Research Article

Mechanical Characterization of Anchor under Uniaxial Compression Loading Conditions

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Bolt reinforcement technology plays an important role in supporting the construction of many engineering fields, and the uniaxial loading characteristics and behavior tests of anchors have great significance to the research and application of anchors. Therefore, four anchor specimens GA ~ GD were fabricated and tested to explore the macro and microbehavior characteristics of anchors under uniaxial compression. The stress-strain curves for GA ~ GC specimens under uniaxial compression were analyzed. The stress-strain curve, elastic strain and creep strain, the failure results, and electrochemical impedance spectroscopy of specimen GD under multistage loading were investigated. The results showed a series of behavior characteristics of anchor under uniaxial compression. Under uniaxial compression, the shapes of stress-strain curves of three specimens GA ~ GC were similar, and they had experienced four different stages from stage I to stage IV, respectively. After calculating the uniaxial compressive strength of the three specimens, the average uniaxial compressive strength of these specimens was $\sigma_c = 8.31$ MPa. The stress-strain curve of the specimen GD was obtained by a multi-stage loading test. The total strain of the specimen consisted of elastic strain and creep strain. In the whole process of loading, the proportion of elastic strain was greater than that of creep strain, and the proportion range of elastic strain was 51.90% ~ 55.82%. Seven electrochemical impedance spectrum curves of the specimen GD under multistage compression load were obtained. The dispersion and concentration of Nyquist curves were affected by different loading levels; the higher the loading level, the more dispersed the Nyquist curve is. In the measured Bode diagram, compared with the previous six measurements, the variation laws of impedance value and phase angle measured at the seventh time in the failure stage of the specimen were quite different. The above research and conclusions can provide some reference for the test theory and engineering application of anchors.

1. Introduction

Rock bolting support can improve the strength and shear resistance of the rock, making the rock bear greater cooperation, and improving the stability of an engineering rock tunnel [1, 2]. The use of anchor bolt makes the rock bear greater cooperation, and therefore improves the stability of a layered rock tunnel [3]. For this reason, many types of anchor bolts are used in mine and tunnel construction, and the waveform anchor bolt technology is used in the support of underground phosphate rock [4]. Lei et al. [5] studied the uniaxial compression test of fractured rock specimens without anchorage, full-length bonded anchorage, and prestressed anchorage. The results showed that the length of the crack had little effect on the anchorage specimen, and full-length bonded anchorage and prestressed anchorage could significantly improve the strength of the anchor and restrain the deformation of the fractured rock mass. Kan et al. [6] pointed out that the anchoring effect of anchor solid was related to the parameters of the anchoring agent used and the mixing speed applied in anchoring installation. The anchoring agent and the mixing speed would affect the anchoring strength. Sakhno et al. [7] adopted the full-length drilling self-extending mixture anchoring technology...
developed in the Wieliczka mine to improve the maximum anchoring capacity of the anchor and the elastic deformation bearing capacity of the anchor. Wu et al. [8] studied the uniaxial compression mechanical behavior of prestressing anchors in coal mining by numerical simulation and considered that the bolt had the function of absorbing and storing energy. Ren et al. [9] conducted a uniaxial compression test on the anchorage column of a weak interlayer in the laboratory and found that the existence of anchor rod improved the ductility of the stress-strain curve of the specimen. Xiao et al. [10] used a compression shear test to study the mechanical properties of CFRC composite grouting materials under long-term water immersion conditions. Zhu et al [11] established the coupling effect model of equal creep deformation and stress and verified the model by a uniaxial creep test. It was found that there was a nonlinear relationship between prestress loss and the increase in stress level. With the increase of axial load, the specimen produced compression deformation and transverse expansion. The first mock exam was carried out by Zhu and others [11], and the model of creep deformation and stress was established. Zhao et al. [12] studied the creep deformation characteristics of red sandstone under uniaxial compression and multi-stage loading. Sun et al. [13] studied the failure characteristics of anchors under multi-stage loading and corrosion by indoor test. Zheng et al. [14] conducted a uniaxial compression test on fiber reinforced concrete, and discussed the influence of fiber type and fiber content on the uniaxial compressive strength of fiber reinforced concrete, showing nonuniformity and nonlinearity. Different fiber content would also change the failure mode of the specimen. Algburi et al. [15] studied the relationship between axial load and axial strain of composite reinforced concrete by uniaxial compression. Zainal et al. [16] studied the experimental mechanical properties of hybrid fiber reinforced wonton materials with super-plasticizer by unidirectional loading.

Electrochemical impedance spectroscopy (EIS) is a multi-purpose and destructive testing technology [17]. Electrochemical impedance spectroscopy is also widely used in the research of nanocomposite preparation [18], carbon steel corrosion [19], lithium-ion battery [20], and metal oxide electrode [21]. Viacheslav et al. [22] believed that electrochemical impedance spectroscopy could reveal the dynamic characteristics of local heterogeneous interfaces. Ribeiro and Abrantes [23] used electrochemical impedance spectroscopy to monitor the corrosion state of reinforced concrete. Peng et al. [24] characterized the permeability of grouted fractured rocks by electrochemical impedance spectroscopy. Electrochemical impedance spectroscopy was used to monitor the corrosion state of reinforced concrete. Song [25] constructed the equivalent circuit model of the AC chemical impedance spectrum of concrete and pointed out that water-cement ratio and hydration time will affect the equivalent circuit. Dhouibi et al. [26] used electrochemical impedance spectroscopy to determine the effect of corrosion inhibitors on the corrosion resistance of reinforcement. Deus et al. [27] studied the corrosion rate of the reinforcement in concrete under the influence of chloride and temperature by electrochemical impedance spectroscopy. The results showed that the corrosion rate was dependent on temperature. The electrochemical analysis method was used in the experimental measurement of anchor under osmotic pressure [28]. Sohail et al. [29] conducted electrochemical test research on different types of reinforcement under corrosion conditions. He et al. [30] studied the electrochemical impedance spectrum characteristics of X70 pipeline steel corroded by saline sandy soil by electrochemical method and scanning electron microscope. It was considered that when the water content exceeds 18%, the main corrosion process was point corrosion or local corrosion. The Nyquist curve of the electrochemical test can reflect the development of cracks in mudstone under the condition of the freeze-thaw cycle [31, 32]. Li et al. [33] studied the change of resistivity of coal under different loading modes. The results showed that the resistivity of coal would change with different loading modes, which may be related to the change in pore structure and stress state of coal.

In conclusion, the above-related research methods, research results, and engineering applications provided a meaningful reference for the further study of anchor characteristics. The study of this article focused on the behavior characteristics of anchor under uniaxial loading. Anchor specimens were made and tested in the laboratory. The tests included a uniaxial compression test, multi-stage loading test, and electrochemical impedance spectroscopy test. The structure of the rest of the article is as follows. The second section introduces the test materials and methods. The third section provides the test results and discussion. Lastly, the fourth part presents the conclusions of the study.

2. Materials and Methods

2.1. Specimen Preparation. The general idea of specimen making is to select the mold with the appropriate size, next arrange the anchor rod simulation device in the mold, and then pour the mold, vibrate, compact, and maintain. The specific process can be divided into the following six steps.

1. In the laboratory of Zhongyuan University of Technology, internal size 150 mm × 150 mm × 150 mm mold was selected, and the release agent was evenly applied on the inner side of the mold.

2. Then, the threaded rod with a diameter of 5 mm, gasket, and nut were used to simulate the anchor bolt, the anchor agent was applied on the surface of the anchor bolt, and then the anchor bolt was arranged at the geometric center of the mold.

3. One solid steel bar with a diameter of 1 cm was arranged on the other four geometric center points of the mold, and the surface of each solid steel bar was coated with a release agent.

4. Cement, gypsum, quartz sand, water, and boron were mixed according to the mass ratio of 1:0.25:0.25:0.12. Then, the mixture was thoroughly stirred in the mixer. After mixing evenly, the mixture was
poured into the mold. Then, the test block was placed on the shaking table for vibration and compaction.

(5) After the sample was cured at room temperature for 24 h, demoded and taken out of the embedded solid rigid bar, and inserted the steel porous water pressure pipe coated with anchoring agent into the reserved hole. A conductive electrode sheet was pasted in the middle of the porous steel pipe.

(6) Placed the anchored rock specimen at room temperature and in a naturally dry environment for 28 days. The fabricated specimen can prepare for the unidirectional compression test of the specimen in the next step. The schematic diagram of the test specimen is shown in Figure 1.

2.2. Test Apparatus

2.2.1. Uniaxial Compression Test Machine. The uniaxial compression test was carried out by the YR-2000 rock testing machine. The main parameters of the testing machine are shown in Table 1.

2.2.2. Electrochemical Workstation. CHI660E electrochemical workstation was used to measure the electrochemical characteristics of the test specimen in real-time. The main parameters of the CHI660E electrochemical workstation are shown in Table 2.

2.3. Test Process. Uniaxial compression test, uniaxial multi-stage loading test, and electrochemical impedance spectroscopy test were carried out.

(1) According to the preparation method of experimental specimens, four specimens for test shall be prepared in the laboratory.

(2) Three of the four specimens (GA, GB, GC) were used to carry out the uniaxial compression test without permeability. Then, the stress-strain curve of each sample was analyzed. The force applied by the testing machine to the specimen is $F$. The stress of the test specimen is $\sigma$. The contact area between the test specimen and the testing machine is $S$. The stress of the test specimen can be calculated by the following formula:

$$\sigma = \frac{F}{S}. \quad (1)$$

(3) The remaining specimen GD was used to carry out a uniaxial multi-stage loading test without penetration. Then, its multi-stage loading mechanical characteristics and electrochemical impedance spectroscopy characteristics were analyzed.

3. Results and Discussion

3.1. Uniaxial Compression Test. In order to accurately obtain the uniaxial compressive strength of the test specimens, the method of taking the average value of multiple groups of tests was adopted. The uniaxial compression tests on $n$ specimens in total were carried out and each of the $n$ test specimens was taken and named as $i$. Through the uniaxial compression test, the uniaxial compressive strength of the specimen $i$ is $\sigma_{ci}$. The uniaxial compressive strength of these test specimens is recorded as $\overline{\sigma_c}$. Then the relationship between $\overline{\sigma_c}$ and $\sigma_{ci}$ can be expressed by the following formula:

$$\overline{\sigma_c} = \frac{1}{n} \sum_{i=1}^{n} \sigma_{ci}. \quad (2)$$

First, the three test specimens were numbered GA, GB, and GC, respectively. Secondly, the three specimens were subjected to uniaxial compression test, and the stress-strain curves of each specimen were obtained. The peak compressive strength of GA, GB, and GC test specimens were 8.31 MPa, 8.4 MPa, and 8.23 MPa, respectively. Using the formula (2), the average uniaxial compressive strength of the tested specimens is $\overline{\sigma_c} = 8.31$ MPa.

The shape of the uniaxial compression stress-strain curve of GA, GB, and GC was similar. In order to study the characteristics of the uniaxial compression test process of the
specimen in detail, the GA specimen was taken as an example for analysis. According to the curve variation law, the stress-strain curve of specimen GA was divided into four different stages.

1. Stage I: Gap compaction stage. The stress-strain curve formed at this stage shows an upward concave curve. There were different volumes of pores in the fabricated specimen GA. When subjected to external force, the pores' volume in the anchor specimen GA gradually decreased.

2. Stage II: Elastic deformation stage. The main reason for the deformation at this stage was that when the specimen was subjected to external stress, friction will occur between the internal cracks of the specimen, and there will be force and reaction force between the pores. Ideally, the deformation at this stage will recover with the disappearance of external force, and the stress-strain curve of the specimen at this stage basically presented the characteristics in a straight line.

3. Stage III: Stable development stage of microfracture. Under the continuous action of gradually increasing external stress, new cracks began to form in the specimen. The stress-strain curve formed in this stage showed a relatively gentle shape. The overall curve at this stage had a downward trend, indicating that the microcracks in the specimen were developing and changing.

4. Stage IV: Unstable development stage of microfracture. At this stage, the crack development speed of the specimen accelerated rapidly and gradually developed into a macrofracture surface. In this process, the specimen’s bearing capacity decreased rapidly, but the specimen will still maintain a certain bearing capacity.

3.2. Multistage Loading Test. The test specimen was loaded in stages. The loading process was divided into six different levels and the loading sizes at all levels are shown in Table 3.

The test machine’s loading speed to the specimen GD was 1 kN/min. The holding time of each constant pressure level stage was about 8 hours. The specimen’s change process of strain during multi-stage loading levels is shown in Figure 2. For each loading stage, the strain of the specimen will increase with the increase of the load on the specimen. At the moment after the failure of the specimen, the strain of the specimen increased rapidly. The characteristics of the specimen GD after failure are shown in Figure 3. There were longitudinal cracks on the four sides of the specimen. Some surface materials even separated and fell off.

It can be seen from Table 4 that the elastic strain value and creep strain value of test specimen GD increased with the progress of loading. Furthermore, it was found that the elastic strain value of the test specimen GD at each stage was greater than its creep strain value. According to the details of Table 4, the increase of elastic strain was gradually reduced with the increase of the load grade, while the increase of creep strain was increased with the subsequent increase of the load level at most of the load levels. The variation law of elastic strain and creep strain reflects that the elastic strain
and creep strain of anchor specimen were jointly controlled by the value of the loading process and the length of loading time. In addition, the proportion of elastic strain value and creep strain value in the total strain value was shown in Table 4. In the first loading stage, the elastic strain of the specimen accounted for 55.21% of the total strain, 55.82% of the total strain for the second loading stage, 54.04% of the total strain for the third loading stage, 52.61% of the total strain for the fourth loading stage and 51.90% of the total strain for the fifth loading stage. The increase of elastic strain of loading stages 2 to 6 was 0.074, 0.067, 0.062, 0.053, and 0.040, respectively. The increase ratio of elastic strain at each stage was 41.11%, 26.38%, 19.31%, 13.84%, and 9.17%, respectively. On the other hand, the proportion of creep strain in the total strain for the loading stages 1 to 6 was 44.79%, 44.18%, 45.96%, 47.39%, and 48.10%, respectively. The increase of creep strain of loading stages 2 to 5 was 0.055, 0.072, 0.072, and 0.059, respectively. The increase ratio of creep strain at each stage was 37.67%, 35.82%, 26.37%, and 17.10%, respectively. The results showed that the proportion of creep strain in total strain showed a slight upward trend. During the whole loading process, the elastic strain of the specimen accounted for more than 50% of the total strain, and the elastic strain produced by the specimen was greater than the creep strain of the specimen.

3.3. Electrochemical Test. The changes in microstructure in specimen GD were monitored by the electrochemical method in real-time. A total of seven sampling monitoring operations were conducted. The first sampling operation shall be carried out before the multi-stage loading test. The time point of the other 6 sampling operations was 10 minutes before the end of each step loading. The data obtained from these seven sampling operations were numbered from A to G in chronological order.

Assuming that the test frequency was expressed in \( \omega \), then the impedance expression in electrochemistry can be expressed as follows:

\[
Z(\omega) = Z'(\omega) + jZ''(\omega),
\]

where \( Z \) is impedance, \( Z' \) is the real part of the impedance, \( Z'' \) is the imaginary part of the impedance. The values of impedance \( Z \), real part of the impedance \( Z' \) and imaginary part of impedance \( Z'' \) change with frequency \( \omega \). Therefore, the electrochemical Nyquist impedance spectrum curves

**Figure 3:** Failure characteristics of specimen GD. ((a)-(d) are the four sides of test specimen GD.).
and Bode diagram curves of the tested specimen can be obtained by changing the test frequency.

Figure 4 plotted the seven Nyquist curves of specimen GD at different sampling times. Through the comparative analysis of these seven groups of curves, it can be found that:

1. Generally, the geometric shapes of Nyquist curves measured for specimen GD at different times are similar, but the geometric dimensions of these curves were different. On the one hand, the first 4 test curves $A \sim D$ were closer in space in the three-dimensional coordinate axis, while the last 3 test curves $E \sim G$ are more dispersed in space in the three-dimensional coordinate axis. On the other hand, with the loading time of the specimen, compared with the data curve measured at the previous time, the Nyquist curve obtained at the latter time showed the characteristic that the length gradually becomes shorter.

2. With the change of test frequency, the real part $Z'$ and imaginary part $Z''$ of the impedance of the tested specimen were also changing. In the lower frequency band of the frequency, with the increasing frequency, the real part of the impedance $Z'$ and imaginary part of the impedance $Z''$ of each test curve had an overall trend of decreasing. In the higher frequency band of the frequency, the variation law of the real part $Z'$ and imaginary part $Z''$ of the impedance gradually did not tend to be unified.

3. The morphological changes of electrochemical curves and the changes in impedance at different test times were analyzed. It was found that when the load increased and the loading time became longer, the pores in the specimen were gradually compressed and the volume of the specimen became smaller. Consequently, cracks in the specimen developed and finally the specimen was damaged. The test curve law reflected the development and inoculation of pores and cracks in the specimen to a certain extent.

By analyzing each area curve in Figure 5(a), it can be seen that the impedance value decreases with the increase of detection frequency. From the shape of the test line, the cumulative detection value of the low-frequency phase was greater than that of the high-frequency phase. The total area accumulation chart showed the characteristics of high first and then low. Comparing the characteristics of each area curve, it can be found that the larger the stress loading value and the longer the time for the specimen, the faster the impedance value decreases. Except for the last group of G area curve, the cross-sectional areas of the other six groups had a relatively small intercept along the vertical direction. The reason was that the test time of group G data was obtained in the sixth loading level stage, in which cracks and even damage appear in the specimen. The crack and

| Load level | 1st level | 2nd level | 3rd level | 4th level | 5th level | 6th level |
|------------|-----------|-----------|-----------|-----------|-----------|-----------|
| Elastic strain | 0.180/55.21% | 0.254/55.82% | 0.321/54.04% | 0.383/52.61% | 0.436/51.90% | 0.476/- |
| Increase of elastic strain | — | 0.074/41.11% | 0.067/26.38% | 0.062/19.31% | 0.053/13.84% | 0.040/9.17% |
| Creep strain | 0.146/44.79% | 0.201/44.18% | 0.273/45.96% | 0.345/47.39% | 0.404/48.10% | — |
| Increase of creep strain | — | 0.055/37.67% | 0.072/35.82% | 0.072/26.37% | 0.059/17.10% | — |
| Total strain | 0.326/100% | 0.455/100% | 0.594/100% | 0.728/100% | 0.84/100% | — |

Figure 4: Nyquist diagram of anchor specimen GD.
failure had a great influence on the test results of electrochemical impedance. The variation area curves of phase angle with frequency at different times of specimen GD are shown in Figure 5(b). In the \( \ln \omega - \varphi \) coordinate axis, the distribution of \( A \sim F \) area curves had differential characteristics, and the area curve \( G \) was independent of them. \( A \sim F \) area curve showed the characteristics of upward convexity. With the increasing detection frequency, the phase angle values of the seven curves were increasing. Among the seven groups of curves, the phase angle of group \( G \) was the fastest to increase. The test results showed that the more serious the internal damage of the specimen is, the greater the influence on the phase angle is obtained by the electrochemical test.

![Bode diagram of anchor specimen GD](image_url)

Figure 5: Bode diagram of anchor specimen GD. (a) Area stack diagram of impedance change. (b) Area stack diagram of phase change.
4. Conclusions

In this study, four groups of anchor specimens GA ∼ GD were made in the laboratory. Then, uniaxial compression tests were carried out on three groups of specimens GA ∼ GC, and a multi-stage loading test was carried out on specimen GD. Specimen GD’s elastic strain, creep strain and total strain of under each loading stage were analyzed. The electrochemical test characteristics of specimen GD at 7 different loading stages were studied. The test process was tested and analyzed, and the experimental method in this paper can also be used in similar research work. The following main conclusions can be obtained from the experimental work.

(1) In order to obtain the uniaxial compressive strength value of the anchor specimen accurately, three groups of specimens GA ∼ GC were used for the uniaxial compression test. Their uniaxial compression process included four stages, stage I to stage IV. Then, the average method was used to get the average compressive strength of the three specimens. Finally, the average uniaxial compressive strength of the specimens was 8.31 MPa.

(2) The specimen GD was damaged during the 6th stage of loading. The total strain of specimen GD during loading was composed of elastic strain and creep strain. During the whole loading process, the proportion of elastic strain in the total strain was greater than that of creep strain, and the proportion of elastic strain was between 51.90% and 55.82%.

(3) During the test, the electrochemical workstation was used to collect the data of specimen GD seven times. The Nyquist curve and Bode curve obtained at each detection time were analyzed. It was proved that the electrochemical test results had a certain correlation with the damage degree of the specimen. In particular, the electrochemical test curves at the failure stage showed more significant differences.

Data Availability

The data used to support the findings of the study are included within the article.

Conflicts of Interest

The authors declare no conflict of interest.

Authors’ Contributions

J. H. and H. W. designed the research methods. D. L. tested the specimens. G. S. and Z. W. analyzed the data and wrote the manuscript.

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