Research on the full-section anchor cable and C-shaped tube support system of mining roadway in island coal faces

Renliang Shan, Pengcheng Huang, Honghu Yuan, Chi Meng and Shupeng Zhang

School of Mechanics and Civil Engineering, China University of Mining and Technology (Beijing), Beijing, China

ABSTRACT
Anchor cables often break in various forms. Tensile failure can be resisted by using high-strength materials, while there is no good solution for shear failure. A new supporting structure called Anchor Cable and C-shaped tube that can bear the transverse shear force was invented and a preliminary introduction to the mechanism of the structure is given. Field investigations and in-situ stress tests were carried out on the panel 3210 in the Nanguan Mine. The failure modes of the surrounding rock and cables and the in-situ stress test results show that the working face is obviously affected by the horizontal stress. Thus, a new full-section anchor cable and C-shaped tube support scheme were proposed. The results of FLAC3D show that the new scheme is excellent in controlling the surface convergence and plastic zone extension. The rationality of the scheme was verified by two-and-a-half months of monitoring. Compared with the original scheme, the amount of surface displacement was at least 20% smaller, and the time for the displacement to reach equilibrium was at least 27.4% shorter. The surface of the roadway is flat without supporting material damaging. The new scheme is worth popularizing in similar working conditions.

1. Introduction

With the continuous mining of coal resources, there are fewer and fewer coal seams that are easy to excavate. Currently, most coal mining activities in China have become deep mining activities (Zhang and Barla 2019; Xie et al. 2019). The stress environment of deep surrounding rock is complex (Yu et al. 2019), which greatly increases the difficulty of resource exploitation. Coal mine safety accidents occur frequently (Wang and Meng 2018; Zhai et al. 2016).

During the period of coal mining, to maintain high-output and high-efficiency mining and to mitigate the strain balance between mining and tunneling (Qian et al. 2016), many coal mines choose the skip mining method for coal mining, therefore, many isolated island working faces are produced. Due to the influence of the goaves on both sides of the working face, the stress in the face coal body is superimposed, the peak value is increased, and the stress-concentration area is expanded, resulting in a large compressive strength at the top of the face and a strong mine pressure (Guo et al. 2019). Compared with other roadways, the stress environment of support components in isolated working faces is more complex.

The Nanguan mine is located in Lingshi County, Shanxi Province, China. The panel 3210 of the Nanguan mine is a typical isolated island working face. Many broken anchor cables and bolts were found during field investigation on the panel 3210. Most of them were broken in tension or shear, and the fracture locations were mostly distributed within 2 m of the roof. This indicates that the support system bears not only tension but also the shear force, which cannot be ignored on the island working face. The failure in cable bolts is mostly due to the combination of shear failure and tensile failure (Rasekh et al. 2017). Current rock bolt support design methodologies consider only the axial capacity, however, shear failure is the main failure mode of anchorage bolts in coal mines (Liu et al. 2019). Combined load conditions could decrease the rock bolt shear and axial capacity by 30% and 18% (Pinazzi et al. 2020). Therefore, the shear strength of bolt and anchor cable are essential considerations in support design.

Generally, the range within 2 m above the roof is where the free end of the bolt or anchor cable is, and the anchor cable and bolt are not coupled with the surrounding rock. Moreover, the surrounding rock within 2 m above the roof, especially in the mining roadway in the island coal face, is relatively broken. Shear dilatancy is also a part of the reason for the fracture of the bolt or anchor cable.

Many scholars have studied the shear mechanical properties of anchor bolts and anchor cables. These conclusions can be used as a reference for support design. It was found that the rock bolt contribution to the joint shear strength standardized by the bolt
tensile strength was the largest, followed by cable bolts and FG bolts (Li et al. 2016). Increasing the pretension load decreased the peak shear load of the cable bolts (Aziz et al. 2018). A larger diameter rockbolt was able to resist a greater degree of shear displacement under the same shear loading condition, weak rock made it difficult for the system to accommodate large shear displacements, and the rock was crushed before the rockbolt developed its maximum shear capacity (Li et al. 2019).

In recent years, there have been many new techniques and tools to address the deformation of surrounding rock and the failure of supporting materials. A pressure-relief mining technology without advanced tunneling and coal pillars (PRMT) for longwall mining that can reduce roadway tunneling, reduce coal loss and improve roadway stability has been proposed in China (Wang et al. 2020). The constant-resistance and large-deformation (CRLD) anchor cable is a device that includes high resistance, large elongation, and strong energy absorption because of the special structure set on the CRLD bolt (Sun et al. 2017). CRLD anchor cable is suitable for solving soft rock swelling and has been widely used in deep soft rock roadways with good results (Tao et al. 2017). The TCC yielding rock bolt is another bolt which can bear shear force. It has a smooth bar with no or very weak bonding to the grout that can stretch to accommodate rock dilatation (Wu et al. 2019). Both the CRLD anchor cable and TCC rock bolt adapt to large deformation through axial changes to reduce the resulting shear force, while anchor cables and C-shaped tubes are support structures that directly resist the shear force through C-shaped tubes.

2. A brief introduction of anchor cables and C-shaped tubes

Anchor cables and C-shaped tubes are abbreviated as ACC, and ACC is used to represent the anchor cable and C-shaped tube in the following paragraphs. The ACC is also known as “Kangjianmaoguansuo” in Chinese. It is an invention patent that is a support structure consisting of an anchor cable and a C-shaped tube. This support structure can bear the horizontal shear forces (Shan, Tao, and Kong 2014). Figure 1(a,b) are the physical and structural drawings of the ACC.

Structure of the ACC: The ACC is composed of an anchor cable and a C-shaped tube, which is similar to the combination of anchor cables and slit wedge tubing bolts, which can not only exert a high pretightening force on the ACC, but also improve the shear resistance like the slit wedge tubing bolt and enhance the overall anchorage force with the deformation of the surrounding rock.

The main innovation lies in that the free end of the anchor cable is protected by the C-shaped tube. As shown in Figure 2, when the entire structure is subjected to transverse shear forces, the C-shaped tube is gradually deformed and compressed until the free end is wrapped to enhance the shear resistance of the anchor cable. The C-shaped tube connects the support plate and the anchor agent at the anchorage section together. When the surrounding rock around the support plate is broken, the loss of pretension of the anchor cable will be reduced, so that the pretension of the anchor cable will not completely fail.

The mechanism of the full-section ACC support system is as follows:

1. The theory of extrusion reinforced arch is more suitable for the roof where surrounding rock is broken.
2. A full-section ACC support system can form a layer of extrusion and reinforced belt in the surrounding rock by using short anchor cables with a high pretightening force and c-shaped tubes, which enhances the bearing capacity of the roof. Especially in a broken roof, the free end of the anchor cable easily bears the bulk force of the crushed surrounding rock and is cut by shear. Under the premise of not affecting the high pretightening force applied by the anchor cable to enhance the overall strength of the surrounding rock, the c-shaped tube covers the free end of the anchor cable and plays a similar role to that of a full-grouted cable. When the free end is subjected to transverse shear forces, the c-shaped tube is subjected to annular deformation and compression, and the free end of the anchor cable is finally wrapped up by the c-shaped tube, which greatly improves the shear resistance of the free end of the anchor cable.

(1) The shear force anchor cable with a high pretightening force will decrease when tension increases. According to the literature (Li et al. 2016), under the joint action of tension and shear, the tension and shear forces of the cable body at the position where the cable breaks meet the following Equation (1):

\[
\left(\frac{N_0}{N_f}\right)^2 + \left(\frac{Q_0}{Q_f}\right)^2 = 1
\] (1)

In Equation (1), \(N_0\) and \(Q_0\) are the tensile and shear forces (kN), respectively, at failure of a bolt; \(N_f\) is the ultimate tensile strength of a bolt (kN); and \(Q_f\) is the ultimate shear strength of a bolt (kN). Equation (1) shows that under combined action of shear and tension, the shear force anchor cable will decrease when the pretightening force increases. Therefore, in today's trend of pursuing
a high pretightening force in roadway supports, the shear property of anchor cables is important. The ACC can provide shear resistance at the free end, thus resolving the contradiction between high pretension and shear resistance of the anchor cable.

(3) Due to the broken surrounding rock with a relatively low strength in the roof, when the anchor cable preload force is too large, the support plate will crush the surrounding rock on the roof surface. Meanwhile, the pretightening force will be lost. The c-shaped tube provides a link between the anchoring agent at the anchorage section and the support plate. When the surrounding rock of the roof is broken, the c-shaped tube provides the support force in the axial direction, reduces the loss of the pretightening force of the anchor cable and prevents the pretightening force of the anchor cable from completely failing.

(4) The ACC is used in conjunction with a W-type steel band. The W-type steel band has a large rigidity and can cover a wide area, which can balance the internal force of each anchor cable and prevent the anchor cable from being broken. Compared with reinforced ladder beams, the W-type steel band belongs to a type of surface
support. It is much better and more suitable for controlling the deformation of the surface in a roadway than reinforced ladder beams.

3. General situation of the tailgate 3210 in Nanguan mine engineering background

The length of the panel 3210 in the Nanguan Mine is 1210 m and the length of the setup entry is 180 m. The coal face has the shallowest depth of 439 m, and a deepest depth of 602 m, and the average dip angle of the coal seam is 10°. To the east of the panel 3210 is the panel 3208, which has been exhausted. The panel 3212 which has also been exhausted, is in the west of the panel 3210. The panel 3210 is located north of the boundary of the Third Mining Area and south of the downhill roadway of the west wing of the Third Mining Area. The widths of the coal pillars between the working face and the goaf on both sides are both 21 m. The panel 3210 is a typical island working face. A sketch of the location of the panel 3210 is shown in Figure 3(a).

According to the geological exploration data, the stratigraphic position diagram of tailgate 3210 is shown in Figure 3(b) below.

The original support scheme of tailgate 3210 adopted the combined support of bolts, anchor cables, reinforced ladder beams, and hexagonal metal meshes. The diameter of the bolt is 22 mm. The length of the bolt is 2400 mm. The diameter of the anchor cable is 21.6 mm. The length of the anchor cable is 6300 mm.

3.1. Roof support method

There were 7 bolts in the roof at a distance of 750 mm and the distance between the two rows was 800 mm. There were 3 anchor cables at a distance of 1000 mm, and the distance between the two rows was 1600 mm.

Anchor cables were located between the two rows of bolts. The connection of each bolt or anchor cable in a row was achieved by a reinforced ladder beam. The hexagonal metal meshes were also compacted by reinforced ladder beams. The torque of the nut was not less than 300 N·m, and the pretightening force of the anchor cable was not less than 100 kN.

3.2. Side support method

The types of bolts and anchor cables used on both sides of the roadway were the same as those used in the roof. There were 3 bolts on the left side and 4 bolts on the right side of the roadway at a distance of 850 mm between 2 bolts in the same row, and the distance between two rows was 800 mm. There was a cable on each side replacing the second bolt of the two sides at a distance of 3200 mm between two rows. The dip angle of the side anchor cable was 45°. The connection of each bolt or anchor cable in a row was achieved by a reinforced ladder beam. The hexagonal metal meshes were also compacted by reinforced ladder beams. The torque of the nut was not less than 300 N·m, and the pretightening force of the anchor cable was not less than 100 kN. A sectional drawing of the original support scheme is shown in Figure 4.

During the on-site investigation of the tailgate 3210 and its surrounding roadways, the following problems were found:

1) In the downhill roadway of the west wing next to the panel 3210, the whole section was compressed into a triangle after local roadway repair, as shown in Figure 5(a). As shown in Figure 5(b), there was large-scale surrounding rock protruding. As shown in Figure 5(c), a large number of bulges occurred in the rock surrounding the roof along the middle line of the roof in the section without repair. This indicated that the horizontal stress of this stratum was obvious, there was a surrounding rock dislocation phenomenon, and the support members were easy to shear.

2) There were many bolts cut by shear in the tailgate 3210 (see Figure 5(d)). In Figure 5(d), it can also be seen that the roof rock of the tailgate 3210 was weak and broken and the broken surrounding rock was trapped by the hexagonal metal mesh forming a bulge, which seriously threatened the construction safety. The bolts and cables were retrieved for fracture analysis and it was found that the fracture of the bolt cables showed shear failure behaviors, indicating that the transverse shear force of the roof had a great influence on the support members, as shown in Figure 5(e). As shown in (f) and (g), the rock surrounding the roof of the tailgate 3210 was seriously deformed. Due to the weak rock and the use of flexible reinforced ladder beams for the connection of supporting members, the linear support had a poor effect on the deformation control of the surrounding rock, resulting in large-scale plastic deformation of the rock surrounding the roof. The roadway side was full of coal, there was a large horizontal stress in the working face and the side was prone to deformation. The support effect of ordinary bolts is general. The plastic deformation of the upper part cannot be completely controlled by a single anchor and the reinforced ladder beam, so the anchor was covered by the deformation of coal.

Therefore, the deformation and failure characteristics of the surrounding rock of the tailgate 3210 in the Nanguan Mine are summarized as follows:

The surrounding rock is lithologically weak and broken in the tailgate 3210. The effects of horizontal stress are obvious. The roof shear force has a substantial impact on the support members, and the reinforce-ment ladder beams do not match the stiffness of the bolts and anchor cables, resulting in serious deformation of surrounding rock.
4. In-situ rock stress measurements in the tailgate 3210

As the two roadways of the panel 3210 were just excavated, a winch chamber in the coal area without affecting the construction was selected to conduct in-situ stress test, so as to understand the approximate surrounding rock stress state of the panel 3210 and provide reference for numerical simulation. The test method was the stress relief method. The drilling direction was 10 degrees from the side to the roof for drilling and the drilling depth was 8.5 m. A part of the core calibration curves and stress relief curves are listed in Figure 6. The stress relief method for testing the ground stress follows the following formulas:

\[ E = \frac{K}{\left(\frac{R^2}{R^2 - r^2}\right)} \]  

(2)

\[ u = \frac{\varepsilon_\theta}{\varepsilon_z} \]  

(3)

\[ \varepsilon_\theta = \frac{1}{E} \left( \sigma_x + \sigma_y \right) k_1 + 2 \left( 1 - \mu^2 \right) \]  

(4)

\[ \left( \sigma_y - \sigma_x \right) \cos 2\theta - 2 \tau_{xy} \sin 2\theta \]  

(5)

\[ \varepsilon_z = \frac{1}{E} \left[ \sigma_z - \mu (\sigma_x + \sigma_y) \right] \]  

\[ \gamma_{zz} = \frac{4}{E} \left( 1 + u \right) \left( \tau_{yz} \cos \theta - \tau_{zx} \sin \theta \right) k_3 \]  

(6)
In Equations (2) and (3), $K$ is the correction coefficient, $p_0$ is the confining pressure (MPa), $R$ is the outer diameter of the core (mm), $r$ is the inner diameter of the core hole (mm), $\varepsilon_\theta$ is the average hoop strain, and $\varepsilon_z$ is the average axial strain.

In Equations (4)–(6), $\varepsilon_\theta$, $\varepsilon_z$ and $\gamma_{\theta z}$ are the circumferential strain, axial strain and shear strain, respectively, $\sigma_x$, $\sigma_y$, and $\sigma_z$ are normal stresses in three directions (MPa), $\tau_{yz}$, $\tau_{xz}$, and $\tau_{xy}$ are shear stresses (MPa), $k_1$ to $k_4$ are calculation coefficients, and $\theta$ is the strain gauge angle.

The stress level near the tailgate 3210 in the Nanguan Mine is obtained through a numerical calculation, as shown in Table 1. It can be seen from the measured results of the in-situ rock stress test that the stress level near the tailgate 3210 of the Nanguan Mine is not very high, and the deformation is mainly due to the weak surrounding rocks. Because the horizontal stress and vertical stress are close, the shear force will cause shear failure of the support members under certain circumstances.

5. Support countermeasures of the tailgate 3210

According to the results of the field investigation and in-situ rock stress test, a full-section ACC support scheme was proposed for controlling the deformation of the surrounding rock and bolt breakage.

The full-section ACC support scheme adopted the combined support of the ACC, W-type steel band and hexagonal metal mesh. A sectional drawing of the original support scheme is shown in Figure 7.

The ACCs were all combined with an anchor cable with a diameter of 21.6 mm, and a length of 3000 mm and a C-shaped tube with a diameter of 28 mm, an inner diameter of 24 mm, and a length of 2000 mm.

Roof support method: There were 7 ACCs in the roof at a distance of 700 mm and the distance between two rows was 800 mm. The connection of each ACC in a row was achieved by the W-type steel bands. The hexagonal metal meshes were also compacted by W-type steel bands. The pretightening force of the ACC was not less than 200 kN.

Figure 4. The sectional drawing of the original support scheme.
Side support method: There were 4 bolts on the left side of the roadway at a distance of 700 mm between 2 ACCs in the same row and the distance between two rows was 800 mm. There were also 4 bolts on the right side of the roadway at a distance of 750 mm between 2 ACCs in the same row, and the distance between two rows was 800 mm. The connection for each ACC in a row was achieved by the W-type steel bands. The hexagonal metal meshes were also compacted by W-type steel bands. The pretightening force of the ACC was not less than 200 kN.

5.1. Numerical simulation

The numerical simulation software FLAC3D was used to compare the original and new schemes, so as to find out the causes of the problems in the field investigation. By comparing the surface displacement of roadway and

Table 1. The measured results of the in-situ rock stress test.

| Classification | Stress (MPa) | Dip (°)   | Azimuth (°) |
|----------------|-------------|-----------|-------------|
| $\sigma_3$     | -5.77       | -16.45    | 130.35      |
| $\sigma_2$     | -6.68       | 58.17     | 68.75       |
| $\sigma_1$     | -6.88       | 26.42     | 211.92      |
| $\sigma_x$     | -6.24       | -         | -           |
| $\sigma_y$     | -6.44       | -         | -           |
| $\sigma_h$     | -6.65       | -         | -           |
Figure 7. The sectional drawing of the full-section ACC support scheme.

Figure 8. The boundary conditions of the model.

Table 2. The surrounding rock parameters of each layer.

| Stratum     | Density (kg/m³) | Bulk modulus (GPa) | Shear modulus (GPa) | Cohesion (MPa) | Friction angle (°) | Tensile strength (MPa) |
|-------------|-----------------|--------------------|---------------------|----------------|--------------------|------------------------|
| Siltstone   | 2550            | 4.9                | 2.5                 | 5.4            | 31                 | 3.1                    |
| Fine-arenite| 2080            | 4.3                | 2.45                | 1.8            | 34                 | 2.9                    |
| Coal        | 1700            | 3.1                | 1.8                 | 0.7            | 25                 | 0.8                    |
| Mudstone    | 2520            | 4.1                | 2.3                 | 5.9            | 30                 | 1.3                    |

Table 3. Parameters of the support member.

| Type                     | Anchor cable | Bolt | Beam |
|--------------------------|--------------|------|------|
| Diameter (mm)            | 21.6         | 22   | -    |
| Xcarea (mm²)             | 366          | 380  | 60   |
| Modulus of elasticity (GPa) | 195        | 200  | 200  |
| Breaking load (kN)       | 500          | 216  | -    |
| The outer ring perimeter of the anchoring agent (mm) | 100 | 100 | -   |
| Rigidity of anchoring agent/(MN/m/m) | 17.5 | 17.5 | -   |
| Bond strength of anchoring agent/(MN/m) | 0.44 | 0.44 | -   |
| Poisson’s ratio          | -            | -    | 0.3  |
The displacement cloud diagrams of the two support schemes are shown in Figure 10. The surface deformation data of the roadway are listed in Table 5. According to the data in Table 5, the deformation of the top and bottom plates is less than the convergence of the two sides. Under the same conditions, the floor heave volume of the ACC scheme decreased by 0.66 cm compared with the original support scheme which was optimized by 4.3%. Compared with the original scheme, the roof subsidence volume decreased by 2.92 cm, which was optimized by 28.74%. The two-side movement volume decreased by 24.08 cm, which was optimized by 47.33%.

The field investigation results are consistent with the distribution range of plastic zone through numerical simulation, the original and new schemes were compared which was more reasonable.

The length, width and height of the model were 60 m, 10 m and 40 m respectively, as shown in Figure 8. The bottom plate of the model was fixed and the surrounding horizontal displacement was fixed. The stress boundary in the vertical direction of 6.45 MPa was applied to the upper part of the model according to the in-situ stress test results. The mol-coulomb model was used for the calculation. As shown in Figure 9, in the ACC simulation, the cable unit was used to simulate the anchor cable, the PILE unit, which could withstand shear forces in FLAC3D, was used to simulate the C-shaped tube, and the BEAM unit was used to simulate the W-type steel band.

The parameters used in the numerical simulation are listed in Tables 2–4 below:

1. Displacement field analysis
2. Stress state analysis
3. Sidewall stability analysis
4. Roadway stability analysis
5. Deformation field analysis
6. Field monitoring data

The parameters used in the numerical simulation are listed in Tables 2–4 below:

Table 4. Pile unit-related parameters.

| Type | modulus of elasticity (GPa) | Poisson’s ratio | Xcarea (mm²) | The outer ring perimeter (mm) | Stiffness per unit length of shear spring (MPa) | Cohesion per unit length of shear spring (MN/m) | Stiffness per unit length of normal spring (MPa) | Cohesion per unit length of normal spring (MN/m) | Friction Angle of shear spring (MPa) |
|------|---------------------------|----------------|--------------|-------------------------------|-----------------------------------------------|-----------------------------------------------|---------------------------------------------|-----------------------------------------------|-------------------------------|
| Pile | 200                       | 0.3            | 4.02         | 100                           | 13                                           | 13                                            | 13                                          | 0                              | 25                            |

Table 5. Displacement comparison table.

| Type                                      | The original scheme | The ACC scheme | Optimization rate |
|-------------------------------------------|---------------------|----------------|-------------------|
| Deformation of left side/cm              | 23.48               | 14.92          | -                 |
| Deformation of right side/cm             | 27.39               | 11.87          | 47.33%            |
| Maximum movement of the two sides/cm     | 50.87               | 26.79          | 47.33%            |
| The deformation of the top plate/cm      | 10.16               | 7.24           | 28.74%            |
| The deformation of the bottom plate/cm   | 15.18               | 14.52          | 4.3%              |
| Maximum movement of the top and bottom plates/cm | 25.34       | 21.76          | 14.13%            |

Table 6. Field monitoring data.

| Type | Displacement of two sides/mm | Displacement of the roof and floor/mm | Deformation stability time of two sides/days | Deformation stability time of roof and floor/days |
|------|------------------------------|---------------------------------------|---------------------------------------------|--------------------------------------------------|
| 1#   | 257                          | 401                                   | 42                                          | 60                                               |
| 2#   | 227                          | 403                                   | 42                                          | 46                                               |
| 3#   | 204                          | 320                                   | 40                                          | 50                                               |
| 4#   | 234                          | 291                                   | 29                                          | 35                                               |
| 5#   | 80                           | 160                                   | 25                                          | 20                                               |
and corner strengthened support for coal roadways (Shan et al. (2015)), increasing the support strength of the side can improve the stability of the whole roadway and reduce the roadway deformation. Therefore, the control effect of the ACC support scheme on the surrounding rock deformation is stronger than that of original scheme.

(2) Plastic zone analysis
5.2. Field experiment

Field experiments were conducted to evaluate the supporting effect of the ACC support scheme, field experiments were conducted in the tailgate 3210. The ACC support scheme was used for approximately 200 meters of the roadway. Two measuring stations, No. 1 and No. 2 were set up, while in the support section of the new scheme, measuring stations No. 3, No. 4 and No. 5 were set up. The measuring stations of the original scheme were 20 m and 10 m away from the starting points of the implementation of the new scheme. The measuring stations of new schemes No. 3, No. 4 and No. 5 were arranged at the three sections of 20 m, 40 m and 60 m after the implementation of the new scheme.

The surface displacements, including the roof and floor displacement and the displacement of the two sides, were monitored by the “cross point method”, and the surrounding rock deformation was stable approximately two months after the observation period. The field monitoring data are shown in Figure 12 and Table 6.

(a) Displacement of two sides (b) Displacement of the roof and floor

(1) Displacement of two sides
In the original scheme, the average displacement of the two sides was 242 mm, while in the new scheme, the average displacement of the two sides was 173 mm with an average optimization rate of 28.5%.

In the original scheme, the deformation stabilization time of the first and second test stations was approximately 42 days. In the new scheme, the average deformation stabilization time was 32 days. The ACC support scheme can quickly control the deformation of surrounding rock. Compared with the original scheme, the time for the deformation of the ACC support scheme to reach the stable state was shortened by 23.8%. A high preload made the surrounding rock restore the three-dimensional stress state in time, especially the coal pillar of the island coal face, which experienced from complex stress and serious damage. Timely restoration of the three-dimensional stress state can restore the stability of the surrounding rock as soon as possible.

(2) Displacement of the roof and floor
According to Figure 12(b), although the displacement of the roof and floor of the No. 3 measuring station was the largest of the three measuring stations that adopted the new scheme, it was optimized by...
20.2% and 20.6% respectively compared with measuring stations No. 1 and No. 2, which adopted the original schemes. At station No. 4 station, compared with stations No. 1 and No. 2, the optimization rate of the top and bottom plate movement was approximately 27.4%. No. 5 had the smallest displacements of the roof and floor, and compared with stations No. 1 and No. 2, the optimization rate was approximately 60%.

In terms of the time for the stability of the top and bottom to reach stability, the average number of days for roof and floor deformation stabilization in the original scheme was 53 days, while the average number of days for deformation stabilization in the new scheme was 35 days. In terms of the amount of displacement of the roof and floor, the ACC support scheme took 34% less time to reach stability than the original scheme.

(3) The supporting effect of the ACC support scheme

After intensive monitoring for up to 72 days, the support effect diagram of the 200 m test section with the full-section ACC support scheme being adopted is shown in Figure 13. The surface of the whole supporting section is smooth. There is no break anchor cable and no large-scale roof bulge. The deformation of both sides of the roadway has been effectively controlled. As the original support is a reinforced ladder beam, the surrounding rock is weak and broken, and the reinforced ladder beam is too soft, so the anchor rod and anchor cable are basically equivalent to independent work. In the ACC support scheme, the W-type steel band is used to combine all supporting elements into a whole. The scheme increases the support density of the roof, and adopts high pretightening force on the anchor cable, forming an extrusion reinforcement layer in the shallow surrounding rock, which increases the bearing capacity of the unstable surrounding rock on the surface. Therefore, the plastic zone distribution and surface displacement are smaller than those of the original scheme.

6. Conclusions

(1) The ACC is a support structure that can bear the transverse shear force. By means of the C-shaped tube, the anchor cable is wrapped while absorbing the energy of the deformation of the surrounding rock to improve the overall stiffness and shear resistance of the anchor cable and solve the problem of nonshear resistance of the anchor cable under a high preload from the structure.

(2) The in-situ rock stress measurement was conducted in the panel 3210 of the Nanguan Mine, and the measured results of the in-situ rock stress measurement showed that the stress level near the tailgate 3210 of the Nanguan Mine was not very high. The vertical stress and horizontal stress were close to each other and played a leading role in the roadway deformation.

(3) FLAC3D numerical simulation results show that the full-section ACC support scheme had better effect on control of roadway deformation and plastic zone development than the original scheme.

(4) A field support test was conducted in the tailgate 3210 of the Nanguan Mine. The ACC support scheme was used for approximately 200 meters in the roadway. Five measuring stations were set, and deformation monitoring was conducted for two and a half months. It is found that the ACC support scheme could reduce the roadway deformation and stability period and the shrinkage rate of the roadway section and the support section was flat without anchor cable breaking.

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Notes on contributors

Renliang Shan, Professor and doctoral supervisor of School of Mechanics and Civil Engineering, China University of Mining and Technology-Beijing. Mainly engaged in the teaching and research of geotechnical engineering.

Pengcheng Huang, Doctoral student of School of Mechanics and Civil Engineering, China University of Mining and Technology-Beijing. Mainly engaged in scientific research in the field of mine support.

ORCID

Renliang Shan http://orcid.org/0000-0002-4559-0935
Pengcheng Huang http://orcid.org/0000-0001-7225-4825
Honghu Yuan http://orcid.org/0000-0002-0388-0627

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