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Research Article

Corrosive Environment Assessment and Corrosion-Induced Rockbolt Failure Analysis in a Costal Underground Mine

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As an effective ground-reinforcing system, rockbolts have been widely used in underground excavations. Corrosion of rockbolts has been one of the most reasons for rockbolts system failure. In this paper, the chemical composition and pH values of the groundwater in Sanshandao Gold mine are first tested. Corrosion of the slotted rockbolts used in roadways of the mine is analysed. The corrosion rate of rockbolts is evaluated based on experimental results from similar corrosive conditions. A time-dependent analytical model on anchoring force degradation caused by corrosion of the rockbolt is developed. Furthermore, the effects of corrosion rate and geometric parameters of the slotted rockbolts on anchoring force degradation are discussed. Suggestions on rockbolts support design in corrosive conditions are given. It has been found that, with the corrosion time increasing, the anchoring force between the rock and the rockbolt gradually decreases. The larger the corrosion rate is, the faster the anchoring force decreases. For long-term service roadways under corrosive conditions, a slotted rockbolt with a smaller radius and thicker wall can enhance the anchoring force.

1. Introduction

Rockbolts support is an effective ground-reinforcing system to keep stability of underground excavations, which has been widely used in subways, road tunnels, and underground mines. The performance of rockbolts is affected by the service environment, e.g., the ground stress, rock properties, and groundwater. The groundwater containing complex chemical compositions can make rockbolts corrosion. Corrosion of rockbolts has been of concern in many underground constructions, which can result in failure of reinforcing system and finally cause destruction of underground excavations [1]. The corrosion cost for underground construction of coal mines in China is estimated to be around 12.27 billion dollars in 2014 [2]. Therefore, there is a well-justified need for investigation corrosion of rockbolts in underground mines and its effect on the stability of underground constructions.

Rockbolts can be divided into metal rockbolts and nonmetal rockbolts based on the materials [3–5]. The nonmetal rockbolts are made of wood or glass, which are used on some temporary support cases. Millions of metal rockbolts are being installed worldwide every year. Nowadays, most studies on rockbolts only consider the mechanical performance of rockbolts with no structural changes. Former carried out pull-out tests on rockbolts and found that the axial stress of the bolt decreases exponentially from the point and loading the end of the bolt [6]. Chen et al. proposed an analytical model for load transfer behaviour of fully grouted bolts [7, 8]. Ma et al. carried out numerical modelling to investigate the nonlinear behaviour of rockbolts in tension. Kang et al. studied the stability of construction with rockbolt support under dynamic loads [9, 10].

With the service time and application amount of rockbolts increasing, corrosion of rockbolts has been widely observed. Some researchers paid attention to understand the effect of corrosion on the performance of rock support and reinforcement. Crosky and Hebblewhite analysed 44 failed rockbolts from four underground mines in Australia and found that most of the broken rockbolts appeared to have failed by corrosion [1]. Wu et al. analysed the steel mesh corrosion in underground coal mines and found the underground constructions are in a typical corrosive condition [11].

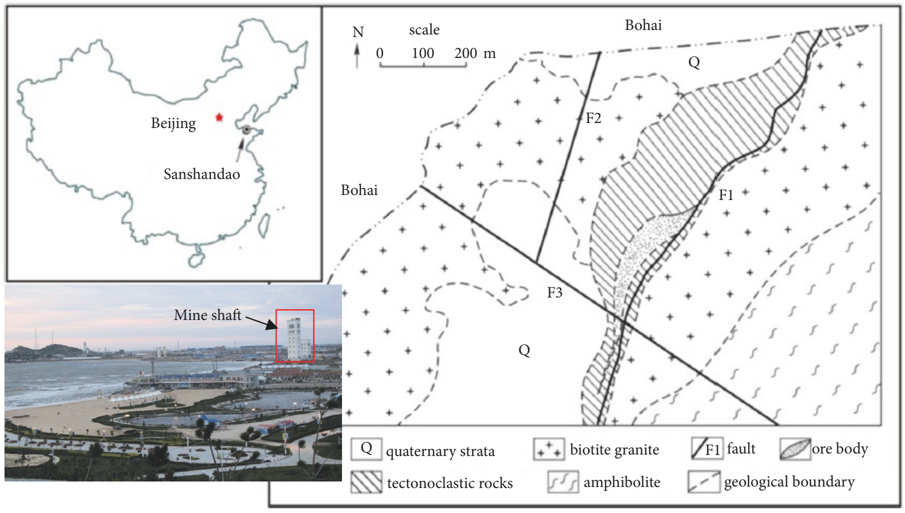

Figure 1: Hydrogeological sketch of the Sanshandao Gold mine.

Further, Wu et al. developed a framework for simulation stress corrosion cracking of cable bolts [12, 13]. Song et al. introduced the applications of smart sensors in monitoring corrosion of rockbolts [14]. Vandermaat et al. proposed a back-calculation method for predicting failure stress of rockbolts affected by stress corrosion cracking. However, current geotechnical engineering design methods for underground mining have only a minor amount of information regarding corrosion of rockbolts and its effect on the stability of underground constructions [15]. Slotted rockbolts are a type of rockbolts working by frictional resistance between the bolt and the rock [14]. The slotted rockbolt is easy to install and its cost is cheap, which is the most common rockbolt in underground mines. The anchoring force degradation of slotted rockbolts caused by corrosion has not been well understood.

This paper attempts to evaluate the corrosion of slotted rockbolts and corrosion-induced anchoring performance degradation in a coastal underground mine. The working condition of rockbolts and the groundwater flowing in Sanshandao gold mine are first analysed. The chemical composition and pH value of the groundwater are tested. Then the corrosion of rockbolt is discussed and the corrosion rate is estimated based on experimental results from several similar mines. A time-dependent analytical model for the anchoring force degradation caused by corrosion is developed. The effects of corrosion rate and geometric design of rockbolts on the anchoring force degradation are discussed. Finally, suggestions on rockbolts support design are given for the corrosive condition of the mine.

2. Corrosion Environment Assessment of Sanshandao Gold Mine

Sanshandao mine is an underground gold mine located in Jiaodong Peninsula where the largest gold resources in China exist. As shown in Figure 1, the mine is a coastal mine and a part of the deposit is under the sea. The hydrogeology of the mine is complex because three faults with a range of thickness 1~10 m exist in the mine area. Moreover, the fault F2 develops into the Bohai sea, which results in a powerful water conductivity. For evaluating the groundwater condition, a groundwater gushing survey is first carried out.

The groundwater inflow in the roadways of the mine is shown in Figure 2. It can be seen that the groundwater is very rich in the mine. The water gushes and seeps out from the surrounding rock. According to the metallogenic and geological condition, probably the groundwater comes from the ancient seawater stored in the rock. Figure 2(a) illustrates that the support steel has been corroded. Figure 2(b) shows that the rock surface has been dissolved at the roof of the roadway. The red-brown substance is corrosion products of minerals in the rock. The total water inflow of the Sanshandao Gold mine is approximately 14,000 m^3/day.

The chemical compositions of groundwater have a significant effect on the corrosion process of steel rockbolt. Accurate chemical analyses of groundwater are carried out. Water samples are in situ collected from 15 typical inflow points at different depths. As recommended by the Water Test Code ISO/TS 13530:2009 [16], the ion composition of water samples is obtained by ion chromatography and the pH value is obtained by electrode method. Major ion compositions and pH of the groundwater samples are obtained in Table 1. It can be found that the main anions of the groundwater are Cl^-, SO_4^{2-}, and HCO_3^-, and the main cations of the groundwater are Na^+, Mg^{2+}, and Ca^{2+}. The concentration value of Cl^- ranges within 11,728.50~25,382.65 mg/L. The average value of the Cl^- concentration is 18,737.90 mg/L, which is close to the Cl^- concentration of standard sea water [17]. Moreover, the pH value of the groundwater value ranges within 4.68~7.14 and the average value is 6.18. Therefore, the groundwater of Sanshandao Gold mine is mainly acid water. The anion and cation with the highest content of the groundwater are Cl^- and Na^+, respectively. The acid groundwater with

Table 1: Chemical composition of groundwater in Sanshandao gold mine.

Number	Depth	Cl^- (mg/L)	SO_4^{2-} (mg/L)	HCO_3^- (mg/L)	Na^+ (mg/L)	Mg^{2+} (mg/L)	Ca^{2+} (mg/L)	pH
1	510	16523.88	2261.24	297.12	8847.47	487.02	1045.30	6.43
2	510	16025.40	1807.01	100.94	6955.79	1124.45	965.45	6.20
3	525	13444.68	2057.21	234.41	7497.21	731.36	898.88	7.05
4	525	19365.27	2342.32	79.50	10054.26	668.48	854.01	5.89
5	555	20894.24	2145.96	175.90	9784.20	475.51	1164.71	5.22
6	555	15998.05	2167.64	141.46	7751.26	746.70	1224.83	6.38
7	555	11728.50	1325.37	268.11	6450.37	733.50	746.10	7.14
8	600	21828.79	2365.68	231.56	10789.73	982.22	1432.36	6.11
9	600	19154.18	2298.28	231.70	9452.80	754.51	581.44	5.71
10	600	21149.15	2356.63	54.55	10052.42	1384.30	1841.09	6.80
11	645	19422.77	3089.85	389.54	6894.24	912.45	1288.27	4.68
12	645	25382.65	2877.16	255.53	12329.65	1898.21	1154.32	6.27
13	690	21583.90	2132.05	103.36	9446.21	1463.83	1397.62	5.97
14	690	22114.57	2415.61	98.85	11336.05	1093.48	888.97	6.04
15	725	16452.45	1448.19	30.80	8369.97	975.24	856.32	6.75

(a) Water gushing from the roof

(b) Water seepage from the roof

(c) Water gushing from the sides

(d) Water accumulation at the floor

Figure 2: Groundwater condition in the Sanshandao Gold mine.

high content of Cl^- makes the metal rockbolt serve in a corrosive environment. The corrosion of rockbolt should not be ignored for keeping the roadway stable.

3. Rockbolt Corrosion in the Roadways

3.1. Corrosion of Rockbolt Attacked by the Groundwater. The excavation depth of Sanshandao Gold mine has reached -800 m level where the ground stress is very high. To ensure that roadways are stable and safe, a large amount of rockbolt is used to support rock. In consideration of mining cost, rockbolts used in the mine are the slotted metal bolt as shown in Figure 3. After the excavation of roadways, boreholes are drilled and then the slotted bolts are installed into the boreholes. The diameter of boreholes is smaller than that

Table 2: Corrosive conditions and corrosion rates in several mines [15].

Name of Mines	Cl^- (mg/L)	pH	Temperature (°C)	Flowing	Corrosion rate at 94^{th} day (mm/a)
Enterprise	2529.54	7.5	35.2	Strong	1.32
Leinster	5054.28	7.32	27.4	Strong	1.19
Darlot	18128.22	7.5	26.7	Strong	0.85
Kundana	39522.09	7.4	26.9	Strong	0.41
Olympic Dam	19142.51	7.9	27	Strong	0.33
Argo	92459.70	7.22	27.4	Strong	0.08

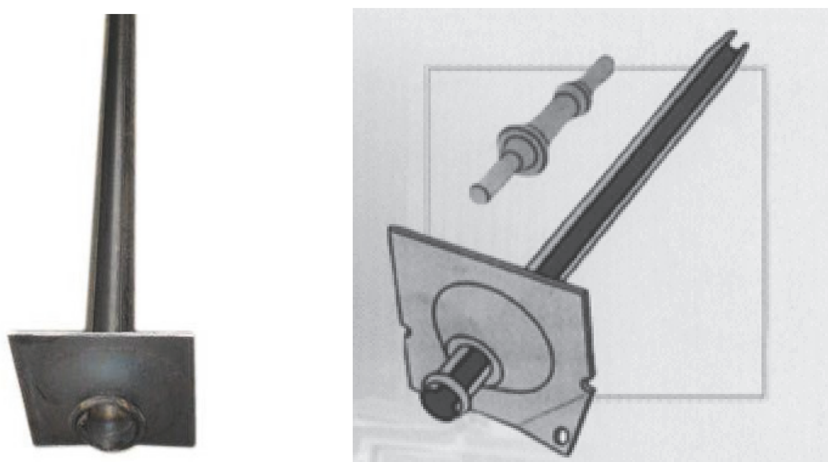

Figure 3: Slotted rockbolts used in Sanshandao gold mine.

of the rockbolt. A radial spring force is created by the compression of the C-shaped steel tube and a tight friction contact between the rock and the bolt is generated. There are many faults and fractures around the rock of roadways, which can be passes of the groundwater. As illustrated in Figure 4, the groundwater flows from the fault and fractures into roadways and reaches to attack the rockbolt. Because of the high content of chloride ion and low pH value of the groundwater, the electrochemical corrosion cells form and then the rockbolt gradually corrodes. Hassell concluded corrosion rates of rockbolt under several underground mines in Australia [15]. The corrosion rate and working conditions of rockbolts are introduced in Table 2. It can be seen that the corrosion rate in different corrosive environment ranges from 0.08 mm/a to 1.32 mm/a. And the temperature has a significant influence on the corrosion rate. According to the theory of reinforcement corrosion in concrete, the higher the temperature is, the larger the corrosion rate of steel bar is [18, 19]. The temperature of groundwater in Sanshandao gold mine varies from 35°C to 45°C. The deeper the mining depth is, the higher the temperature is. The average chloride ion content of the groundwater in Sanshandao mine is about seven times larger than that in Enterprise mine. Moreover, the pH value of the groundwater in Sanshandao mine is lower than that of mines in Table 2. It can be estimated that the corrosion rate of rockbolts in Sanshandao gold mine is higher than or similar to that of mines in Table 2. It should be mentioned that the corrosion rate of rockbolt is related to chloride ion, temperature, oxygen and metal composition, etc. This paper tries to analyse rockbolts failure under different corrosion rates.

3.2. Anchoring Force Degradation Induced by Rockbolt Corrosion. The anchoring force of rockbolt is the maximum force when pulling out the rockbolt from the rock, which is the most important parameter for assessing the effect of support. Most researches on rockbolt supporting did not consider the corrosion of rockbolt. The mechanical model of slotted rockbolt is shown in Figure 5.

The model describes a two-dimensional plain strain problem. The load between the rock and the rockbolt is assumed as uniform. The maximum stress of circular tube can be expressed as

$$\sigma_{\max} = \frac{12qR^2}{d^2} \tag{1}$$

where $\sigma_{\max}$ is the maximum stress of rockbolt, which is the yield stress for calculating the maximum anchoring stress; q is the maximum radial stress; R is the inner radius of rockbolt; and d is the thickness of rockbolt.

The frictional force F between the rock and the rockbolt can be obtained as

$$F = 2\pi Rq\mu \tag{2}$$

where μ is the frictional coefficient between the rock and bolt.

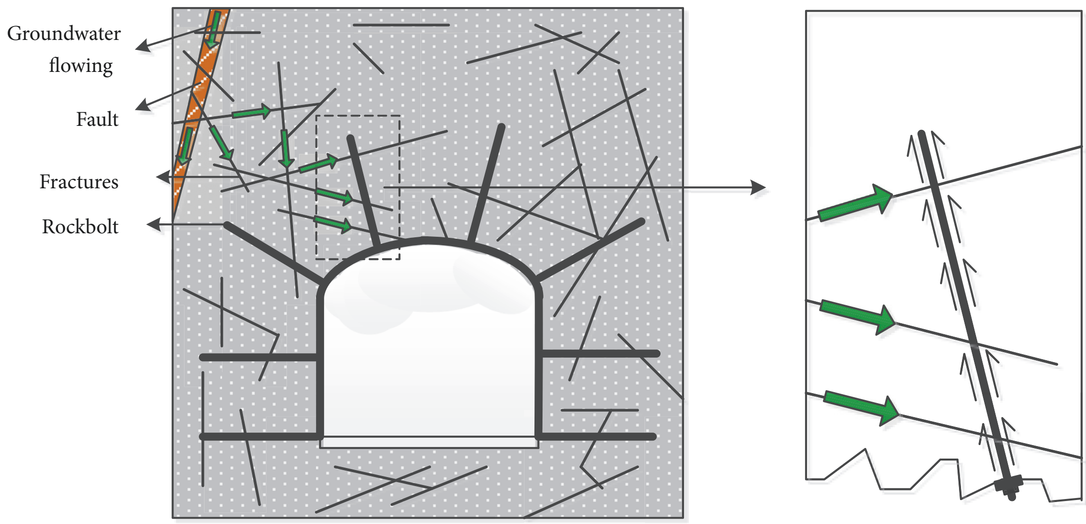

Figure 4: Rockbolt attacked by the groundwater.

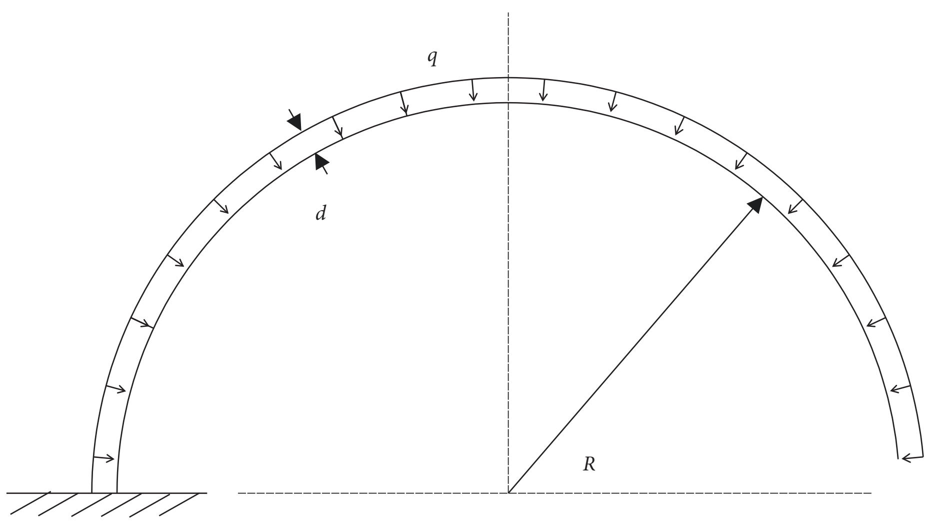

Figure 5: Mechanical model of the slotted rockbolt.

Combining (1) and (2), the maximum frictional force can be expressed as

$$F_{\max} = \frac{\pi \mu \sigma_{\max} d^2}{6R} \tag{3}$$

The friction force along the length direction of the rockbolt is in hyperbolic distribution and the maximum value is at the surface of roadway [20, 21]. The anchoring force can be expressed as

$$N = \frac{\pi \mu \sigma_{\max} d^2}{6R\alpha} \frac{e^{\alpha l} - e^{-\alpha l}}{e^{\alpha l} + e^{-\alpha l}} \tag{4}$$

where N is the anchoring force; l is the length of rockbolt; and α is a coefficient related to rock and rockbolt deformation properties:

$$\alpha = \sqrt{\frac{K}{Ed}} \tag{5}$$

where K is the shear stiffness of rock and E is the elastic modulus of rockbolt.

Corrosion makes the thickness of slotted rockbolts decrease with the time:

$$d = d_0 - t * v_d \tag{6}$$

where d_0 is the initial thickness of the slotted rockbolt; t is the corrosion time in years; and v_d is the corrosion rate in depth.

The time-dependent anchoring force of rockbolt could be calculated by the above equations. The values and units of parameters are shown in Table 3.

Figure 6 illustrates the time-dependent anchoring force under different corrosion rates. It can be seen that the original anchoring force of the rockbolt is about 42 kN which has a good agreement with the design value. The initial anchoring force can ensure the stability of roadways in Sanshandao gold mine. With the service time increasing, the anchoring

Table 3: The basic values and units of parameters.

Parameters	Value	Unit	Description
μ	0.40	/	Frictional coefficient
σ_{max}	375	MPa	Yield strength of the rockbolt
d_0	0.0025	m	Original thickness of the rockbolt
R	0.02	m	Radius of the rockbolt after installation
K	45	MPa/m	Shear stiffness of rock
E	210000	MPa	Elastic modulus of the rockbolt
l	1.80	m	Length of the rockbolt
v_d	0.05~1	mm/a	Corrosion rate in depth
t	/	year	Corrosion time
N	/	1000 kN	Anchoring force

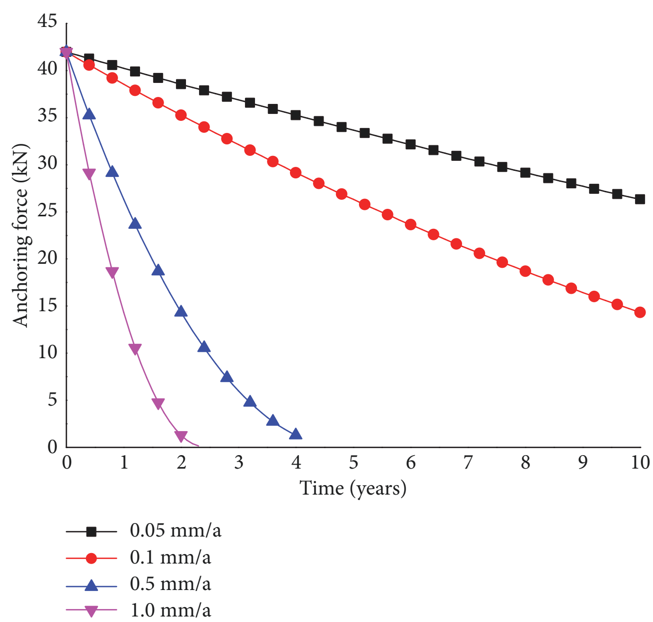

Figure 6: Anchoring force degradation induced by rockbolts corrosion.

force is gradually decreasing. It is because corrosion reduces the effective thickness of the slotted rockbolt. The larger the corrosion rate is, the faster the anchoring force decreases. When the corrosion rate is 1 mm/a, the anchoring force decreases to half of initial value at first year, while when the corrosion rate is 0.05 mm/a, the anchoring force decreases to about 60% of the initial value at tenth year. Therefore, corrosion of the rockbolt has great significant influence on the anchoring force. If the corrosion has not been considered when designing or using the rockbolt, the roadways may be unstable in the serving period. It should be noted that the analysis on the anchoring force only considers the thickness reduction of the slotted rockbolt. The effects of corrosion products on frictional coefficient and stress corrosion cracking of rockbolts are not considered. In fact, with the corrosion degree increasing of rockbolt, the corrosion products will be washed away by the flowing groundwater. The strength of rockbolt would be reduced because of corrosion. Moreover, the stress corrosion of rockbolt may occur under high stress conditions. However, the effects of corrosion on the frictional coefficient and the strength of the slotted rockbolt are not very clear now. More experimental researches should be carried out on the corrosion of rockbolt.

3.3. Parametric Studies of the Rockbolt on Anchoring Force Degradation. The radius, thickness, and length of the slotted rockbolt are three important parameters when designing a rockbolt. Taking corrosion rate 0.5 mm/a as examples, the effects of radius, thickness, and length of slotted rockbolt on anchoring force are discussed. Figure 7 shows the anchoring force degradation under different radius of the rockbolt. The smaller the rockbolt radius is, the larger the anchoring force is. With the increasing of corrosion time, the anchoring force is smaller and smaller. The radius of rockbolt has little effect on the final failure time. However, in the effective service period of rockbolts, a smaller value of rockbolt radius has a better anchoring ability for roadways. Figure 8 illustrates the anchoring force under different thicknesses of slotted rockbolts. It can be found that the thicker the rockbolt is, the larger the anchoring force is. For a slotted rockbolt with

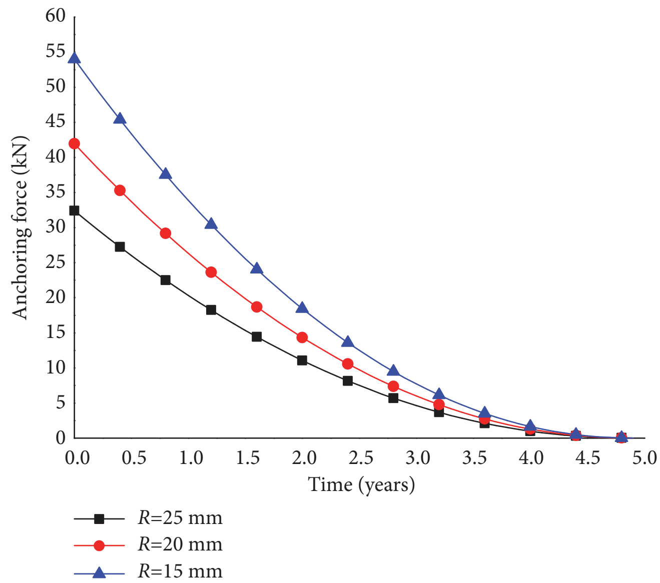

Figure 7: Anchoring force degradation under different radius of rockbolts.

thickness 2.0 mm, the anchoring force reduces to 10 kN at about 1.5 years when the anchoring force for thickness 3.0 mm is about 35 kN. Therefore, for roadways under a corrosive environment, it is necessary to use a thicker slotted rockbolt. The effect of lengths of rockbolts on anchoring force is shown in Figure 9. It can be seen that the longer the rockbolt is, the larger the anchoring force is, while for long-term service time of rockbolt, the anchoring forces are similar for different lengths of rockbolts.

4. Suggestions for the Rockbolts Support Design in Corrosive Underground Mines

Rockbolt support is the most common support type for roadways in underground mines. However, many roadway failure accidents occur due to inappropriate rockbolt support designs. The serivce period of roadways in underground mines varies from about 1 to 50 years according to the purposes of roadways. Most managers simplify the roadways as temporary constructions and ignore the durability of roadways. However, the corrosion of rockbolts has a great significiant infuence on the stability of roadways, especially for high corrosive environment or long-term service roadways. The following suggestions are given for rockbolt support under corrosive underground mines: (1) Comprehesive tests and analyses on the groundwater inflow, chemical composition of the groundwater, fracture network of the rock, and corrosion rate should be carried out. The corroson rate and corrosion degree of metal rockbolt should be measured and monitored. (2) The service time of roadways should be considered when designing rockbolt support. For long-term service roadways under corrosive conditions, a slotted rockbolt with a smaller radius and thicker wall can enhance the anchoring force. (3) More researches on stress corrosion and pitting corrosion of rockbolt and effect of corrosion on the friction between the rock and rockbolt can be carried out for better understanding

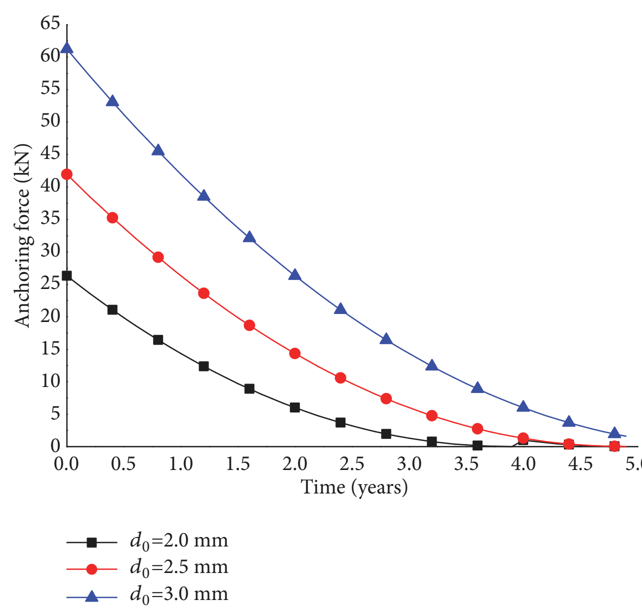

Figure 8: Anchoring force degradation under different thicknesses of rockbolts.

corrosion-induced rockbolt failure. (4) Corrosion prevention methods like barrier coatings and hot-dip galvanization can be used to prevent or minimize rockbolt corrosion. Special rockbolts made of stainless steel or fiber reinforced plastics can be used under economic permitted level.

5. Conclusions

In this paper, the chemical composition and pH value of the groundwater in Sanshandao gold mine were first tested. The corrosion mechanism of the slotted rockbolt used in the roadways was analysed. The potential corrosion rate of

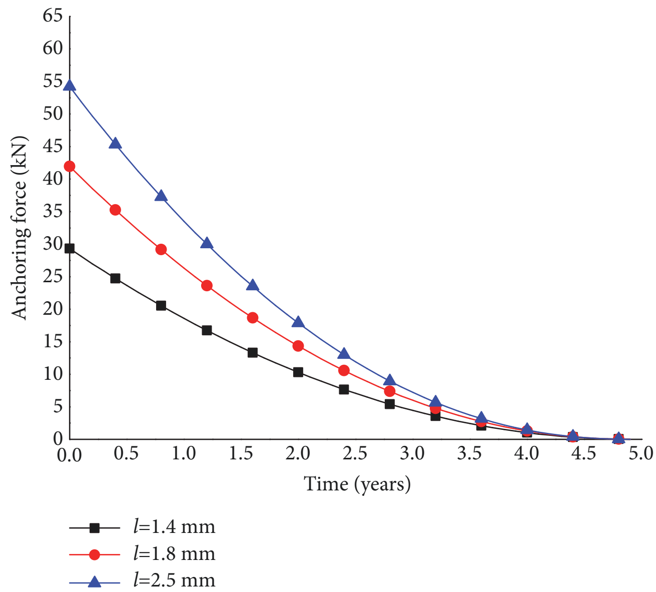

Figure 9: Anchoring force degradation under different lengths of rockbolts.

rockbolt was evaluated based on results from similar corrosive conditions. An analytical model for the anchoring force degradation of rockbolts caused by corrosion was developed. Further, the effects of corrosion rate and geometric parameters of the rockbolt on the corrosion-induced anchoring force degradation are investigated. Finally, suggestions on rockbolt support design in corrosive underground mines are given. It has been found that the groundwater in Sanshandao gold mine contains high concentration chloride ion and the pH value of the groundwater ranges within 4.68~7.14. The metal slotted rockbolt used in the roadways is attacked by the groundwater flowing in the fractures. It is estimated that the corrosion rate of the slotted rockbolt is in the range of 0.5~1.5 mm/a. The anchoring force between the rock and the rockbolt will gradually decrease with the corrosion time of the rockbolt increasing. The larger the corrosion rate is, the faster the anchoring force decreases. For long-term service roadways under corrosive conditions, a slotted rockbolt with a smaller radius and thicker wall can enhance the anchoring force.

Data Availability

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

Consent

Consent to submit has been received explicitly from all authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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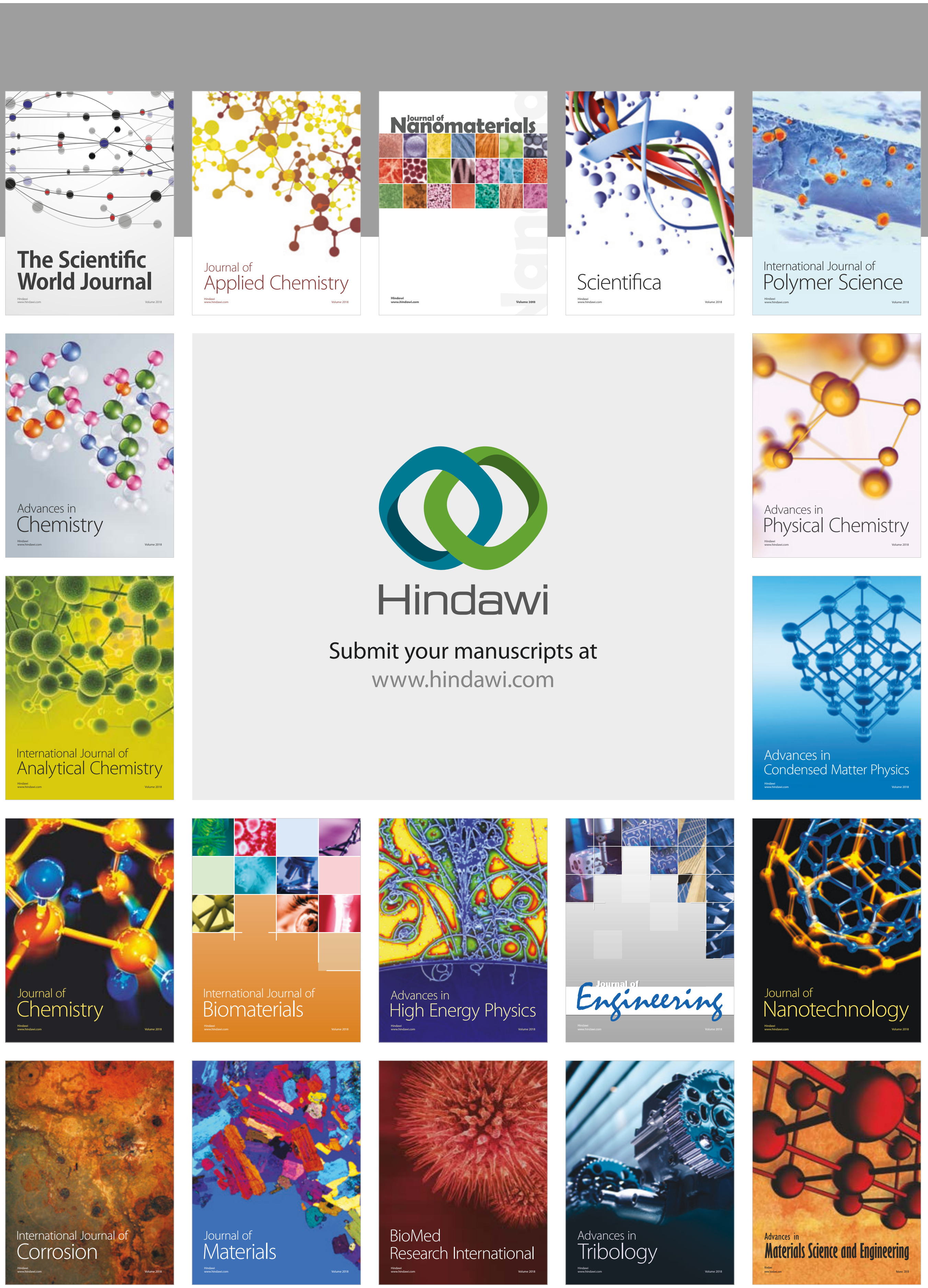
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