cement stone body is gradually compacted by the filling effect of corrosion products and then continued to expand and finally the strength gradually decreased. Yang et al. [17] analyzed the resistance to Mg^{2+} and SO_4^{2-} of ordinary portland cement using XRD spectroscopy, which showed that Mg^{2+} reacted with cement hydrate to form $Mg\,(OH)_2$, and the product had no structural support. Shi et al. [18, 19] studied the long-term stability of polymer-modified mortars containing chloride ions internally, and the results showed that polymer-modified mortars had a high resistance to chloride ion attack, and their corrosion resistance was affected by their permeability effect. Bai et al. [20, 21] prepared cement slurry stones with different water-cement ratios and fly ash content and studied the changes in the mechanical properties of cement slurry stones in seawater environment.

Although domestic and foreign scholars carried out a lot of related research studies on seawater erosion, these results mainly focus on the research of reinforced concrete, cement soil, and cement stone body. Due to the geoenvironmental nature of geotechnical engineering and the different injected media, the characteristics of the grouting plus solids and the erosion resistance must be different. Cement soil is often used in geotechnical engineering under the environment of seawater, groundwater, and other erosion. Under such environmental conditions, cement soil often contains some corrosive ions, such as SO_4^{2-} and Cl^- , and its mechanical properties are affected by environmental erosion, for example, the strength and durability of cement soil will change to different degrees. Sand layer is the most common bad geology in seawater environment. It is imperative to carry out targeted research on sand layer grouted body in seawater environment so as to provide professional guidance on sand layer grouting design.

In order to solve the problem of long-life grouting design for sand layer in seawater environment, firstly, an accelerated test of grouted body erosion under seawater erosion is designed to study the mesomorphological characteristics of seawater erosion on grouted body erosion and to reveal the mechanism of seawater erosion and solids. Secondly, the evolution law of grouting plus solid strength under different conditions of slurry water-cement ratio and seawater erosion time is analyzed. Finally, the strength degradation ratio index of seawater environment to grouting plus solids is proposed, and the quantitative relationship between seawater erosion time and grouting plus solids strength is established.

2. Ion Erosion Simulation Test in Seawater Environment

2.1. Simulation Test Plan. The influence of seawater environment on grouted body is mainly due to the erosion of cement hydration cement by chloride ions, resulting in the loss of the solid components of grouted body and increasing the internal pores of the solids and microcracks or pores at the interface of cement and sand. The main factors affecting cement hydration cementitiousness are the water-cement ratio and the degree of hydration of the slurry, and the degree of cement hydration is directly related to the water-cement ratio of the slurry. Therefore, in order to study the erosion of seawater environment on grouting plus solids, the effects of water-cement ratio and erosion time of slurry on the degradation are mainly studied.

2.1.1. Water-Cement Ratio of Slurry. The commonly used slurry for sand layer grouting is cement slurry, with water-cement ratios of 0.8 : 1, 1 : 1, 1.4 : 1, and 2 : 1, respectively.

2.1.2. Grouting Pressure. According to the study of the conditions of osmotic grouting, as well as the laboratory test of sand osmotic grouting and a lot of engineering practice experience, when the osmotic grouting pressure is 0.5 MPa [22], the slurry penetrates and diffuses sufficiently in the sand layer, so the grouting pressure selected in this test is 0.5 MPa.

2.1.3. Grading of Injected Sand Grains. According to the sand layer penetration test and reinforcement test analysis, it can be known that the sand particle gradation is in the range of 1~2 mm, and the slurry diffuses sufficiently in the sand injection layer, so the sand particle size range selected in this test is 1~2 mm. The porosity and permeability coefficients are shown in the Table 1.

2.1.4. Conservation of the Environment. According to the accelerated test design, the long-term mechanical properties of grouted body under seawater environment are studied. The temperature of the curing box is 35°C, and the mass concentration of sodium chloride used in the curing solution is 11.15%. Compared with the climate and sea water around the Jiao Zhou Bay of China, the acceleration rate is 88.15 times.

2.2. Test Plan in Grouting Phase

Table 1: Physical and mechanical parameters of sand-injected layer.

Injected media number	Particle size range (mm)	Porosity φ (%)	Permeability coefficient (k/cm/s)
1	1~2	37.4	5.857×10^{-2}

(1) The fastening device is fixed for the plexiglass tube by screw connection. A hard disk filter is placed at the bottom of the plexiglass tube, which not only supports the weight of the sand injection layer but also prevents the loss of sand particles. The injected sand particles are put into the plexiglass tube in layers, and the sensor is embedded. After the filling in the plexiglass tube is completed, the top is closed and fixed on the test bench. The penetration grouting test device is shown in Figure 1 [23].

(2) The grouting pipeline is connected, the pressure sensor, flow sensor, manual grouting pump, and other devices are connected in series, and the cement slurry is prepared according to the set water-cement ratio, and it is placed in the storage bucket for backup.

(3) The slurry is pumped by a manual grouting pump, and the grouting rate is controlled uniformly according to the designed grouting rate. The cement slurry in the slurry storage bucket is constantly stirred to prevent the slurry from settling.

(4) When the slurry emerges from the top of the plexiglass tube, grouting is stopped and the grouting pipeline is cleaned.

2.3. Test Plan in the Curing Phase

2.3.1. Principle of Accelerated Test Design. This test uses temperature and concentration parameters to accelerate the erosion of the grout and solids. In terms of temperature, the chemical reaction is mainly accelerated by increasing the temperature and increasing the activation energy of ions. The test climate and seawater are based on Qingdao Jiaozhou Bay subsea tunnel data.

(1) Temperature. Arrhenius equation:

$$K = \exp\left(\frac{E}{R}\left(\frac{1}{T_1}-\frac{1}{T_2}\right)\right). \quad (1)$$

Among them, E/R is activation energy, and the value of the Atkinson test is taken as 14242 [24]; K is the reaction rate constant; T is the Kelvin temperature, Kelvin = Celsius + 273.15; $T1$ is the natural temperature; and $T2$ is the test temperature.

According to the actual measurement, the average annual temperature in the sea area of Qingdao Jiaozhou Bay is 17°C. This experiment uses a constant temperature of 35°C, so the acceleration coefficient is 17.63.

(2) Accelerated concentration.

$$F_d = \frac{C_s^{\text{lab}}}{C_s}. \quad (2)$$

Among them, C_s^{lab} is the laboratory test grouting plus solid surface chloride ion concentration (mass concentration) and C_s is the seawater grouting plus solid surface chloride ion concentration (mass concentration).

The mass concentration of sodium chloride in the seawater is 1.86% to 2.6%. In this test, the mass concentration of sodium chloride is 11.15%, which is 5 times that in seawater.

According to the calculation method of the accelerated corrosion coefficient in the laboratory test, multiplying the acceleration coefficients of various factors, it can be obtained that the degradation acceleration coefficient of the test in this paper is $17.63\times5=88.15$ times.

2.3.2. Test Steps in the Conservation Phase

(1) After the slurry is condensed, the plexiglass tube is cut, and a coring device is used to core the standard test piece at a distance of 20 cm from the grouting port, and the test pieces are placed in a curing box with seawater and maintained. The process is shown in Figure 2.

(2) The curing box is put into the standard curing box, the constant temperature function of the standard curing box (without humidification) is selected, the temperature is kept around 20°C, and the water is changed every 7 days.

(3) The sample is put after curing for 28 days in a new curing box, the temperature of the curing box is set to 35°C, the curing solution is prepared with coarse salt, the mass concentration of sodium chloride is 11.15%, and the water is changed every 3 days.

(4) To be maintained age reached 3 d, 7 d, 14 d, 28 d, 56 d, 90 d, 180 d, 225 d, and 270 d, and the uniaxial compressive strength of the sample is tested.

3. Analysis of Seawater Erosion Simulation Test Results

3.1. Mesomorphology and Structural Characteristics of Grouting plus Solids. Scanning electron microscope (SEM) is an observation resort between transmissive electron microscopy and optical microscopy that uses a very narrow high-energy electron beam of focus to scan samples; through the interaction between the beam and the material, various types of physical information are to be collected, enlarged, and then imaged to achieve the purpose of scientific research and widely used in the field of scientific research. It mainly

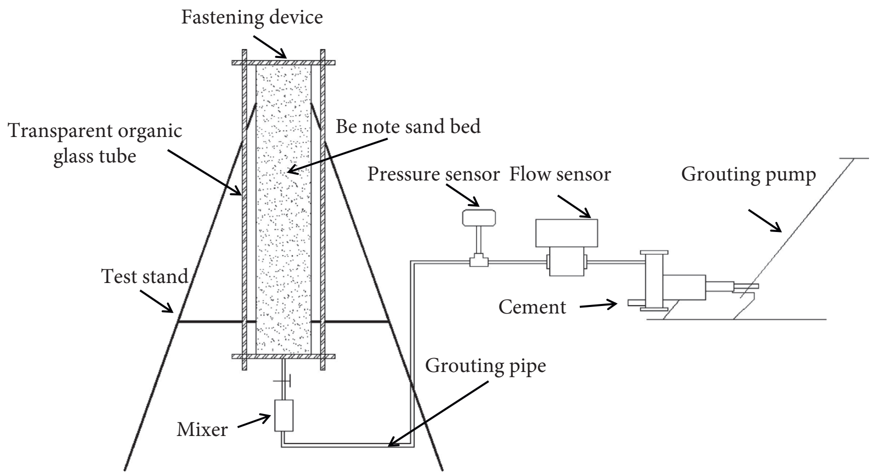
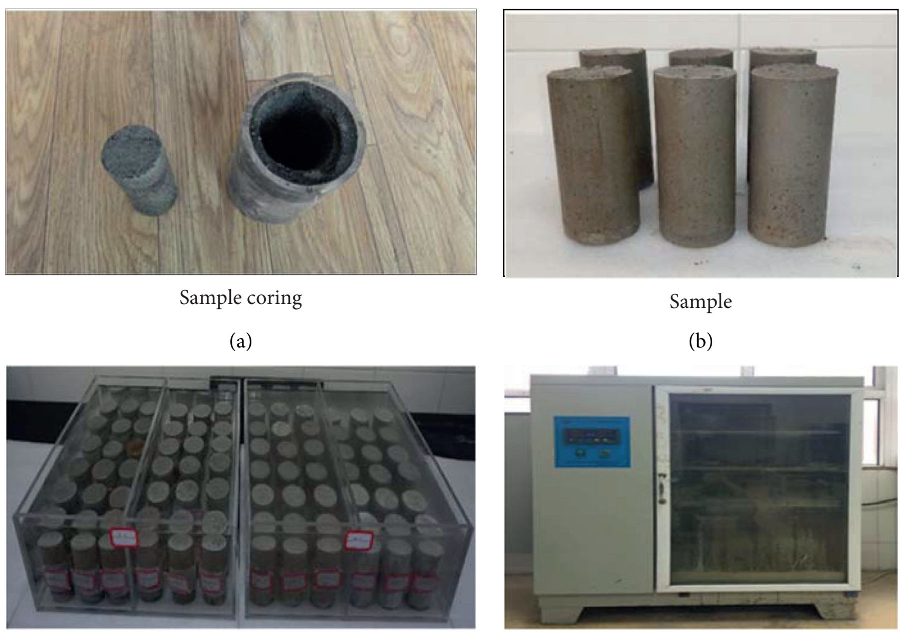


Figure 1: Penetration grouting test device.



Sample coring

(a)

Sample

(b)

Sample water culture

(c)

Maintenance box

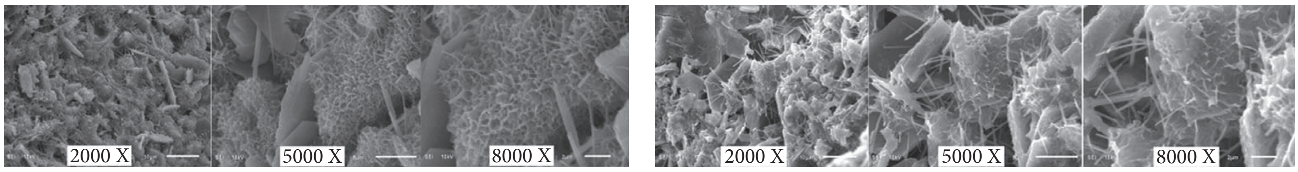
(d)

Figure 2: Coring and curing of grouted body sample: (a) sample coring; (b) sample; (c) sample water culture; (d) maintenance box.

includes the following steps: (1) sample preparation, (2) SEM instrument operation, and (3) take out the sample.

Figure 3 is a SEM analysis image of sand layer grouting plus solids with a water-cement ratio of 1 : 1, which are cured for 225 days under clean water and seawater environments. It can be seen that there is a significant difference in microstructure between the two. Under the condition of clear water curing, the sand layer grouting plus solids structure is tight, the cementation and integrity are relatively good, and the pores are relatively small, showing a dense network and fluffy structure, while in the seawater conservation environment, the sand layer grouting plus solids increases the porosity and the shape, and fluff-like structure is not obvious, and the interior gradually shows fibrous and needle-like structures. It shows that the erosion of seawater causes certain deterioration of sand layer grouting plus solid cement hydration cement, which causes the grouting plus solid to increase porosity, reduce strength, and increase permeability.

3.2. Grouting plus Solid Compressive Strength Deterioration. The uniaxial compressive strength of grouting plus solids is a measure of the bearing capacity of grouting plus solids. The main reason for sand layer grouting is that the sand layer has no self-stabilization and bearing capacity. The sand-filled layers are connected together by the cement slurry, and the hydration reaction of the cement slurry increases the strength of the cement itself. Under seawater erosion conditions, chloride ions react with the components of cement hydration cement to reduce the cement's ability to cement



Clean water conservation of the environment

(a)

Seawater conservation environment

(b)

Figure 3: Microstructure of 225 d sand layer grouting plus solids curing. (a) Clean water conservation of the environment. (b) Seawater conservation environment.

sand particles and the strength of cement. With the increase in time, the erosion of the seawater environment on the grouted body is gradually intensified, which is likely to cause the overall structure of the grouted body to be unstable. Therefore, it is extremely critical to study the long-term stability of grouted body in seawater environment.

This section uses the above experimental design to accelerate the curing of grouted body. Because the general design of subsea tunnels and subways is a hundred-year plan, the design goal is "no major repairs in fifty years and use in one hundred years." According to this time node, the strengths of 1 d, 4 d, 25 d, 50 d, 100 d, 150 d, 200 d, 250 d, 300 d, 350 d, and 400 d in the accelerated curing box are tested, respectively. The corresponding ordinary seawater curing time is 90 d, 1a, 6a, 12a, 24a, 36a, 48a, 60a, 72a, 84a, and 96a. The change of grouted body strength of sand layer under seawater environment as a function of slurry water-cement ratio and time is shown in Figure 4.

Analyzing this diagram, we can see that the deterioration of grouting plus solids in the seawater environment changes with time. From the analysis of the deterioration curve of solids with a water-cement ratio of 0.8 : 1, the strength of grouting plus solids decays slowly before the erosion time 30a. The main reason is that the smaller the water-cement ratio of the slurry, the higher the degree of cement hydration reaction and the dense solid structure, which results in fewer voids such as microcracks and microcracks in the grouting reinforcement, and seawater intrusion grouting with less solids and lower erosion. As time goes on, the early erosion leads to the decomposition of cement hydrated cementite, and new voids such as cracks and pores are formed inside the grouting plus solids. Within 30a to 80a, the seawater erosion rate is faster, especially the peak erosion rate reached around 60a; after 80a, the cement hydration cement is completely eroded, the strength of grouting plus solids is low, and the bearing capacity is lost. The current experimental research on the erosion of slurry stones [25] found that the loss of CaO in cement is closely related to the strength of the stones. The test shows that when the cumulative consumption of CaO in the stones reaches 25%, the strength of the cement stones is half of the initial value before the damage, and the strength of the stones decreases extremely quickly. From this, it can be determined that when the grouting plus solids strength value reaches half of the 28 d strength, the grouting plus solids loses the bearing capacity and impermeability. That is, under seawater erosion conditions, the time when the strength of grouting plus solids deteriorates to half the strength of 28 d is set as the critical time

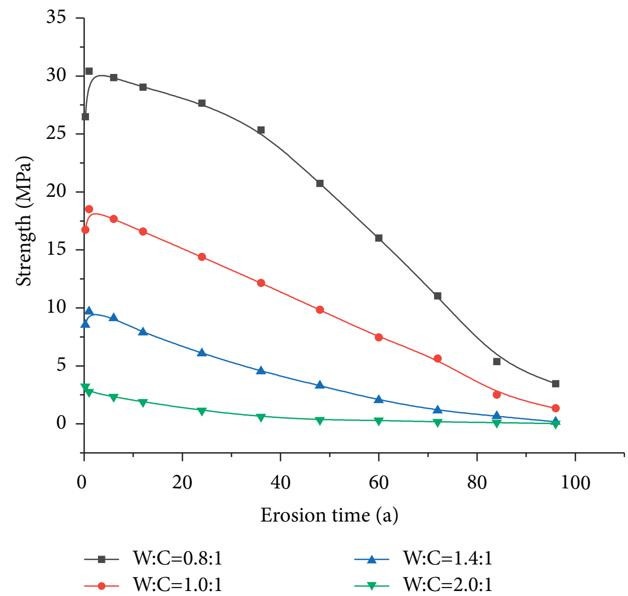


Figure 4: The weakening law of grouted body strength with time.

of the life of grouting plus solids. According to this, the critical time for grouting plus solids with a water-cement ratio of 0.8 : 1 is about 75a.

The grouted body deterioration curve with a water-cement ratio of 1 : 1 and the grouting reinforcement degradation basically show a linear attenuation. Compared with grouted body with a water-cement ratio of 0.8 : 1, hydration reaction of grouted body cement with a water-cement ratio of 1 : 1 is weakened, microcrevices and microcracks are increased in the grouting reinforcement, and the erosion rate of seawater is accelerated. It can be seen from the figure that when the grouting plus solids strength reaches half the strength of 28 d, the equivalent curing time is about 60a. Therefore, the critical time for grouting plus solids with a water-cement ratio of 1 : 1 is about 60a.

The grouting plus solids degradation curve with water-cement ratio of 1.4 : 1 and the degradation curve of grouting plus solids are obviously accelerated, and the degradation rate increases during the start of curing. The main reason is that as the water-cement ratio of the cement slurry increases, the degree of hydration gradually decreases, and the initial microcracks and microcracks of grouting plus solids gradually increase. The more seawater enters the solids, the faster the erosion rate. It can be seen from the figure that when the grouting plus solids strength reaches half of the 28 d strength, the equivalent curing time is about 30a. Therefore, the critical time for grouting plus solids with a water-cement ratio of 1.4 : 1 is about 30a.

When the water-cement ratio of grouting plus solid is 2 : 1, the initial strength of grouting plus solids is low, and the effect of seawater on the grouting plus solids is more significant. It can be seen from the figure that when the grouting plus solids strength reaches half of the 28 d strength, the equivalent curing time is about 15a, so the critical time for grouting plus solids with a water-cement ratio of 2 : 1 is about 15a.

4. Relationship between Grouting plus Solids Strength Degradation Ratio and Water-Cement Ratio

The grout water-cement ratio directly affects the strength of grouting plus solids and the degree of deterioration affected by seawater. It is particularly important to establish the relationship between the grout water-cement ratio and the grouting plus solids deterioration. Because the strength of grouting plus solids is generally based on the strength of water curing for 28 d, the strength degradation ratio M of the seawater environment to the grouting plus solids is defined. The ratio of the strength of grouting plus solids after seawater erosion Q_q to the strength of grouting plus solids cured by water 28 d Q_{28d} is compared with study of the strength degradation ratio of seawater environment to grouting plus solids.

$$M = \frac{Q_q}{Q_{28d}}. \tag{3}$$

Under different slurry water-cement ratios, the law of grouting plus solid strength degradation ratio with erosion time is shown in Figure 5.

Analyzing this chart, it can be seen that the strength degradation ratio of grouting plus solids increases with the increase in water-cement ratio under seawater environment. When the water-cement ratio is 0.8 : 1, the curve of grouting plus solids deterioration ratio is upward convex. The early stage is relatively gentle, and the medium-term change rate is fast. When the water-cement ratio is 1 : 1, the degradation ratio linearly decays with time. When the water-cement ratio is 1.4 : 1, the grouting plus solids degradation ratio curve is downward convex. When the water-cement ratio is 2 : 1, the initial decay is faster, and the decay of grouting plus solid degradation is a typical downward convex. It can be seen that with the change of grouting slurry water-cement ratio, the deterioration of seawater on sand grouted body presents different rules. The greater the water-cement ratio, the greater the erosion of grouted body by the seawater environment and the faster the erosion rate. The main reason is that as the water-cement ratio of the slurry increases, the degree of cement hydration reaction decreases. After the cement gel solidifies, the microcracks and microcracks in the reinforcement increase due to the shrinkage of the cement slurry and the presence of residual water in the slurry. After seawater enters grouted body, the contact area between seawater and cement is increased, thereby increasing the erosion rate.

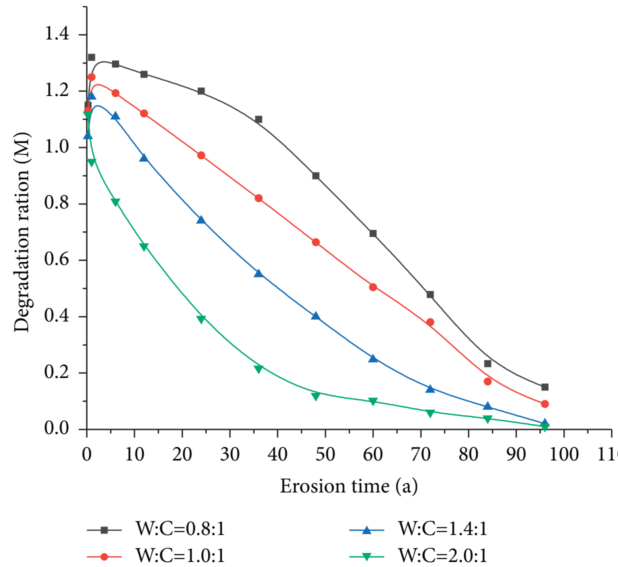


Figure 5: The weakening law of grouted body degradation ratio with time.

In order to study the relationship between the grouting plus solids strength degradation ratio and the slurry water-cement ratio, the degradation ratio is fitted to time. According to the curve type of the degradation ratio and time, $M = at^2 + bt + c$ is more suitable where the parameters a, b, and c are constants related to the slurry water-cement ratio.

By fitting, the values of the constants a, b, and c for each slurry water-cement ratio are obtained as shown in Table 2.

The constants a, b, and c are parameters determined by the slurry water-cement ratio. According to the relationship between the constants a, b, and c and the slurry water-cement ratio, a function form of $y = Ax^2 + Bx + C$ is used for fitting.

By fitting, the relationship between the constants a, b, and c and the slurry water-cement ratio N_{wc} is as follows, where the unit of the value of a is 10^{-5}.

$$\begin{cases} a = -16.97N_{wc}^2 + 66.98N_{wc} - 50.26 \longrightarrow R^2 = 0.997, \\ b = 0.019N_{wc}^2 - 0.0696N_{wc} + 0.037 \longrightarrow R^2 = 0.999, \\ c = -0.177N_{wc}^2 + 0.169N_{wc} + 1.309 \longrightarrow R^2 = 0.962. \end{cases} \tag{4}$$

In summary, through the water-cement ratio N_{wc} of the cement slurry, the parameters a, b, and c of the deterioration ratio of grouting plus solid strength can be obtained. According to the function form of grouting plus solid deterioration ratio M and erosion time, the quantitative relationship between grouting plus solid strength deterioration ratio and time is finally obtained. Aiming at the problem of lack of consideration of seawater erosion factors in the current grouting design under seawater environment, quantitative optimization is of great significance for the

Table 2: Constant values of degradation ratio.

Slurry water-cement ratio	Constant value			
	$a/\times 10^{-5}$	b	c	R^2
0.8	−7.7971	−0.0058	1.3482	0.985
1	0.21744	−0.01276	1.2702	0.997
1.4	9.9927	−0.02202	1.21554	0.999
2	15.8747	−0.02429	0.93438	0.98

reinforcement design of sand layers in seawater environment.

5. Conclusion

(1) The acceleration test of grouted body erosion under seawater erosion environment is designed to study the microscopic morphological characteristics of seawater erosion on grouted body erosion. The results show that seawater erosion causes fibrous and needle-like structures inside the solidified cement. At the microlevel, the mechanism of seawater erosion plus solids is revealed.

(2) The evolution law of grouting plus solid strength under different water-cement ratios and different seawater erosion time is obtained. The study found that the effective time of grouting plus solid with water-cement ratios of 0.8 : 1, 1 : 1, 1.4 : , and 2: 1 is 75a, 60a, 30a, and 15a.

(3) The strength degradation ratio index of seawater environment to grouting plus solids is proposed, and the quantitative relationship between seawater erosion time and grouting plus solids strength is established, which provides a basis for grouting and strengthening of sand layers under similar seawater environments.

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.

Acknowledgments

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