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Study on the Influence of Radial Pressurization on Anchoring Performance of Bolts

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Abstract

Supporting soft rock roadways in coal mines has long posed a formidable challenge. Addressing issues such as the formation of soft rock strata, poor fracture development, limited tolerance, and the frequent and severe damage sustained by conventional bolts due to their low elongation and bearing capacity, this study employs bottom expansion and filling technology. It combines theoretical analysis with booster bolt pull-out tests to scrutinize the radial stress distribution of bolts under extrusion forces. Moreover, it conducts a comparative analysis of bolt bearing characteristics under varying radial pressurization conditions, delving into the impact of radial directional increases in compressive stress on bolt anchoring performance.

Keywords

Anchors, Pressure Dispersion, Axial Forces, Anchoring Effect

1. Introduction

The soft rock roadway rock formation is weak, the fracture development tolerance is poor, and the conventional bolt has frequent and serious damage due to low elongation and bearing capacity. Under dynamic load, the traditional bolt cannot control the movement of the rock mass, and it is easy for the bolt to slip and fail, resulting in damage of the surrounding rock [1] [2].

At present, a lot of progress has been made in the research of bolt support nursing theory and technology. Scholars at home and abroad have improved the anchor support technology, changed the anchor structure by reaming, increased the contact area between the anchoring system and the surrounding rock mass, and then increased the adhesion or friction resistance between the anchor solid and the rock layer, so that the anchoring force was significantly improved, and the purpose of strengthening the surrounding rock was realized. In the 70s of the 20th century, Zhai *et al.* [3] discussed the enlarged head bolt in "Anchoring Technology of Rock Formation and Soil". With the development of the times and the advancement of technology, Japan proposed permanent trapezoidal reaming bolt technology. Zeng Qingyi *et al.* [4] proposed that applying a higher locking tension to the expansion head bolt can better limit the deformation of the foundation pit and reduce the displacement of the foundation pit according to the bolt uplift detection and the observation of foundation pit displacement. Yang Zhuo *et al.* [5] proposed a terminal bag with high-pressure grouting expansion and reaming technology, which adopts the end bag wrapping design and is equipped with a balanced air pressure device, which combines with high-pressure jet reaming technology through grouting expansion and reaming in the surrounding bag, which not only significantly improves the ultimate pull-out ability of the anchor and the anti-corrosion durability of the device, but also prevents the deformation of the anchor head. Li Wenbin [6] proposed that the positive wedge reaming increases the overall shear strength of the anchor anchoring system at the joint surface while increasing the solid section of the anchor at the joint surface, thereby improving the shear resistance of the anchor anchoring system. Chen Haohua *et al.* [7] introduced a novel grout-expanding soil anchor system, addressing the limitations of traditional expansion head anchors. These anchors come equipped with expanding anchor claws, eliminating the need for specialized hole-expanding machinery. Under grout injection, they can seamlessly expand and grout, ensuring continuous support. Guo Gang *et al.* [8] using FBI sensors, monitored the frictional forces and end forces experienced by the hole-expanding anchor rod during pullout. Their findings revealed that the anchor rod's load-bearing capacity primarily stems from the end forces in the expanding section, and this capacity positively correlates with burial depth. Zeng Qingyi *et al.* [9] proposed applying higher tension to the expansion head anchor rod based on anchor rod pullout tests and foundation pit displacement observations. This approach effectively restrains foundation pit deformation, thereby reducing displacement. Li Kun *et al.* [10] conducted numerical simulations of the expansion head anchor rod using ABAQUS software. Through this, they highlighted the gradual impact of the expansion head from top to bottom, significantly affecting nearby soil stress distribution and leading to shear failure—a significant end effect. Zhang Luosong [11] performed anchor rod pullout experiments on expansive cement anchoring material. Their results demonstrated that expansive expansion rods have significantly higher ultimate pullout capacities compared to conventional cement slurry anchors. The ultimate pullout capacity of expansion rods is directly proportional to ultimate compressive strength and the content of the expansive anchoring agent, reaching a maximum ultimate tensile capacity of 336%.

However, the current research on bolt support technology for increasing anchoring performance focuses on changing the structure of the bolt or surrounding rock itself by physical or chemical means, and the study of the mechanical property change caused by the change of radial force of the bolt by filling the high-strength material after reaming is still relatively lacking, so this paper analyzes the radial stress distribution of the bolt when it is squeezed by theoretical analysis and drawing experiment on the basis of the bottom expansion and filling technology, and studies and analyzes the anchoring mechanism and bearing mechanism of the radial increase compressive stress bolt.

2. Analysis of the Anchoring Effect of the Booster Bolt

In the project, the cement slurry in the late stage of the traditional cement-based anchor is easy to shrink, resulting in a crack between the anchor solid and the surrounding rock, and when subjected to external load, the cement grout is shear failure, and the surrounding rock of the borehole is also damaged, resulting in the slip failure of the anchor.

The self-stressing slurry is injected into the anchor hole to produce radial expansion compressive stress on the hole wall under the constraint of the rock mass, forming a radial pressurized anchor system, the self-stressing slurry produces a compaction effect with the surrounding rock around the anchor hole, giving full play to the reverse extrusion ability of the anchor solid relative to the surrounding rock, increasing the friction and adhesion between the anchor solid and the surrounding rock of the borehole, thereby effectively improving the ultimate bearing capacity of the anchor. When the bolt is anchored in a soft rock layer, the bonding strength of the interface between the grouting body and the surrounding rock mass is generally less than the friction between the bolt and the grouting body, and the ultimate bearing capacity of the bolt depends on the maximum friction between the bolt and the grouting body. Under the constraint of the surrounding rock of the borehole, the compressive strength and shear strength of the anchor solid are improved, and the overall diameter of the anchor solid becomes larger, and it can be seen from Equation (1) that the ultimate bearing capacity of the anchor is enhanced with the increase of the diameter of the anchor solid, and the anchoring effect is significantly improved.

The overall diameter becomes larger, and it can be seen from Equation (1) that the ultimate bearing capacity of the bolt increases with the increase of the solid diameter of the anchor, and the anchoring effect is significantly improved.

After extensive research, it has been shown that when the surrounding rock mass is relatively complete and has high strength, the friction force at the interface between the grouting body and the surrounding rock mass in the anchoring system is generally greater than the bonding force at the interface between the anchor rod and the grouting body. Therefore, the tensile pull bearing capacity of the anchor rod mainly depends on the size of the bonding force at the interface between the anchor rod and the grouting body. The calculation formula for the tensile pull bearing capacity of the anchor rod is as follows:

$$P_s = \pi d L_b R_b \tag{1}$$

Among them, P_s is the ultimate tensile and tensile bearing capacity of the anchor rod; d is the diameter of the anchor rod; L_b is the anchoring length; R_b is the average bonding stress at the interface between the anchor rod and the grouting body.

The stress model of the pressurized anchor rod anchor solid and surrounding rock is shown in **Figure 1**. After the self stressing cement slurry is compacted and expanded, radial expansion compressive stress q_n is generated around the anchor hole. The surrounding rock mechanical model is regarded as an infinite elastic body under radial compressive stress, and the anchor solid generates radial strain and circumferential strain. At this point, the radial and circumferential stresses on the hole wall are:

$$\sigma_\rho^n = -\frac{a^2}{\rho^2} q_n \tag{2}$$

$$\sigma_\theta^n = \frac{a^2}{\rho^2} q_n \tag{3}$$

The boundary conditions of the anchor hole are:

$$\sigma_\theta^n = \sigma_\rho^n = |q_n| \tag{4}$$

According to the generalized Hooke's law:

$$\varepsilon_\rho^n = -\frac{q(1+\mu_n)}{E_n} \tag{5}$$

According to the force model of the anchor body, it can be seen that the anchor body is q_n reaction force. The radial and circumferential stresses generated on the boundary under the action of q_m are:

$$\varepsilon_\theta^n = \varepsilon_\rho^m = |q_m| \tag{6}$$

According to General Hooke's Law:

$$\varepsilon_\rho^m = -\frac{q_m(1+\mu_m)}{E_m} \tag{7}$$

At this point, the boundary conditions between the anchor body and the surrounding rock are:

$$\varepsilon_\rho^m = \beta - \varepsilon_\rho^m \tag{8}$$

$$q_m = q_n = q \tag{9}$$

Substituting the two Hooke's Law formulas into the last boundary condition yields the following formula:

$$q = \frac{\beta E_n E_m}{E_n(1+\mu_m) + E_m(1+\mu_m)} \tag{10}$$

Among them, E_m, μ_m is the elastic modulus and Poisson's ratio of the anchor solid, E_n, μ_n is the elastic modulus and Poisson's ratio of the borehole surrounding rock, β is the coefficient of expansion of the anchor solid.

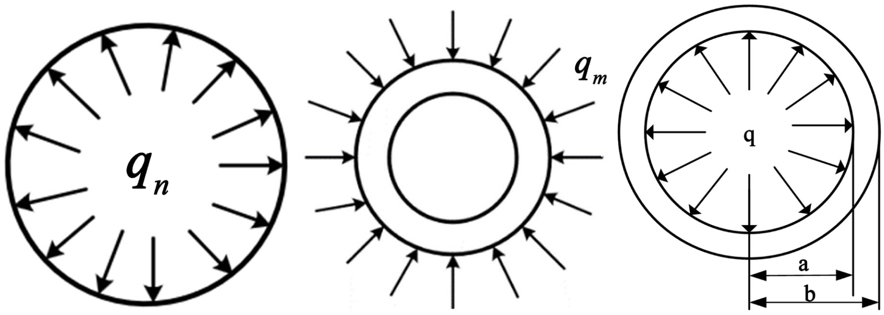

Figure 1. Stress model of anchor solid and surrounding rock. (a) Internal force of borehole surrounding rock; (b) Anchor body subjected to external force; (c) Internal force on anchor body.

From this, it can be seen that the maximum pulling force of the pressurized anchor rod is:

$$P_u = (qf + c)\pi Dl = \left[\frac{f\beta E_n E_m}{E_n(1+\mu_m) + E_m(1+\mu_m)} + c\right]\pi Dl \quad (11)$$

In the formula, l is the anchorage length, D is the anchor hole diameter, and f, c are the friction coefficient and bonding coefficient between the anchor solid and the surrounding rock, respectively.

3. Pressurized Anchor Rod Pull-Out Experiment

3.1. Procedure

1) Set experimental groups and parameters

The experiment was divided into five groups: A, B, C, D, and E. Among them, Group A is a common cement anchoring group, Group B is a self stressing cement anchoring group with 3% expansion agent added, Group C is a self stressing cement anchoring group with 5% expansion agent added, Group D is a self stressing cement anchoring group with 7% expansion agent added, and Group E is a self stressing cement anchoring group with 9% expansion agent added. According to the principle of three-way matching, a left-hand threaded steel anchor rod with a diameter of 20 mm and a length of 600 mm was used in this experiment. Both sets of anchoring forms adopt end anchoring, with an anchoring end length of 200 mm, a free end length of 400 mm, a pore size of 50 mm, and a cement slurry of 15 mm on both sides of the anchor rod. The experimental equipment required for the pull-out experiment includes a left-hand threaded steel anchor rod, a dial gauge, a force gauge, and a manual hydraulic pump:

2) experimentation

The first step of the experiment is to make two sets of surrounding rock test blocks, and mix them according to the selected ratio of similar materials in the surrounding rock Φ PVC pipes with a diameter of 30 mm and a length of 200 mm are embedded in a 150 mm × L235 mm cylindrical mold in advance. The materials are mixed evenly without bubbles and poured into the mold. The materials are fully vibrated and then placed horizontally. The second step of the experiment is to air dry the test block. After the material solidifies, remove the mold, slowly rotate and pull out the PVC pipe, and ventilate the test block from light. The air drying cycle is 14 days. The third step of the experiment is to anchor. Firstly, clean the interior of the anchor hole, and inject ordinary cement slurry and self stressing cement slurry into two sets of surrounding rock test blocks using a syringe. After the cement slurry is evenly filled, install the anchor rod, and keep it horizontal and stationary after it is completely solidified. The fourth step of the experiment is to pull out the anchor rod. After three days of grouting, a manual hydraulic pump is used to pull out the anchor rod. A force gauge is used to record the load on the anchor rod when it is pulled out, and a dial gauge is used to record the specific displacement of the anchor rod when it is pulled out. The experimental steps are shown in Figure 2.

3.2. Experimental Results

Analyze the pull-out results data of five groups A, B, C, D, and E, using ordinary cement anchoring group A as the reference group and cement anchoring group B, C, D, and E with different amounts of expansion agent as the comparison group. The pull-out law of the anchor rod with expansion agent cement anchoring group is obtained. The maximum pull-out force of the anchor rod obtained from the five groups of experiments is shown in Table 1.

The axial load curve of group A ordinary cement anchorage is shown in Figure 3.

From Figure 3, it can be seen that the average axial ultimate pull-out force of ordinary cement anchor rod anchoring is 14.28 KN, and the ultimate pull-out force of the anchor rod reaches its peak when the relative displacement of the anchor rod is 8.5 mm. When the pull-out load is less than the ultimate pull-out force of the anchor rod, the force of the anchor rod is in a stable state, and there is basically no displacement change in the anchoring section. When the pulling load is greater than the ultimate tensile strength of the anchor rod, the axial stress on the anchor rod increases sharply and the displacement also changes significantly. As the displacement of the anchor rod increases, the pulling force gradually reaches its peak. After the pulling force on the anchor rod reaches its peak, the displacement load curve value slowly decreases, and ultimately the anchoring system fails. The load on the anchor rod decreases from a horizontal state to the minimum value.

The axial load curve of anchor bolt anchoring with a 3% expansion agent dosage in Group B is shown in Figure 4.

From Figure 4, it can be seen that the average axial ultimate pull-out force of anchor bolts with a 3% expansion agent dosage is 18.37 KN, which is 40% higher than that of ordinary cement anchor bolts. The ultimate pull-out force of the anchor rod reaches its peak when the relative displacement of the anchor rod is 8.34 mm. As the pulling load increases, the axial stress on the anchor rod gradually increases. The displacement load curve of the anchor rod reaches its peak,

(a) (b) (c)

Figure 2. Experimental steps. (a) Preparation of test blocks; (b) Anchor rod anchoring; (c) Anchor rod pulling.

Table 1. Pullout resistance of anchor rods with different amounts of expansion agents.

Number of groups	number	Maximum pulling force/KN	Average maximum pulling force/KN
A) group (Ordinary cement slurry)	1#	14.32	14.28
	2#	13.61	
	3#	14.90	
B) group (3% Expansion agent dosage self stressing slurry)	4#	19.35	18.37
	5#	17.29	
	6#	18.55	
C) group (5% Expansion agent dosage self stressing slurry)	7#	30.20	30.82
	8#	31.44	
	9#	30.82	
D) group (7% Expansion agent dosage self stressing slurry)	10#	39.25	40.98
	11#	41.58	
	12#	42.12	
E) group (9% Expansion agent dosage self stressing slurry)	13#	22.51	22.24
	14#	23.48	
	15#	20.73	

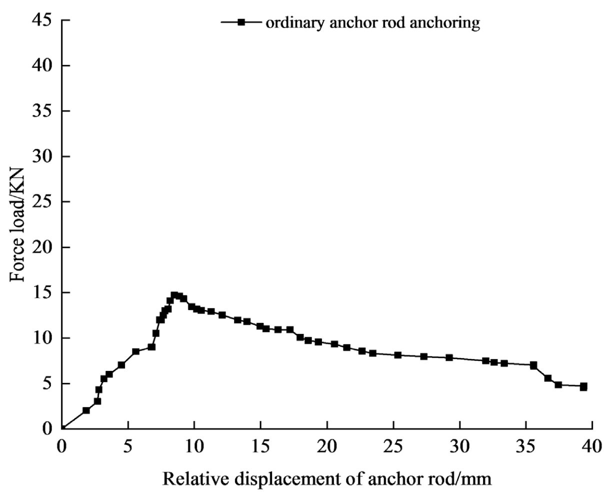

Figure 3. Changes in axial load displacement curve of ordinary cement anchorage.

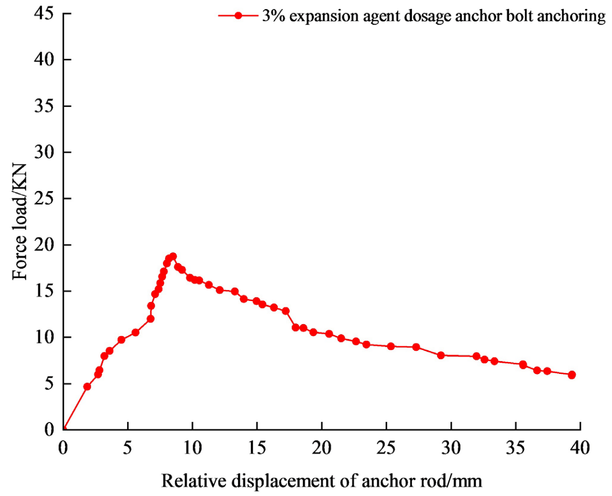

Figure 4. Changes in axial load displacement curve of anchorage with 3% expansion agent content.

which is as slow as the displacement load curve of the ordinary cement anchor rod. As the relative displacement of the anchor rod increases, the axial force of the anchor rod decreases from a flat state to the minimum value after the anchoring system fails. The minimum load force value is greater than the minimum axial force value of the ordinary cement anchor group.

The axial load curve of anchor bolt anchoring with a 5% expansion agent dosage in Group C is shown in **Figure 5**.

From **Figure 5**, it can be seen that the average axial ultimate pull-out force of anchor bolts with a 5% expansion agent dosage is 30.82 KN, which increases by 115% compared to ordinary cement anchor bolts. The ultimate pull-out force of anchor bolts reaches its peak when the relative displacement of the anchor rod is 8.34 mm. As the pulling load increases, the axial stress on the anchor rod gradually increases. The displacement load curve of the anchor rod reaches its peak, which is as slow as the displacement load curve of the ordinary cement anchor rod. As the relative displacement of the anchor rod increases, the axial force of the anchor rod decreases from a horizontal state to the minimum value after the anchoring system fails. The minimum load force value is greater than the minimum axial force value of the ordinary cement anchor group.

The axial load curve of anchor rod anchoring with 7% expansion agent in Group D is shown in **Figure 6**.

From **Figure 6**, it can be seen that the average axial ultimate tensile strength of the anchor rod with a 7% expansion agent dosage reaches 40.98 KN, which is 187% higher than that of the ordinary cement anchor rod. The ultimate tensile strength of the anchor rod is significantly improved. The anchor group with a 7% expansion agent content has a fast increase in load and force, while the relative displacement of the anchor rod changes relatively little. As the pulling load increases, the axial force of the anchor rod rapidly reaches its peak, and the displacement load curve slowly decreases like that of the ordinary cement anchor

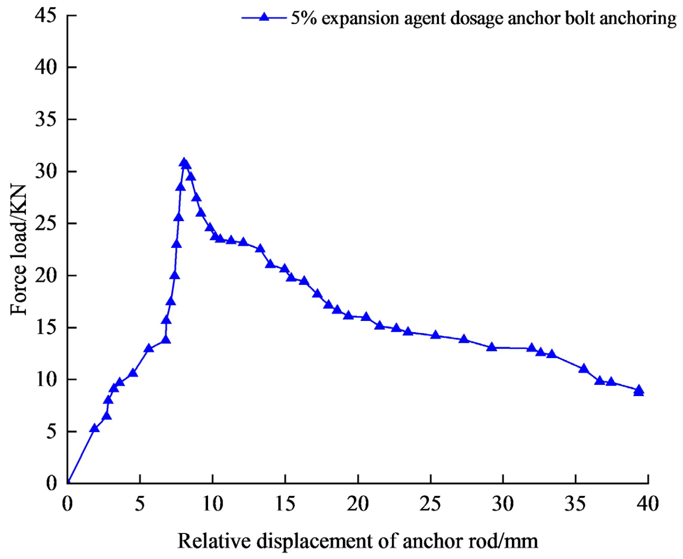

Figure 5. Changes in axial load displacement curve of anchorage with 5% expansion agent content.

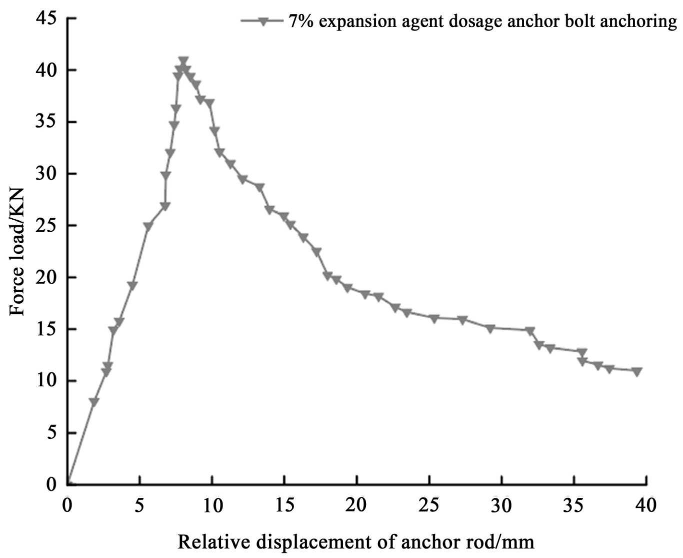

Figure 6. Changes in axial load displacement curve of 7% expansion agent content anchorage.

group, then gradually decreases to the minimum value. The minimum value of load bearing capacity is still greater than the minimum value of load bearing capacity of the ordinary cement anchoring group.

The axial load curve of anchor rod anchoring with a 9% expansion agent dosage in Group E is shown in **Figure 7**.

From **Figure 7**, it can be seen that the average axial ultimate tensile strength of anchor bolts with a 9% expansion agent dosage is 22.24 KN, which is 84% lower than that of the anchor group with a 7% expansion agent dosage. As the relative displacement of the anchor rod increases, the displacement load curve reaches its peak and then sharply decreases. After the anchor fails, the displacement

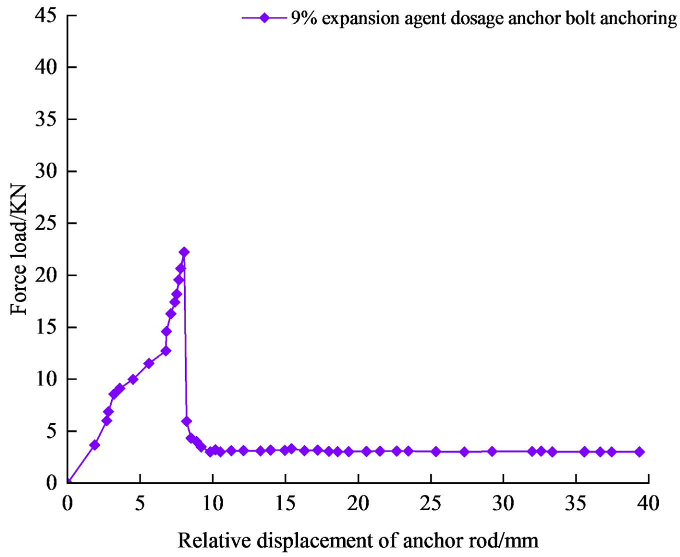

Figure 7. Axial load displacement curve variation of 9% expansion agent dosage anchoring.

load curve decreases to 3 MPa. This is because the expansion pressure stress generated by the anchoring material with a 9% expansion agent dosage is close to the material's ultimate self stress, resulting in loose and micro cracks on the surface of the material, and the interface between the surrounding rock and the anchor solid cannot be compacted. The failure state is shown in Figure 8.

Figure 9 shows a comparison of the axial load curves of anchor bolts with different radial pressure increases. It can be seen from the figure that,

The ultimate pull-out resistance of anchor rods with a 3% expansion agent dosage is roughly the same as that of ordinary anchor rods, and the growth rate of the stress load curve of both is basically the same. The relative displacement values of anchor rods with peak stress load are equal, both of which are 8.5 mm. The ultimate tensile strength and load curve growth rate of anchor rods with 5% and 7% expansion agent dosage significantly increased compared to ordinary anchor rod anchoring. The maximum ultimate load of anchor rods with 7% expansion agent dosage reached 40.98 KN, with the fastest growth rate of load curve and the maximum residual anchoring force after anchoring failure. From the load curve of the anchor rod with a 9% expansion agent dosage, it can be seen that as the relative displacement of the anchor rod increases, the residual anchoring force after anchoring failure decreases to 3 MPa and remains stable. The residual anchoring force after anchoring failure is much smaller than that of ordinary anchor rod anchoring.

This is because the radial compressive stress generated by the anchor rod anchoring system with a 7% expansion agent dosage reaches 1.5 MPa. On the one hand, the diameter of the anchor body increases with the action of the expansion agent, and the expanded anchor body can exert the ultimate tensile strength of the entire anchoring system in the shortest distance. On the other hand, due to the compressive stress generated by the anchor body along the

Figure 8. Failure state diagram of surrounding rock anchor solid interface.

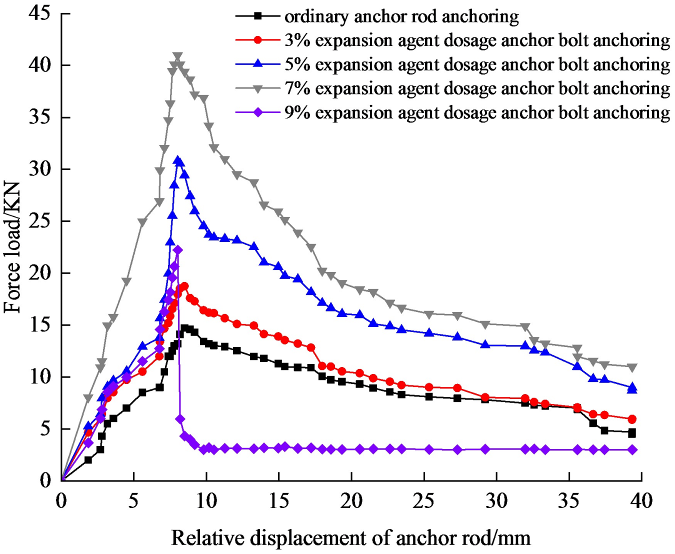

Figure 9. Comparison of axial load curves for anchor bolts with different pressurization sizes.

anchor hole diameter on the surrounding rock, the friction force between the anchor body and the surrounding rock is greater than that of ordinary anchor rod anchoring, The ductility of anchor rod failure has significantly improved, and after the peak load of the anchor rod is reached, the residual anchoring force is still greater than that of ordinary anchor rod anchoring. Although the radial compressive stress of the anchor rod with a 9% expansion agent dosage reached 1.01 MPa, excessive expansion agent caused the anchor body to loosen and crack slightly, making it unable to compact the interface with the surrounding rock. After the stress load reached the limit value, the anchoring system immediately failed, and its residual anchoring force was smaller than that of ordinary anchor rods.

4. Conclusions

1) Analyzed the reasons for the failure of traditional anchor rod support and

the anchoring mechanics mechanism of pressurized anchor rods. The causes of anchor rod failure and the mechanical mechanism of the interaction between the anchor rod, grouting body, and surrounding rock indicate that the self stressing slurry can effectively increase the radial compressive stress of the anchoring system. The grouting body produces a high gripping force on the anchor rod and a large friction force on the drilling surrounding rock, forming a radial pressurized anchor rod system, greatly improving the ultimate pull-out capacity of the anchor rod and improving the anchoring effect.

2) By establishing a mathematical model of a thin-walled cylinder, the relationship between the measured radial strain value and the radial expansion stress is calculated. The experimental results showed that the expansion effect of the four groups of materials with expansion agent dosages of 3%, 5%, 7%, and 9% was basically completed within 7 days, and then stabilized. The expansion effect of the slurry stone body with a 7% expansion agent dosage is superior to other dosage groups, and the radial stress reaches a maximum value of 1.5 MPa. Therefore, it is recommended to use a ratio of 7% expansion agent in the project.

3) By comparing the anchoring effect of ordinary anchor bolts with different amounts of expansion agent through anchor rod pull-out experiments, the experimental results show that the maximum pulling force of ordinary anchor rod anchoring is 14.28 KN, and the maximum pulling force of anchor rod anchoring with 7% expansion agent dosage reaches 40.98 KN, with an increase in pulling force of 187%. The anchoring effect is obvious.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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