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Experimental Study on Anchoring Physical Properties of Different Anchoring Lengths Coupled with Temperature and Pressure

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Abstract

Aiming at deep roadway anchorage solids, laboratory similar model tests were used to reveal the mechanical properties of anchorage solids with different anchorage lengths under the coupling effect of temperature and pressure, and SPSS statistical analysis software was used to conduct linear regression analysis of the ultimate anchorage force obtained from the tests. The results show that: through multiple linear regression analysis, the influence degree of temperature and pressure coupling on the ultimate anchorage force is arranged in order of anchoring length > surrounding rock strength > temperature > side pressure coefficient, and the linear regression equation of the model is obtained. Compared with the linear regression equation of simulation results, the model has a high explanatory ability.

Keywords

Temperature-Pressure Coupling, Similar Model Test, Ultimate Anchorage Force, Multiple Linear Regression Analysis

1. Introduction

In recent years, as shallow coal is exhausted, coal development in China has entered the deep stage. Raw rock stress and tectonic stress of deep roadway are increasing constantly, and high ground temperature, high ground pressure, high water pressure and strong disturbance put forward more stringent requirements on support technology [1] [2] [3]. In roadway support, the mechanical performance of anchorage, as an important factor to measure the safety of anchorage support, has always been an important research issue in this field. By means of theoretical analysis, mechanical test and numerical analysis, scholars at home and abroad have studied the anchoring mechanical properties of bolt under different conditions, but there are few researches on the anchoring characteristics of solid anchors with different anchoring lengths coupled with temperature and pressure. Xiao Tongqiang *et al.* [4] revealed the drawing characteristics of bolts with different anchoring lengths through the multifunctional bolt drawing system. Liu Jianzhuang *et al.* [5] deduced the bonding shear stress and axial stress function along the long direction of the bolt through the constructed mechanical model. Wang Hongtao *et al.* [6] established a mechanical analysis model of surrounding rock with different anchorage lengths and verified the correctness of the model on site. Wang Qizhou *et al.* [7] optimized the steps of prestressed anchor bolt members in the pile structural unit in Flac3D, established a numerical model of anchor solids with single free plane, and analyzed the internal characteristics of anchor solids under unidirectional loading.

With the increase of mining depth and complexity of mining conditions, the reliability of bolt anchoring needs to be improved urgently. The complexity of engineering conditions makes it difficult to calculate the anchorage force of bolt, and it is difficult to quantify the ultimate anchorage force as an important factor of anchorage safety. In view of this, the ultimate anchorage force under different factors is obtained by laboratory test method, and the test data are analyzed by statistical analysis software. The linear regression equation obtained can provide reference for improving the anchorage safety of coal mine bolt.

2. Experiment Design

2.1. Test Equipment

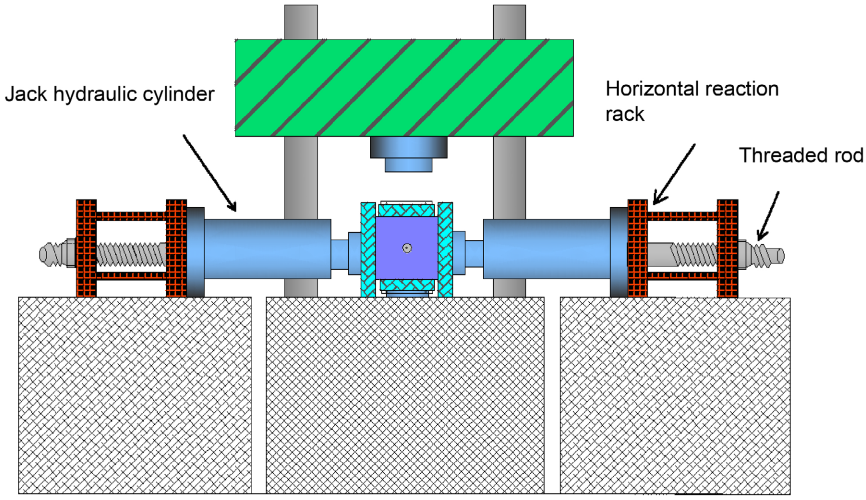
The temperature and pressure loading device developed by the Institute of Underground Structure of Anhui University of Science and Technology was used as the test device to simulate the anchoring physical properties of different anchoring lengths under the temperature and pressure coupling state. The device includes confining pressure loading device, temperature loading device, drawing device, data acquisition and recording device, as shown in **Figure 1**.

1) Confining pressure loading device

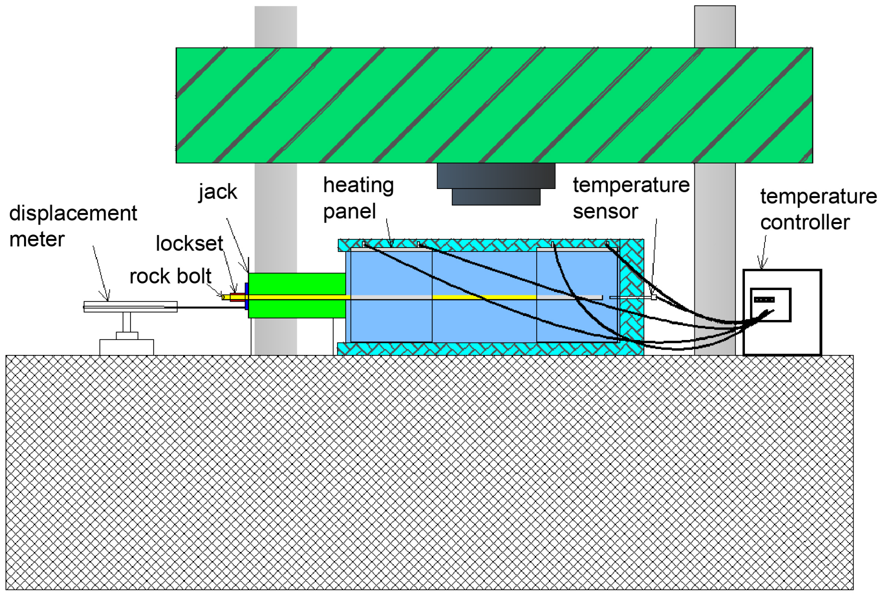
The vertical direction of the test was loaded by WAW-1000C microcomputer controlled electro-hydraulic servo universal testing machine. The stress control was adopted on the testing machine, and the control speed was 0.01 MPa/s. In the horizontal direction, a jack with a maximum loading load of 1000 kN is used for loading. The loading pressure is controlled by a digital display pressure controller, and the movement of the jack is restricted by a self-made reaction frame. A thick iron plate is placed between the anchor solid and the loading head to make the load transfer to the anchor solid more evenly.

2) Temperature loading device

The temperature loading device includes: cast aluminum heating plate, temperature controller, K type thermocouple temperature sensor. The selected cast aluminum heating plate size is length × width × thickness = 200 × 150 × 20 mm,



(a) Front view



(b) Side view

Figure 1. Test device diagram.

power 800 w. The temperature controller is composed of digital display adjusting temperature controller and 220 V AC contactor. The cast aluminum heating plate and the temperature sensor are connected to the temperature controller, and the temperature sensor is placed in the pre-drilled temperature measuring hole on the anchor solid. The cast aluminum heating plate heats the anchor solid. When the temperature reaches the pre-loaded temperature, the AC contactor is disconnected and the heating stops.

3) Pull-out device

The drawing device is composed of ML-300B manual bolt drawing instrument, pressure transmitter and digital display pressure acquisition instrument. Manual bolt puller can provide 300 kN pulling force. Set the digital display pressure acquisition instrument to collect one data per second.

4) Data acquisition and recording device

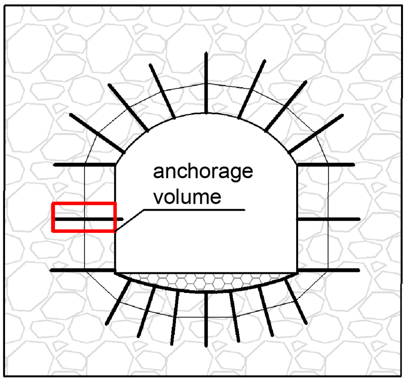
The data collection includes the collection of the strain gauge on the bolt and the displacement meter monitoring the shift of the bolt end through the TDS-630 data acquisition instrument.

2.2. Test Scheme

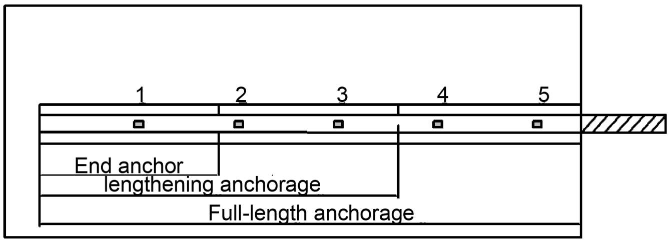
After the excavation of the roadway, the stress state of the surrounding rock is broken and the surrounding rock stress is redistributed. When the stress of the surrounding rock reaches equilibrium again, an anchor solid unit in the roadway is analyzed. The horizontal and vertical stress of the anchor solid are divided into the first and second principal stresses according to the side pressure coefficient. Through the analysis of the anchorage force in the roadway, and considering that there are many experimental factors, the orthogonal test is designed. In the test, cast-aluminum heating plate was used to heat anchor solid and simulate ground temperature infiltration into anchor body. Horizontal and vertical loads are applied to anchor solids to simulate the stress of anchor solids under ground pressure. The tension of bolt is simulated by drawing device. Schematic diagram of anchor solids as shown in Figure 2.

2.2.1. Making Steps and Similarity Ratio of Anchor Solid Model

Similarity simulation test is a test method based on similarity theory, which



(a) Schematic diagram of bearing capacity of anchor solids



(b) Anchorage mode

Figure 2. Schematic diagram of anchor solids.

utilizes the similarity between materials to reflect the similarity law between things or phenomena to the greatest extent. The appropriate geometric similarity ratio and bulk density similarity ratio were selected according to the similarity theory and similarity index, Poisson's ratio μ, internal friction Angle φ, strain ε, temperature T similarity ratio $C\mu = C\varepsilon = C\varphi = C_T = 1$. 32.5 ordinary Portland cement and gypsum are used as cementing materials for anchor solid materials, and river sand is used as aggregate. Polycarboxylic acid of 1% cementing material mass is added to similar materials to increase fluidity. The matching scheme of similar materials is shown in **Table 1**. According to the similarity ratio, the size of the model is determined as length × width × height = 500 × 150 × 150 mm. Considering that the bolt needs to be slotted and attached with strain gauge, a slightly larger bolt size is selected as φ10 mm.

Model making steps: 1) Open holes at both ends of the mold, insert PVC pipe; 2) pour the similar material mixed evenly into the mold; 3) wait for the similar material to set initially, pull out the PVC pipe, and conserve for two weeks; 4) make slots on the anchor rod, stick strain gauge; 5) insert the anchor agent; 6) into the anchor hole, insert the anchor rod into the anchor hole and stand for 24 h. The anchoring system was completed.

2.2.2. Test Scheme and Loading Procedure

According to relevant references, the main factors affecting the anchoring effect in roadway include anchoring length, strength of surrounding rock, temperature and side pressure coefficient. The four factors are selected to design orthogonal experiment as shown in **Table 2**. Three levels were selected for each factor in the test, and SPSS statistical analysis software was used to design the orthogonal scheme as shown in the table below, and multiple linear regression analysis was carried out on the ultimate anchorage force of the anchor solid.

Loading steps: 1) First, the anchor solid is heated until the anchor solid is stable to the predetermined temperature; 2) at the same time, the anchor solid is loaded in the horizontal and vertical direction. When the loading reaches the preset stress, the pressure is stabilized; 3) The anchor bolt is tensed-out with the manual drawing instrument until the anchor bolt loses its anchor. In order to reduce the temperature loss during the test heating process, the anchor solid was covered with insulation material. Apply lubricating oil to the loaded iron plate to reduce the influence of friction on the test.

Table 1. Matching scheme of similar materials.

Specimen number	Sand:Cement: gypsum	Polycarboxylic acid dosage	Water consumption	Compressive strength/MPa
A	5:2:9	Quality of cementitious material 1%	20%	3.10
B	6:4:6	Quality of cementitious material 1%	25%	6.08
C	3:4:4	Quality of cementitious material 1%	28%	9.02

Table 2. Orthogonal test scheme.

Serial number	Anchorage length/cm	Strength of surrounding rock/MPa	Temperature/˚C	Lateral pressure coefficient
1	16	3	30	0.8
2	48	3	45	1
3	32	3	60	1.2
4	32	6	30	1.2
5	16	6	45	1
6	48	6	60	0.8
7	32	9	45	0.8
8	16	9	60	1.2
9	48	9	30	1

3. Test Results and Analysis

Multiple Linear Regression Analysis of Ultimate Anchorage Force of Anchor Solid

The factors that influence the ultimate anchorage force of anchor solid include surrounding rock strength, side pressure coefficient, temperature and anchorage length. According to the sample data obtained from the test, as shown in the table, Y (ultimate anchoring force) was set as the dependent variable, surrounding rock strength (x1), lateral pressure coefficient (x2), temperature (x3), anchoring length (x4) as the independent variable, multiple linear regression analysis was conducted, and the regression model was established.The multiple linear regression model was set as $Y = \beta 0 + \beta 1x1 + \beta 2x2 + \beta 3x3 + \beta 4x4 + \varepsilon$.

In the above equation Y represents the maximum anchoring force; x1, x2, x3, x4, respectively represent surrounding rock strength, lateral pressure coefficient, temperature, and anchoring length; $\beta 0$, $\beta 1$, $\beta 2$, $\beta 3$, $\beta 4$ represent constants, surrounding rock strength, lateral pressure coefficient, temperature, and anchoring length, respectively; ε is residual. Sample data listed in Table 3.

According to the analysis in Tables 4-6, the influence of lateral pressure coefficient on the maximum anchorage is less significant in model t test. The non-significant factor lateral pressure coefficient in the model is excluded, and the three factors of anchorage length, strength of surrounding rock and temperature are analyzed by stepwise analysis method.

As shown in Table 7, R Square = 0.953 of model 3 has a high correlation coefficient, and the independent variable can explain the dependent variable up to 95.3%, indicating a high degree of model fitting. DW = 2.108 is close to 2, and the autocorrelation of the model is small. The variance analysis of the Table 8 model shows that the significance of model 3 reaches the extremely significant level, indicating that the influence of independent variables on dependent variables is far greater than that of random factors. The regression coefficient

Table 3. Sample data.

Serial number	Surrounding rock strength/MPa (x_1)	Lateral pressure coefficient (x_2)	Temperature/˚C (x_3)	Anchoring length /cm (x_4)	Ultimate anchorage force/kN (Y)
1	3.00	0.80	30.00	16.00	9.75
2	3.00	1.20	45.00	48.00	22.50
3	3.00	1.00	60.00	32.00	10.50
4	6.00	1.20	30.00	32.00	26.25
5	6.00	1.00	45.00	16.00	15.00
6	6.00	0.80	60.00	48.00	28.75
7	9.00	0.80	45.00	32.00	23.25
8	9.00	1.20	60.00	16.00	15.75
9	9.00	1.00	30.00	48.00	38.25

Table 4. Model summary.

Model	R	R Square	Adjusted R Square	DW
1	0.977[a]	0.955	0.910	1.966

Table 5. ANOVA[a].

Model		Quadratic Sum	Degree of freedom	Mean Square	F	Significance
1	analysis of regression	661.563	4	165.391	21.203	0.006[b]
	residual error	31.201	4	7.800		
	total	692.764	8			

[a]is the predictive variable for this model. [b]represents the dependent variable of this model.

Table 6. Regression coefficient analysis table.

Model		B	Beta	t	Significance	tolerance	VIF
1	constant	0.611		0.082	0.939		
	lateral pressure coefficient	2.292	0.043	0.402	0.708	1.000	1.000
	surrounding rock strength	1.917	0.535	5.043	0.007	1.000	1.000
	temperature	−0.214	−0.299	−2.814	0.048	1.000	1.000
	anchoring length	0.510	0.760	7.162	0.002	1.000	1.000

Table 7. Model Summary2.

Model	R	R Square	Adjusted R Square	DW
1	0.760[a]	0.578	0.517	
2	0.930[b]	0.864	0.819	
3	0.976[c]	0.953	0.925	2.108

[a]Predictive variables: (constant), anchorage length; [b]Predictive variables: (constant), anchorage length, strength of surrounding rock; [c]Predictive variables: (constant), anchorage length, surrounding rock strength, temperature; [d]Dependent variable: ultimate anchorage force.

Table 8. ANOVA[a] 2.

	Model	Quadratic Sum	Degree of freedom	Mean Square	F	Significance
3	analysis of regression	660.302	3	220.101	33.901	0.001[d]
	residual error	32.462	5	6.492		
	total	692.764	8			

[a]is the predictive variable for this model. [d]represents the dependent variable of this model.

Table 9. Regression coefficient analysis 2.

	Model	B	Beta	t	Significance	tolerance	VIF
3	constant	2.903		0.664	0.536		
	surrounding rock strength	1.917	0.535	5.528	0.003	1.000	1.000
	temperature	−0.214	−0.299	−3.084	0.27	1.000	1.000
	anchoring length	0.510	0.760	7.851	0.001	1.000	1.000

analysis of Table 9 shows that the variance expansion factor VIF of the model is less than 5, and there is no multicollinearity. The t test of the model showed that the significance sig of the three factors of the model was <0.05, indicating that each factor had a significant impact on the dependent variable and the model was reasonable. According to the significance of Table 9, the order of four factors affecting the ultimate anchoring force of anchor solid is in order of anchoring length > strength of surrounding rock > temperature > lateral pressure coefficient. The linear regression equation of the model is $F = 2.903 + 1.917x_1 - 0.214x_3 + 0.510x_4$.

4. Numerical Analysis of Solid Ultimate Anchorage Force of Temperature-Pressure Coupled Anchor

Establishment of the Model

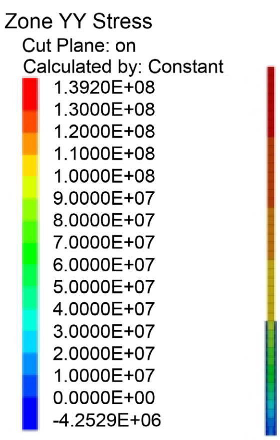
Flac3D was used to establish the anchor solid model according to the test. The model size of anchor solid length × width × height = 500 × 150 × 150 mm. The anchor bolt was modeled by solid element, and the diameter of the anchor bolt was 10 mm and the diameter of the anchor hole was 16 mm, as shown in the figure. The boundary conditions of the model constrained the bottom of the anchor solid in the Y direction, and the stress boundary conditions were set in the X and Z directions. The stress boundary conditions imposed by the model were consistent with the test. Temperature boundary condition considering that temperature mainly affects the physical properties of anchorage agent, the temperature boundary directly applied to surrounding rock is the temperature of preloading. The change of physical properties of anchoring agent with temperature is considered when assigning values to materials. The drawing boundary imposes a gradually increasing stress on the end of the anchor rod along the Y direction. When the plastic failure of the anchor agent layer occurs completely, the anchor solid is judged to lose anchor. Mechanical parameters and constitutive models of surrounding rock and bolt are shown in Table 10, and mechanical parameters of anchorage agents at different temperatures are shown in Table 11.

Table 10. Mechanical parameters of surrounding rock and bolt.

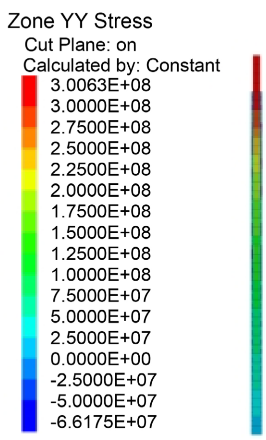
Name of the material	Constitutive model	Elasticity modulus/GPa	Poisson's ratio	Apparent cohesion /MPa	Internal friction angle/˚
surrounding rock (A)	Moore Coulomb	0.5	0.22	0.6	23
surrounding rock (B)	Moore Coulomb	1	0.25	0.8	25
surrounding rock (C)	Moore Coulomb	1.2	0.23	1.2	26
rock bolt	elasticity	200	0.3	1.0	30

Table 11. Mechanical parameters of numerical anchorage agents at different temperatures.

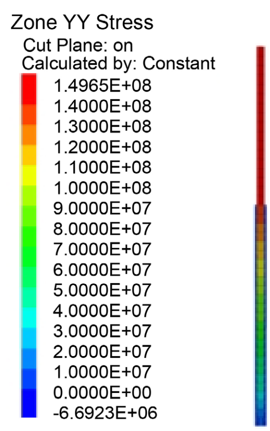
Temperature/˚C	Elasticity modulus/GPa	Poisson's ratio	Apparent cohesion /MPa	Coefficient of thermal expansion/1.0e−5/˚C
30	9.8	0.24	8.8	6.70
45	6.8	0.31	7.5	9.41
60	4.5	0.35	5.5	13.75



(1) a1



(2) a2



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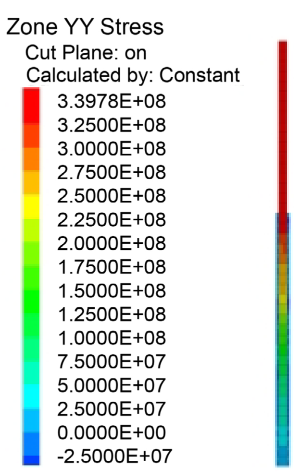
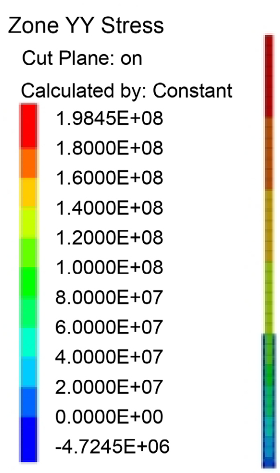
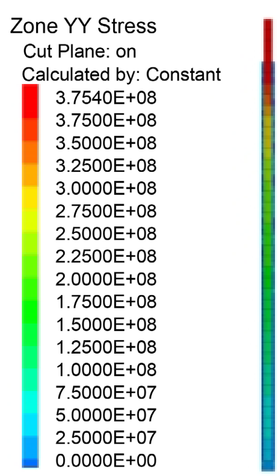


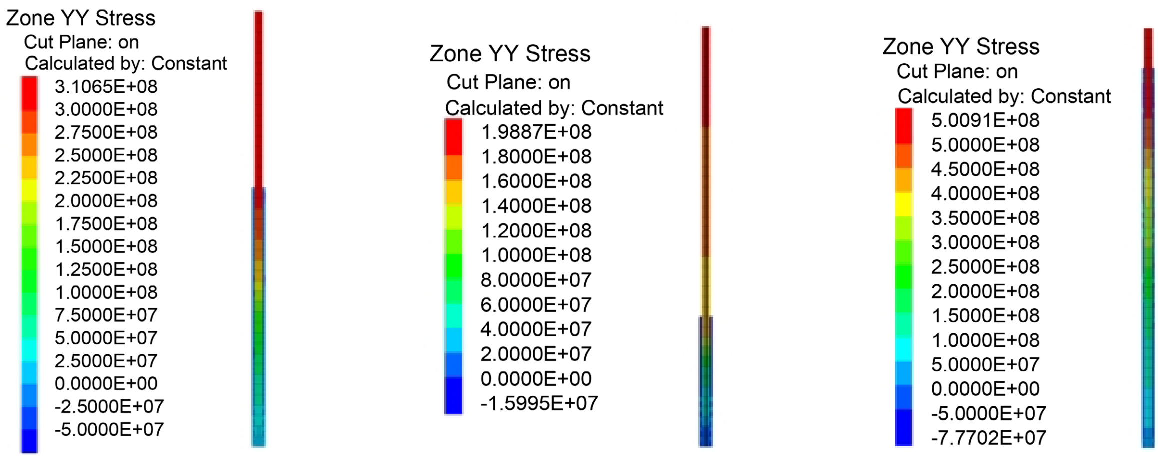
(4) b1



(5) b2



(6) b3



(7) c1 (8) c2 (9) c3

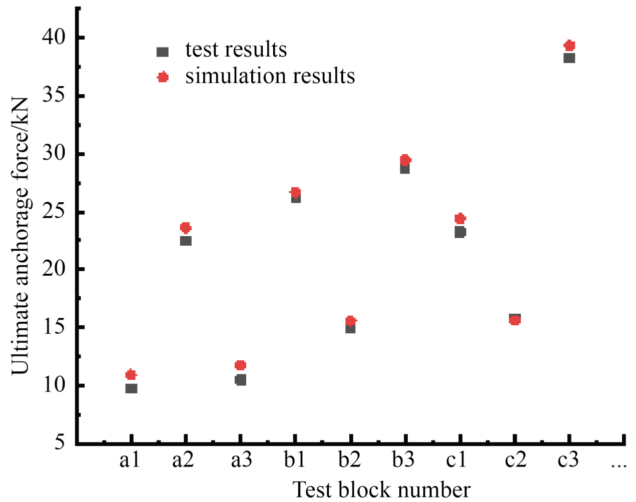


Figure 3. Test simulation comparison figure.

According to the simulation and experimental comparison results of the ultimate anchorage force, it can be seen that the multiple linear regression model has high accuracy, and has a good guiding significance for the anchorage support design of roadway. The comparison of test and simulation results is shown in the Figure 3.

5. Conclusions

1) For anchor solids under different conditions, the drawing test method is adopted to obtain the ultimate anchorage force of anchor solids. Statistical analysis is conducted on the test data, and the order of influence on the ultimate anchorage force of anchor solids is obtained in order of anchorage length > surrounding rock strength > temperature > lateral pressure coefficient.

2) According to multiple linear regression analysis, the linear regression equation of the ultimate anchorage force is $F = 2.903 + 1.917x1 - 0.214x3 + 0.510x4$, and the numerical simulation method verifies that the linear regression equation has a high explanatory ability.

Conflicts of Interest

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

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