

Characteristics on Seawater Corrosion of Intensely Weathered Surrounding Rock of Subsea Tunnel

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Abstract: Existing studies on the durability of subsea tunnel mainly focus on the concrete deterioration and steel corrosion, while there are few on the influence of mechanical properties deterioration of surrounding rock on the durability of subsea tunnel. To improve the accuracy of long-term stability prediction, seawater corrosion tests of intensely weathered surrounding rock of subsea tunnel are carried out. In this study, the strength characteristics of remolded samples of intensely weathered granite under different seawater corrosion is established, and the strength attenuation equation under seawater corrosion is established, and the chemical damage evolution equation and model parameters are formulated, The findings provides the basis for analyzing the influence of corrosion and weakening of surrounding rock on the durability of tunnel within the operation period.

Keywords: Subsea tunnel; seawater corrosion; deterioration of surrounding rock; strength attenuation; damage

1 Introduction

The subsea tunnel is composed of surrounding rock and lining. The surrounding rock is both a loadbearing and load-generating structure; therefore, during the construction and operation periods, the change in the mechanical properties of surrounding rock directly affects the stress on the lining. And the change in the structural stress causes new deformation and cracking of lining concrete, which accordingly accelerates the intrusion of corrosive seawater into the lining, causing deterioration of the structure durability. At present, researches on the durability of subsea tunnel mainly focus on the deterioration of concrete and steel corrosion in seawater [1–6], while there are few on the influence of mechanical properties change of surrounding rock on the durability of subsea tunnel. To do well in the research and design of durability of subsea tunnel, it is of great significance to correctly understand the deterioration law of the mechanical properties of surrounding rock in corrosive environment, analyze the change in the stress on concrete lining as the external load varies, and build the evolutionary model of the mechanical properties of surrounding rock suitable for the application environment.



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Nguyen et al. [7] conducted the accelerated test research on the material properties of set cement, mortar and concrete samples under chemical corrosion and mechanical damage, and the test data showed that the ratio of coarse aggregate had a great influence on the penetration corrosion. Bertron et al. [8] simulated the corrosion of cement-based materials by the organic acid solution with PH value higher than that of on-site corrosion environment, which was suitable for studying the durability deterioration characteristics of the reinforced concrete structures in the underwater area of simulated marine environment. Hidalgo et al. [9] used nitric acid solution to soak concrete samples and increased the solution concentration to accelerate the corrosion thus to study the variation of microstructures of foundation materials under groundwater erosion. Atkinson et al. [10] studied the influence of hydrochloric acid solution and sodium hydroxide solution on the crack expansion speed, stress intensity coefficient and factors of rock, and the results showed that the chemical composition of the solution played a decisive role in rock expansion. Feucht et al. [11] made a three-axial compression test on the sandstone samples with prefabricated cracks under the effect of sodium chloride, calcium chloride and sodium sulfate solution, and studied the chemical corrosion of different kinds of solution on the friction coefficient and strength of crack surface. Karfakis et al. [12] studied the influence of chemical solution on the rock fracture toughness, and the results showed that the fracture toughness in the dry condition was higher than that in the wet condition. Hutchinson et al. [13] used hydrochloric acid and sulfuric acid solution to simulate acid rain in order to study the corrosion of limestone, and the results showed that the dissolution of limestone in these kinds of chemical solutions is different. Sun et al. [14] analyzed the influence of water on the properties of rock such as elastic modulus, strength, friction and deformation through the test and study, and the study showed that the mechanical properties of rock were closely related to water-rock interaction and the weakening of rock strength was in direct proportion to hydration damage. Tang et al. [15] studied the influence of different chemical solution on the uniaxial compressive strength and fracture toughness index of rock through the test, and preliminarily discussed the mechanical mechanism and quantitative method of water-rock reaction. Kang et al. [16–17] defined the chemical damage factor of substrate solute concentration to define the damage evolution of concrete materials. Lackner et al. [18] considered the effects of dissolution corrosion and hydration corrosion, and explained that the corrosion induced by desalting and dehydration was typical in the hydro-chemical corrosion damage of concrete.

The surrounding rock of weathered trough of Xiang'an Subsea Tunnel (in Xiamen China) is in poor conditions, and the lining is subjected to high water pressure and exposed to corrosive environment of seawater for a long time, which will lead to deterioration of the mechanical properties of surrounding rock and increase of the load on lining support, thereby causing deformation and cracking of the tunnel lining structure, and affecting the long-term stability and durability of the project. In this study, the deterioration of mechanical properties is analyzed through indoor seawater corrosion test, and the damage mechanics evolution model of intensely weathered granite under long-term seawater corrosion is established.

2 Corrosion Test Design of Intensely Weathered Granite

The indoor corrosion soaking tests of intensely weathered granite of weathered trough were carried out according to the engineering characteristics of Xiang'an Subsea Tunnel. The main purpose of these tests is to predict the deterioration of long-term mechanical properties of tunnel surrounding rock soaked in seawater for a long time based on the strength attenuation of intensely weathered granite soaked in corrosive solutions with different concentrations for a short time [19-20].

2.1 Test Design

A total of 90 samples of intensely weathered granite were prepared and divided into five groups on average. The filter study was placed on both ends of the sample, and the porous stones were added on the outside of the filter study, as shown in Fig. 1. After the samples were sealed with heat shrink tube, they



Figure 1: Remolded samples of intensely weathered granite

were soaked in five kinds of corrosive solution with different concentrations. After each month of soak, three samples of each group were taken out and dried for uniaxial compression test with a compression rate of 0.0005 mm/s, maximum pressure of 10 kN, and stroke limit of 5 mm. The mean value of the test strength was taken as the strength of the intensely weathered granite. After a 6-month cycle in this way, with the change of time and concentration, the attenuation law for the strength of the intensely weathered granite was obtained.

2.2 Preparation of Remolded Samples of Intensely Weathered Granite

The rock cores were collected in the weathered trough with the moisture content and density unchanged, and then they were mashed, mixed and pressed into 90 remolded samples with the diameter of 38 mm, height of 76 mm and density of 2.08 g/cm³. The rosin alcohol solution was added to the remolded samples to help cementing, so that they would not scatter when soaked and their strength would not be affected. When the rosin alcohol solution was prepared, the solute was 130 g rosin, and the solvent was 132,0 g 99% alcohol. Ten samples were remodeled at a time with 50 g rosin alcohol solution added, i.e., one sample contained about 10 g rosin alcohol solution.

2.3 Preparation of Corrosive Solutions with Different Concentrations

The analysis of the seawater composition in the tunnel area showed different concentrations of corrosive ions of groundwater in the tunnel overburden layer and seawater, higher content of ions such as Ca^{2+} , CI^- and SO_4^{2-} in the tunnel overburden layer than original seawater, and decrease of Mg²⁺ content by 2.4%, as shown in Tab. 1. With reference to the groundwater composition of fully-intensely weathered zones, the five kinds of solutions with different concentrations were prepared, as shown in Tab. 2.

Item	Ca ²⁺	Mg^{2+}	Cl	$\mathrm{SO_4}^{2-}$
Original seawater	370.45	1,171.73	16,501.97	2,125
Seawater after soaking of samples	387.57	1,143.76	17,459.12	2,272
Change	4.6% up	2.4% down	6% up	7% up

Table 1: Seawater composition before and after soaking of samples (mg/L)

3 Analysis of Sample Strength after Soaked in Distilled Water

Considering the influence of hydration and drying on the strength of intensely weathered granite, the distilled water was prepared for soaking test with the influence of hydration eliminated so as to analyze the law of strength attenuation caused by seawater corrosion.

Solution composition	Distilled water	1-time concentration	3-time concentration	5-time concentration	10-time concentration
1					
NaCl	_	23.025	69.074	115.124	230.247
MgSO ₄	_	3.258	9.775	16.292	32.583
MgCl ₂	_	1.988	5.965	9.942	19.884
Ph value	7	6.5	6	5.5	5

Table 2: Composition of artificial seawater for test (g/l)

3.1 Uniaxial Compressive Strength Analysis of Rock Samples

The uniaxial compression test was carried out on the samples after soaked in distilled water. As can be seen from the failure characteristics of the samples, the failure modes were classified into the following two categories:

Category I: the samples in the process of loading generated relatively large radial expansion, the central part continuously peeled off, and the pressure section continued to decrease, resulting in fracture in the middle, as shown in the left sample in Fig. 2. This phenomenon is primarily resulted from the low strength of intensely weathered granite. Under completely dry condition, the cohesion between the particles was very small; the samples would collapse in the case of expansion deformation and lose its strength finally.



Figure 2: Failure modes of uniaxial compression test after soak in distilled water

Category II: the samples in the test generated a number of splitting failure sections, and due to low tensile strength of intensely weathered granite, the failure section was tension-based, as shown in the right sample in Fig. 2.

After soaked in distilled water for different days, the curve of relationship between the deviatoric stress and axial strain was obtained from uniaxial compression test, as shown in Fig. 3. The numbering rule of rock samples was "0-30-1", where "0" means that the corrosive solution is 0-time concentration of seawater (distilled water), "30" means soak for 30 days, and "1" means No. 1 rock sample in the group.

The uniaxial compressive strength of samples after soaked in distilled water for different days is shown in Tab. 3. It can be seen that the uniaxial compressive strength of the sample decreases slowly with the increase of soaking in distilled water. The strength of the intensely weathered granite decreased by 4.48% from 0.677 MPa at d30 to 0.646 MPa at d180.



Figure 3: Stress-strain curves of samples soaked in distilled water for different days. (a) 30 d soaking in distilled water. (b) 60 d soaking in distilled water. (c) 90 d soaking in distilled water. (d) 120 d soaking in distilled water. (e) 150 d soaking in distilled water. (f) 180 d soaking in distilled water

3.2 Rock Sample Strength Attenuation Equation

After comparison and verification [21-22], the logarithmic attenuation function shown in Formula (1) was used to fit the attenuation law of the uniaxial compressive strength of rock samples with the increase of soak days.

$$\sigma_{\rm b}(t) = \sigma_0 \times \left[1 - \alpha_{\rm w} \times \ln(t)\right] \tag{1}$$

where, *t* is soak time (d), $\sigma_b(t)$ is uniaxial compressive strength (MPa) after soaked in distilled water for *t* days, σ_0 is the initial strength (MPa) of sample before soak, and α_w is hydration coefficient.

As shown in Fig. 4, the fitted parameters are $\sigma_0 = 0.737 MPa$ and $\alpha_w = 0.0231$, that is, the attenuation equation of compressive strength of rock samples over soak time is:

(2)

Sample No.		Uniaxial compressive strength (MPa)							
	30 d soaking	30 d soaking 60 d soaking 90 d soaking 120 d soaking 150 d soaking 180 d soaking							
1	0.683	0.646	0.652	0.691	0.653	0.616			
2	0.627	0.693	0.700	0.611	0.638	0.651			
3	0.720	0.673	0.633	0.663	0.666	0.672			
Average	0.677	0.670	0.662	0.655	0.652	0.646			







$$\sigma_{\rm b}(t) = 0.737 \times [1 - 0.0231 \times \ln(t)]$$

In addition to the influence of hydration, the surrounding rock of weathered trough of Xiang'an Tunnel is also affected by seawater corrosion. Therefore, in addition to considering the softening effect of hydration of distilled water, seawater corrosion tests were carried out to analyze the influence of seawater with different concentrations on the strength of intensely weathered granite.

4.1 Uniaxial Compressive Strength of Rock Samples after Corroded by Seawater with Different Concentrations

The surface of the samples before seawater corrosion was yellowish brown. As shown in Fig. 5, after the samples were corroded by seawater and baked at 105°C for 48 hours till constant weight, the results showed that: (1) After 30 days of soaking, white crystals appeared on the surface, and the samples had a little radial expansion after dried; (2) After 90 days of soaking, a large number of white crystals were formed on the surface, and the samples cracked after dried at 105°C; (3) After 180 days of soaking, the expansion deformation was more obvious and the crack widened.

A majority of remolded samples after soaked in artificial seawater had splitting failure from top to bottom after subject to the uniaxial compression test, and there were a large number of white crystals on the surface and even in the splitting cracks, as shown in Fig. 6.

The curves of relationship between the deviatoric stress and the axial strain obtained are shown in Figs. 7-10 after the samples are corroded in seawater with different concentrations for different days, and the numbering rule of rock samples is the same as that described above.



Figure 5: Forms of samples after corrosion and drying



Figure 6: Failure modes of remolded samples after soaked in artificial seawater and subject to uniaxial compression test

(1) Results of 1-time concentration seawater test

After soaked in 1-time concentration seawater, the uniaxial compressive strength of the sample decreased with the increase of corrosion time, which decreased by 8.58% from 0.671 MPa at d30 to 0.618 MPa at d180, as shown in Tab. 4 and Fig. 7.



Figure 7: Stress-strain curves of samples after 1-time concentration seawater corrosion for different days. (a) 30 d corrosion in 1-time concentration seawater. (b) 60 d corrosion in 1-time concentration seawater. (c) 90 d corrosion in 1-time concentration seawater. (d) 120 d corrosion in 1-time concentration seawater. (e) 150 d corrosion in 1-time concentration seawater. (f) 180 d corrosion in 1-time concentration seawater

(2) Results of 3-time concentration seawater test

After soaked in 3-time concentration seawater, the uniaxial compressive strength of the sample decreased with the increase of corrosion time, which decreased by 8.67% from 0.664 MPa at d30 to 0.611 MPa at d180, as shown in Tab. 5 and Fig. 8.

(3) Results of 5-time concentration seawater test

After soaked in 5-time concentration seawater, the uniaxial compressive strength of the sample decreased with the increase of corrosion time, which decreased by 9.26% from 0.661 MPa at d30 to 0.605 MPa at d180, as shown in Tab. 6 and Fig. 9.



Figure 8: Stress-strain curves of samples after 3-time concentration seawater corrosion for different days. (a) 30 d corrosion in 3-time concentration seawater. (b) 60 d corrosion in 3-time concentration seawater. (c) 90 d corrosion in 3-time concentration seawater. (d) 120 d corrosion in 3-time concentration seawater. (e) 150 d corrosion in 3-time concentration seawater. (f) 180 d corrosion in 3-time concentration seawater

(4) Results of 10-time concentration seawater test

After soaked in 10-time concentration seawater, the uniaxial compressive strength of the sample decreased with the increase of corrosion time, which decreased by 8.44% from 0.655 MPa at d30 to 0.604 MPa at d180, as shown in Tab. 7 and Fig. 10.

4.2 Strength Attenuation Equation of Rock Samples after Corroded by Seawater with Different Concentrations

After comparison and verification, the logarithmic attenuation function shown in Formula (3) was used to fit the attenuation law of the uniaxial compressive strength of rock samples with the increase of soaking days.



Figure 9: Stress-strain curve of samples after 5-time concentration seawater corrosion for different days. (a) 30 d corrosion in 5-time concentration seawater. (b) 60 d corrosion in 5-time concentration seawater. (c) 90 d corrosion in 5-time concentration seawater. (d) 120 d corrosion in 5-time concentration seawater. (e) 150 d corrosion in 5-time concentration seawater. (f) 180 d corrosion in 5-time concentration seawater

$$\begin{cases} \sigma_{\rm b}(c,t) = \sigma_0 \times [1 - \alpha_w \times \alpha_c \ln(t)] \\ \alpha_c = A \times c^B \end{cases}$$
(3)

where, *t* is the soaking time (d), $\sigma_b(c, t)$ is the uniaxial compressive strength (MPa) after soaked in distilled water for *t* days, σ_0 is the initial strength (MPa) before soaking which is 0.737 MPa obtained in the distilled water test, α_w is the hydration coefficient which is 0.0231 obtained in the distilled water test, α_c is the corrosion coefficient of seawater concentration, a power function of concentration (*c*), A and B are model coefficients, and *c* is the concentration ($c \ge 1$).



Figure 10: Stress-strain curve of samples after 10-time concentration seawater corrosion for different days. (a) 30 d corrosion in 10-time concentration seawater. (b) 60 d corrosion in 10-time concentration seawater. (c) 90 d corrosion in 10-time concentration seawater. (d) 120 d corrosion in 10-time concentration seawater. (e) 150 d corrosion in 10-time concentration seawater. (f) 180 d corrosion in 10-time concentration seawater.

The fitted values of parameters are shown in Tab. 8 and Fig. 11, that is, the attenuation equation of the compressive strength of rock samples over seawater corrosion time are [23-24]:

$$\begin{cases} \sigma_{\rm b}(c,t) = 0.737 \times [1 - 0.0231 \times \alpha_c \ln(t)] \\ \alpha_c = 1.2079 \times c^{0.0707} \end{cases}$$
(4)

Tab. 9 shows that the corrosion coefficient of seawater increases with the rise of concentration, that is, the increase of seawater concentration accelerates the corrosion of rock samples, resulting in great attenuation of strength.

Sample No.		Uniaxial compressive strength (MPa)					
	30 d soaking	60 d soaking	90 d soaking	120 d soaking	150 d soaking	180 d soaking	
1	0.717	0.665	0.650	0.674	0.652	0.635	
2	0.670	0.713	0.676	0.606	0.603	0.607	
3	0.627	0.608	0.622	0.639	0.632	0.611	
Average	0.671	0.662	0.649	0.640	0.629	0.618	

Table 4: Uniaxial compression test results

 Table 5: Uniaxial compression test results

Sample No.	Uniaxial compressive strength (MPa)						
	30 d soaking	60 d soaking	90 d soaking	120 d soaking	150 d soaking	180 d soaking	
1	0.706	0.649	0.697	0.635	0.641	0.625	
2	0.655	0.701	0.649	0.657	0.630	_	
3	0.631	0.618	0.588	0.607	0.592	0.596	
Average	0.664	0.656	0.645	0.633	0.621	0.611	

Note: "-" indicates that the failure or data of samples in the soak test is seriously abnormal.

 Table 6: Uniaxial compression test results

Sample No.	Uniaxial compressive strength (MPa)						
	30 d soaking	60 d soaking	90 d soaking	120 d soaking	150 d soaking	180 d soaking	
1	0.653	0.695	0.659	0.627	0.610	0.600	
2	0.716	0.678	_	0.605	0.580	0.647	
3	0.615	0.586	0.626	0.655	0.651	0.568	
Average	0.661	0.653	0.643	0.629	0.614	0.605	

Note: "-" indicates that the failure or data of samples in the soaking test is seriously abnormal.

Table 7: Uniaxial compression test results

Sample No.		Uniaxial compressive strength (MPa)						
	30 d soaking	60 d soaking	90 d soaking	120 d soaking	150 d soaking	180 d soaking		
1	0.655	0.649	0.662	0.631	0.580	0.583		
2	0.606	0.614	0.631	0.640	0.632	0.591		
3	0.706	0.678	0.599	0.603	0.610	0.639		
Average	0.655	0.647	0.630	0.625	0.608	0.604		

4.3 Strength Deterioration of Rock Samples after Seawater Corrosion

Fig. 12 shows the curved surface of strength attenuation of intensely weathered granite. It is more intuitive to see the influence of seawater concentration and corrosion time on the uniaxial compressive strength.



Table 8: Fitted values of coefficient

Figure 11: Curve of relationship between uniaxial compressive strength and soak time. (a) 1-time concentration seawater. (b) 3-time concentration seawater. (c) 5-time concentration seawater corrosion. (d) 10-time concentration seawater corrosion

Four sections were obtained in Fig. 12 along the concentration axis with c = 1, c = 3, c = 5 and c = 10 set respectively so that four curves were got as shown in Fig. 13. It can be seen that the prediction curves of different concentrations conform to the test data, which indicates that the strength prediction model well reflects the strength deterioration of the intensely weathered granite after long-term soaking in seawater, and as a result, the long-term strength of rock under seawater corrosion can be estimated.

5 Chemical Damage Evolution Equation of Intensely Weathered Granite

On the basis of the results of seawater corrosion tests, a chemical corrosion damage model based on the uniaxial compressive strength of the material was established as follows:

$$D_{rock} = 1 - \frac{\sigma_b(1,t)}{\sigma_b(0,30)} \tag{5}$$

where, D_{rock} is the chemical damage factor, $\sigma_b(0, 30)$ is the uniaxial compressive strength (MPa) of the intensely weathered granite soaked in distilled water for 30 days, that is, the initial uniaxial compressive strength before the rock sample is corroded, and $\sigma_b(1,t)$ is the uniaxial compressive strength (MPa) of

Concentration	1-time concentration	3-time concentration	5-time concentration	10-time concentration
	seawater	seawater	seawater	seawater
α_c	1.2079	1.3055	1.3536	1.4216

Table 9: Change of corrosion coefficient with concentrations



Figure 12: Curved surface of strength corrosion of intensely weathered granite



Figure 13: Strength corrosion curve of intensely weathered granite

the intensely weathered granite after corroded in 1-time seawater concentration (in-situ seawater concentration) for the time t.

According to the results of the previous test, the D_{rock} values at different time t are calculated by Formula (5), as shown in Tab. 10.

It can be seen that the chemical damage factor increases over time, and the relationship between the chemical damage factor and the corrosion time is fitted by the function shown in Formula (6) [25].

$$D_{rock} = 1 - (1 + \gamma \times t)^{\lambda} \tag{6}$$

where, t is the time of sea water corrosion time (y), D_{rock} is the chemical damage factor of the intensely weathered granite; γ and λ are the parameters of the damage model subject to 1-time seawater concentration.

The fitted results of parameters are $\gamma = 12.236$ and $\lambda = -0.0371$ from Fig. 14, that is, the attenuation equation of compressive strength of rock samples over soak time is:

$$D_{rock} = 1 - (1 + 12.236 \times t)^{-0.0371}$$
(7)

T (day)	30	60	90	120	150	180
D_{rock}	0.0177	0.0387	0.0509	0.0597	0.0665	0.0719
T (year)	1	2	3	5	8	10
D_{rock}	0.0934	0.114	0.127	0.142	0.156	0.163
T (year)	15	20	30	50	80	100
D_{rock}	0.175	0.184	0.196	0.212	0.226	0.232





Figure 14: Curve of chemical damage factor evolution equation of intensely weathered granite

6 Conclusions

In this study, the failure modes, strength characteristics and deterioration characteristics of intensely weathered granite subject to corrosion of seawater with different concentrations and corrosion time are analyzed. The following conclusions are reached:

- 1. Under the uniaxial condition, the rock failure modes are dominated by splitting cracks and expansion cracks. The uniaxial compressive strength of intensely weathered granite decreases with the increase of seawater corrosion time and decreases with the increase of corrosion concentration.
- 2. According to the distilled water soaking test, the attenuation equation of uniaxial compressive strength of intensely weathered granite over hydration time is established, and the corresponding hydration coefficient is determined.
- 3. According to the seawater corrosion tests with different concentrations, the attenuation equation of uniaxial compressive strength of intensely weathered granite after seawater corrosion with different concentrations is established, and the corrosion coefficient of seawater concentration is determined on the basis of test data.
- 4. Based on the attenuation equation of seawater corrosion strength of intensely weathered surrounding rock, the long-term strength of rock under in-situ concentration can be estimated.
- 5. The chemical damage evolution equation based on the uniaxial compressive strength of the material is established, and the long-term engineering stability can be analyzed properly with computerized technology.

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