



FEASIBILITY OF GFRP BOLTS FOR STOPE ROADWAY SUPPORT IN CEMENTED BACKFILL DRIFT MINING: A CASE STUDY OF JINCHUAN NO. 2 MINE

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Abstract: *Conventional rebar bolts used for stope roadway support during cemented backfill drift mining often suffer from high installation demand, high cost, and corrosion damage. Based on Jinchuan No. 2 Mine, this study combined field anchorage force tests, numerical analysis, and field trials to evaluate the feasibility of Glass-fiber-reinforced plastic (GFRP) bolts for stope roadway support. Under full length anchorage, the average anchorage force of GFRP bolts reached 103.53 kN. This was 74.65% of the value for rebar bolts and was sufficient to meet the support requirement of the mining area. The anchorage forces of both GFRP bolts and rebar bolts decreased as anchorage length decreased, but GFRP bolts were more sensitive to anchorage length. Under the same support parameters, GFRP bolt support reduced the stress concentration range, deformation, and plastic zone volume of the surrounding rock. Its overall control effect was close to that of rebar bolt support. During the field trial, the test roadway remained stable. These results indicate that GFRP bolts can serve as a feasible support option for stope roadways in cemented backfill drift mining.*

Keywords: *Cemented backfill drift mining, stope roadways, GFRP bolts, anchorage force tests, numerical analysis, field trials*

1. Introduction

Cemented backfill drift mining has been widely used in underground mines because of its high safety, strong adaptability, and environmental friendliness [1, 2, 3, 4]. During mining, the stability of stope roadways is essential for safe and efficient production. Bolt support is one of the most common support methods. It can mobilize the bearing capacity of the surrounding rock and effectively control roadway deformation and failure [5, 6]. However, the support environment of stope roadways is often complex. Large amounts of backfill water, chemically active gases, and relatively high temperatures are common. These factors can corrode and damage bolts and weaken the overall strength of the support system [7, 8]. In addition, stope roadways usually have a short service life. Their support design must also consider construction efficiency and cost. In the past, metal rebar bolts were mainly used for stope roadway support. However, they have several disadvantages, including high manufacturing cost, large unit weight, inconvenient transport and installation, and poor corrosion resistance. As a result, they cannot fully meet the support requirements of stope roadways during cemented backfill drift mining.

To address these problems, researchers have proposed the use of Glass-fiber-reinforced plastic (GFRP) bolts to replace conventional rebar bolts [9, 10]. As a type of nonmetallic bolt, GFRP bolts are not only cheaper and lighter than rebar bolts, but also have excellent corrosion resistance and chemical stability. Many studies have shown that GFRP bolts can meet the support requirements of roadways under different conditions [11, 12, 13]. However, the support performance of GFRP bolts is strongly affected by surrounding rock conditions

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and support parameters. Their performance can vary greatly under different conditions [14, 15]. In cemented backfill drift mining, the roof of the stope roadway is composed of backfill, while the sidewalls and floor are composed of ore. This forms a typical mixed surrounding rock system. Its physical and mechanical properties are clearly different from those of conventional surrounding rock. In addition, these roadways usually have a rectangular section. Therefore, whether GFRP bolts can provide effective support under such conditions still requires further investigation.

At present, methods for evaluating bolt feasibility can generally be divided into three categories. The first is field anchorage force testing [16, 17]. This method is simple and direct, and it can reflect the actual anchorage performance of bolts with relatively high accuracy. The second is numerical analysis [18, 19]. It establishes a numerical model for the bolt support system and analyzes the stress, displacement, and plastic zone response of the surrounding rock after different types of bolts are applied. The support effect of the bolts is then evaluated based on the calculated results. The third is field testing [20, 21]. In this method, the studied bolts are directly used in roadway support engineering, and roadway stability is evaluated through field monitoring and observation. This method can more comprehensively reflect the overall working state of the surrounding rock and support system. It can also, to some extent, avoid inconsistencies between theoretical analysis and actual field conditions.

Based on this, this study focuses on the stope roadways of Jinchuan No. 2 Mine. It investigates the feasibility of GFRP bolts for stope roadway support in cemented backfill drift mining. First, field anchorage force tests were conducted to evaluate the anchorage performance of GFRP bolts in stope roadways. Second, a numerical model was established for stope roadway bolt support during cemented backfill drift mining. The support performance of GFRP bolts and rebar bolts was then compared. Finally, field testing was carried out to monitor the stability of stope roadways supported by GFRP bolts. The results provide an engineering reference for the selection of support methods for stope roadways in cemented backfill drift mining.

2. Materials and methods

2.1 Case study background

Figure 1(a) shows the location and geological conditions of the Jinchuan No. 2 Mine in Jinchang City, Gansu Province, China. The mine extracts copper nickel ore using a downward layered cemented backfill drift mining method. Jinchuan Nickel Mine is the largest copper nickel sulfide deposit in China and the third largest in the world. It is also a representative large scale application of cemented backfill drift mining.

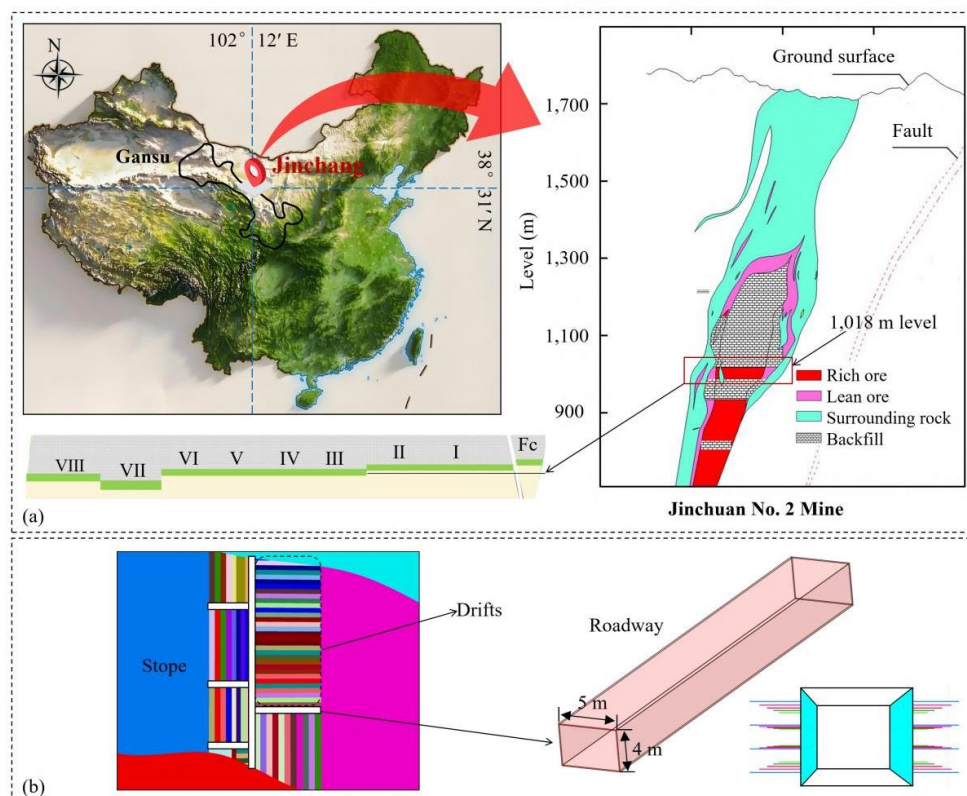


Fig. 1. (a) Geographic location and geological conditions of the Jinchuan No. 2 Mine; (b) stope roadways

This study focuses on Level 1018 m. This level consists of eight panels, namely Fc, I, II, III, IV, V, VI, VII, and VIII. Each panel includes five vertical layers. As shown in Fig. 1(b), the stope roadways have rectangular sections. The roof is composed of backfill, whereas the sidewalls and floor are composed of ore. The roadway is 4 m high and 5 m wide. The sidewalls of the roadway are supported by a single layer bolt mesh shotcrete support system.

2.2 Field anchorage force testing scheme for GFRP bolts

As shown in Fig. 2, the test area was located at the fourth layer of Panel V on Level 1,018 m. The monitoring points were arranged on both sidewalls of the roadway, at a height of 1.5 m above the floor. A total of 24 monitoring points were set. During the test, steel plates were placed between the hydraulic jack and the roadway wall to maintain the overall stability of the testing system. To avoid brittle failure of the bolts caused by shear and extrusion, a steel sleeve and a matching steel nut were installed at the bolt end. The steel sleeve had an inner diameter of 20 mm, an outer diameter of 25 mm, and a length of 250 mm. The steel sleeve was bonded to the bolt end with epoxy resin. A ZY series bolt pullout tester was used in the test. The main auxiliary devices included steel plates, steel sleeves, a hydraulic jack, and steel nuts.

A total of 24 bolts were tested, including 12 GFRP bolts and 12 rebar bolts. The GFRP bolts were 2,200 mm long and 18 mm in diameter, whereas the rebar bolts were 2,250 mm long and 18 mm in diameter. The 12 GFRP bolts were divided into four groups, namely Groups A, B, C, and D, with three bolts in each group. The anchorage lengths of the four groups were full length, three quarter length, half length, and quarter length, respectively. Similarly, the 12 rebar bolts were divided into four groups, namely Groups E, F, G, and H, with three bolts in each group. Their anchorage lengths were also full length, three quarter length, half length, and quarter length, respectively. All tested bolts were anchored with a cement anchoring agent.

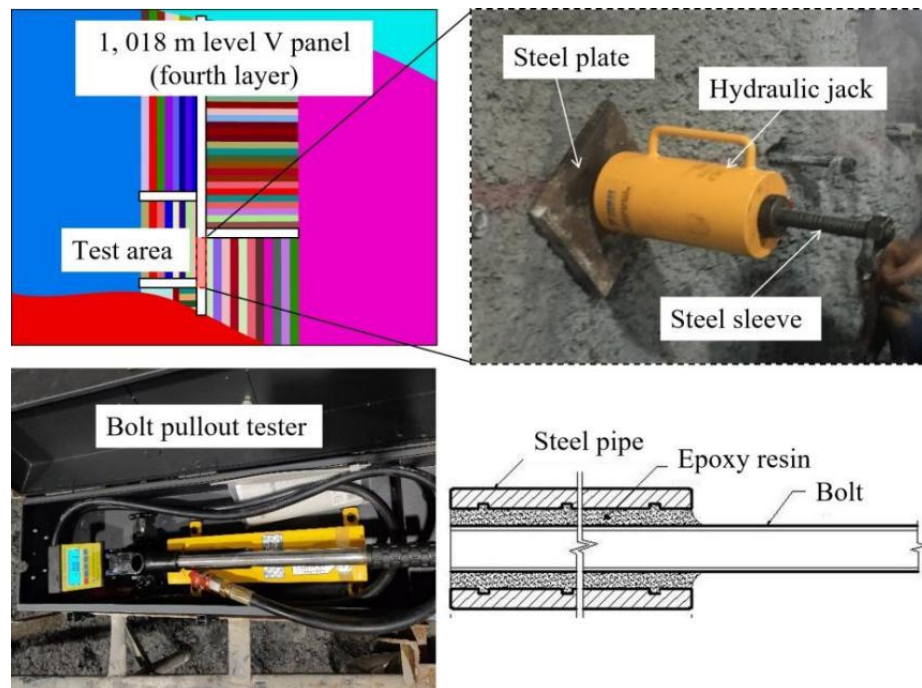


Fig. 2. Field test setup for GFRP bolt anchorage force measurement

2.3 Numerical modeling scheme

Based on the geological conditions, geometric parameters, and support method of the stope roadways in the Jinchuan No. 2 Mine, a numerical model was established in FLAC3D, as shown in Fig. 3(a). In the model, the roof was composed of backfill, whereas the sidewalls and floor were composed of ore. A single layer bolt mesh shotcrete support system was adopted. The bolts were 2,250 mm long and 18 mm in diameter, with a spacing of 1 m. Full length anchorage was adopted, and a cement anchoring agent was used. The steel mesh had a grid size of 150 mm × 150 mm and a diameter of 6.5 mm. The shotcrete thickness was 100 mm. The overall model dimensions were 5 m × 32 m × 32 m, whereas the roadway dimensions were 5 m × 5 m × 4.5 m. The model contained 215,475 nodes and 204,800 elements. The Mohr-Coulomb elastoplastic failure criterion was adopted. The mechanical parameters of the backfill and ore are listed in Table 1 [22]. The mechanical parameters of the rebar bolts and GFRP bolts are listed in Table 2 [23]. The mechanical parameters of the shotcrete layer containing steel mesh are listed in Table 3 [23].

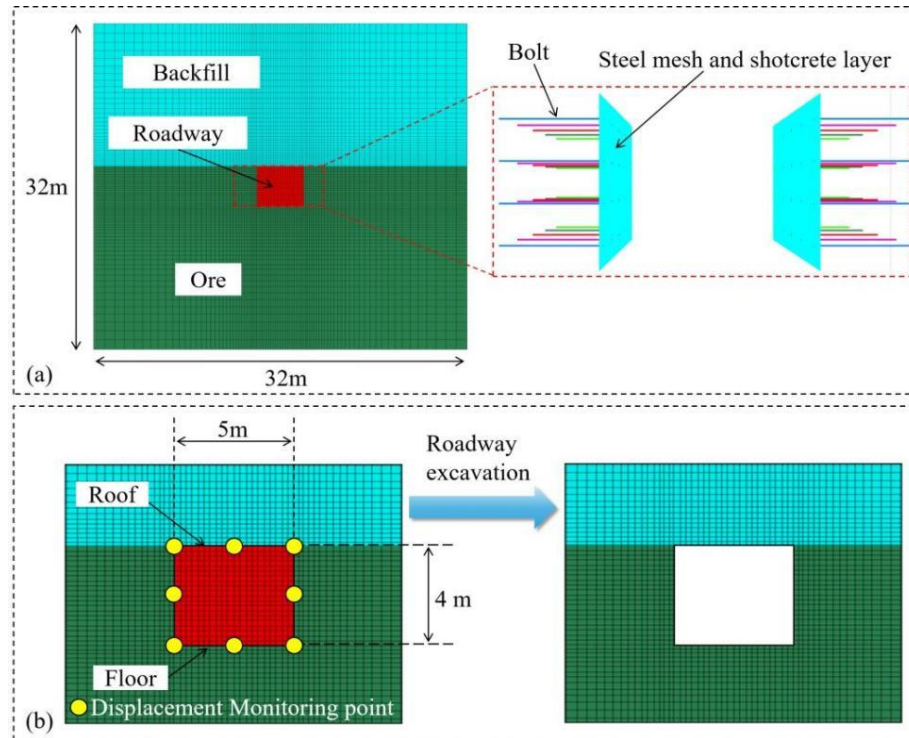


Fig. 3. (a) Numerical model of stope roadway bolt support; (b) layout of monitoring points in the model

In the numerical model, the mining depth was assumed to be 650 m. The initial stresses applied to the model were calculated according to Equation (1).

$$\begin{cases} \sigma_x = 0.022H + 1.863 \\ \sigma_y = 0.034H + 1.083 \\ \sigma_z = 0.028H - 2.131 \end{cases} \quad (1)$$

where σ_x is the principal stress in the X direction, MPa; σ_y is the principal stress in the Y direction, MPa; σ_z is the principal stress in the Z direction, MPa; and H is the depth, m.

Horizontal constraints were applied to the front, rear, left, and right boundaries of the model. A vertical constraint was applied at the bottom boundary. No constraint was applied at the top boundary.

The vertical and horizontal displacements of the roof, floor, sidewalls, and corners of the roadway were monitored. Monitoring points were arranged at the middle of the roof, floor, left wall, and right wall, as well as at the upper corners and lower corners. The layout of the displacement monitoring points is shown in Fig. 3(b).

Three calculation schemes were considered, including unsupported, GFRP bolt support, and rebar bolt support. Excavation was simulated by removing the roadway part from the numerical model.

Table 1. Mechanical parameters of the backfill and ore in the numerical model

Type	Tensile strength (MPa)	Elastic modulus (GPa)	Internal friction angle (°)	Cohesion (MPa)	Density (kg/m ³)	Poisson's ratio
Backfill	0.47	0.90	29.1	1.33	2000	0.26
Ore	0.69	14.25	38.4	1.8	2700	0.3

Table 2. Mechanical parameters of the rebar bolts and GFRP bolts in the numerical model

Type	Tensile strength (MPa)	Elastic modulus (GPa)	Maximum bond strength (kN/m)	Maximum bond stiffness (GN/m ²)	Pretension force (kN)
Rebar bolt	476	210	904	4.72	5
GFRP bolt	480	60	904	4.72	20

Table 3. Mechanical parameters of the shotcrete layer containing steel mesh in the numerical model

Thickness (mm)	Elastic modulus (GPa)	Poisson's ratio	Internal friction angle (°)	Cohesion (MPa)	Normal stiffness (N/m ³)	Shear stiffness (N/m ³)
100	28	0.2	30	1.35	3.4×10^7	3.4×10^7

3. Results

3.1 Anchorage force test results of bolts

The anchorage force test results of GFRP bolts and rebar bolts under different anchorage lengths are presented in Tables 4 and 5, respectively. According to Tables 4 and 5, the average anchorage forces of GFRP bolts and rebar bolts under different anchorage lengths were obtained. The performance ratio of GFRP bolts was also calculated. This ratio was defined as the anchorage force of GFRP bolts divided by that of rebar bolts. The results are shown in Fig. 4.

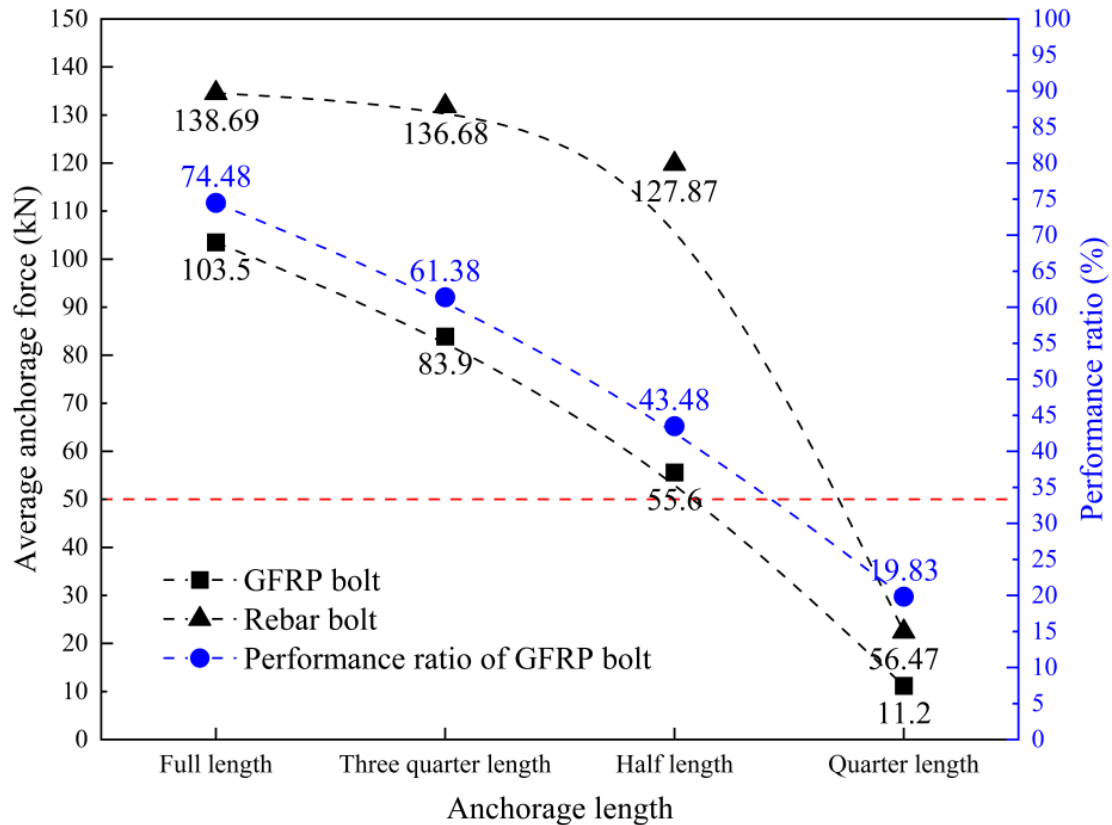


Fig. 4. Anchorage force distribution of GFRP bolts and rebar bolts under different anchorage lengths

As shown in Fig. 4, the anchorage forces of both GFRP bolts and rebar bolts decreased with decreasing anchorage length. However, the reduction patterns were clearly different. The anchorage force of GFRP bolts decreased from 103.53 kN under full length anchorage to 11.20 kN under quarter length anchorage, which was only 10.82% of the full length value. In contrast, the anchorage force of rebar bolts decreased from 138.69 kN to 56.47 kN, which was still 40.71% of the full length value. This indicates that the anchorage force of GFRP bolts was more sensitive to changes in anchorage length than that of rebar bolts. Under the same anchorage length, the anchorage force of GFRP bolts was consistently lower than that of rebar bolts. The gap increased from 25.52% under full length anchorage to 80.17% under quarter length anchorage.

Table 4. Anchorage force of GFRP bolts under different anchorage lengths

Group	No.	Anchorage length	Anchorage force (kN)
A	1	Full length	103.6
A	2	Full length	105.0
A	3	Full length	102.0
B	4	Three quarter length	83.0
B	5	Three quarter length	82.4
B	6	Three quarter length	86.2
C	7	Half length	52.0
C	8	Half length	63.7
C	9	Half length	51.2
D	10	Quarter length	15.4
D	11	Quarter length	11.4
D	12	Quarter length	6.8

Table 5. Anchorage force of rebar bolts under different anchorage lengths

Group	No.	Anchorage length	Anchorage force (kN)
E	1	Full length	137.25
E	2	Full length	138.72
E	3	Full length	140.11
F	4	Three quarter length	137.93
F	5	Three quarter length	135.84
F	6	Three quarter length	136.26
G	7	Half length	125.14
G	8	Half length	131.23
G	9	Half length	127.23
H	10	Quarter length	57.21
H	11	Quarter length	56.32
H	12	Quarter length	55.87

3.2 Numerical results

Figure 5 shows the vertical stress distribution, vertical displacement distribution, and plastic zone distribution after excavation under different support schemes, namely unsupported, rebar bolt support, and GFRP bolt support. The displacements at different locations of the roadway are listed in Table 6. The reduction ratio of each index was calculated as the percentage decrease relative to the unsupported condition.

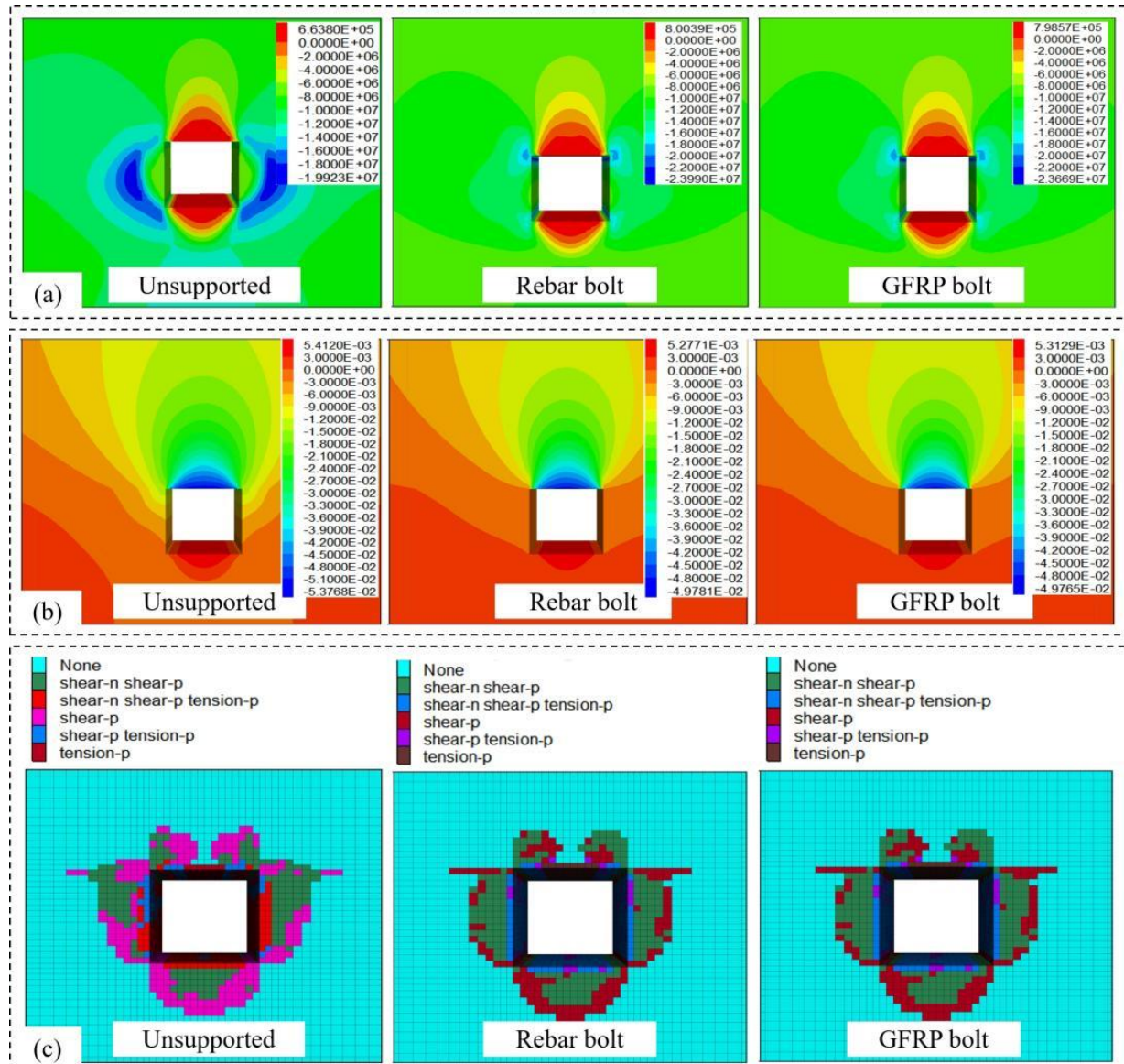


Fig. 5. Distribution characteristics of the stope roadway under different support schemes:
(a) vertical stress; (b) vertical displacement; (c) plastic zone

Table 6. Displacements at different locations of the stope roadway under different support schemes

Index	Unsupported	Rebar bolt support	GFRP bolt support	Reduction by rebar bolt support (%)	Reduction by GFRP bolt support (%)
Volume of the plastic zone in the surrounding rock (m ³)	272.02	237.37	238.88	12.74	12.18
Maximum roof settlement (mm)	53.77	49.78	49.76	7.42	7.46
Maximum vertical displacement of the floor (mm)	5.41	5.28	5.31	2.40	1.85
Maximum vertical displacement of the upper corner (mm)	14.83	3.48	3.49	76.53	76.47
Maximum horizontal displacement of the upper corner (mm)	14.86	7.30	7.43	50.87	50.00
Maximum vertical displacement of the lower corner (mm)	2.08	0.60	0.63	71.15	69.71
Maximum horizontal displacement of the lower corner (mm)	6.02	4.57	4.64	24.09	22.92
Maximum horizontal displacement of the sidewalls (mm)	13.22	6.99	7.12	47.13	46.14

According to Fig. 5 and Table 6, both rebar bolt support and GFRP bolt support reduced the stress concentration range of the surrounding rock and decreased roadway deformation compared with the unsupported condition. Their control effects were especially clear at the upper corners, lower corners, and sidewalls. In addition, both support schemes reduced the plastic zone volume and improved the failure pattern of the surrounding rock.

Further comparison shows that the overall difference between rebar bolt support and GFRP bolt support was small. Compared with GFRP bolt support, rebar bolt support showed only small differences in plastic zone volume and roadway displacement, with corresponding values ranging from 95.24% to 100.04% of those under GFRP bolt support. This indicates that, under the current support parameters, GFRP bolt support provided a surrounding rock control effect close to that of rebar bolt support.

4. Discussion

4.1 Feasibility analysis of GFRP bolts

According to Tables 4 and 5, the anchorage force of GFRP bolts exceeded 50 kN when the anchorage length reached half length or above. In contrast, the anchorage force of rebar bolts exceeded 50 kN even at quarter length anchorage. In the stope roadway support of Jinchuan No. 2 Mine, an anchorage force greater than 50 kN is considered acceptable. Therefore, GFRP bolts can meet the anchorage force requirement when the anchorage length is half length or greater. In actual engineering practice, full length anchorage is used in Jinchuan No. 2 Mine. Under this condition, the anchorage force of GFRP bolts reached 103.53 kN, corresponding to 74.65% of that of rebar bolts, and still satisfied the anchorage force requirement of the mine.

These results show that rebar bolts can maintain relatively high anchorage force even under shorter anchorage lengths. They therefore have stronger adaptability to reductions in anchorage length. In contrast, GFRP bolts show good engineering feasibility only when sufficient anchorage length is ensured.

This result indicates that the field performance of GFRP bolts depends not only on their material properties, but also on the quality of installation. The anchorage force of GFRP bolts decreased to only 10.82% of the full length value when the anchorage length was reduced to one quarter, indicating that their support performance is highly dependent on the effective bonding length. Therefore, incomplete grouting, voids, or discontinuous grout distribution may substantially reduce the effective anchorage length and weaken the anchorage force of GFRP bolts. In engineering practice, uniform and continuous grouting should be ensured along the entire anchorage length. Borehole cleaning, grout preparation, grout injection quality, and bolt installation procedures should also be strictly controlled in accordance with engineering best practices, so that the designed anchorage length can be effectively achieved.

Although the anchorage force of GFRP bolts under full length anchorage was lower than that of rebar bolts, the numerical results showed that GFRP bolt support provided a surrounding rock control effect close to that of rebar bolt support under the same support parameters. These results suggest that, when reasonable support parameters, sufficient anchorage length, and reliable installation quality are ensured, GFRP bolts can serve as a feasible support option for stope roadways during cemented backfill drift mining.

4.2 Engineering verification

As shown in Fig. 6(a), the test area was located at the fourth layer of Panel III on Level 1018 m in the No. 2 Mine. A single layer support system consisting of GFRP bolts, steel mesh, and shotcrete was adopted. The supported roadway was 20 m long, and full length anchorage was used. Except for the GFRP bolts, all other support parameters were the same as those of rebar bolt support. The GFRP bolts were 2200 mm long and 18 mm in diameter. The bolt spacing was 1 m. A cement anchoring agent was used. The steel mesh had a grid size of 150 mm × 150 mm and a diameter of 6.5 mm. The shotcrete thickness was 100 mm.

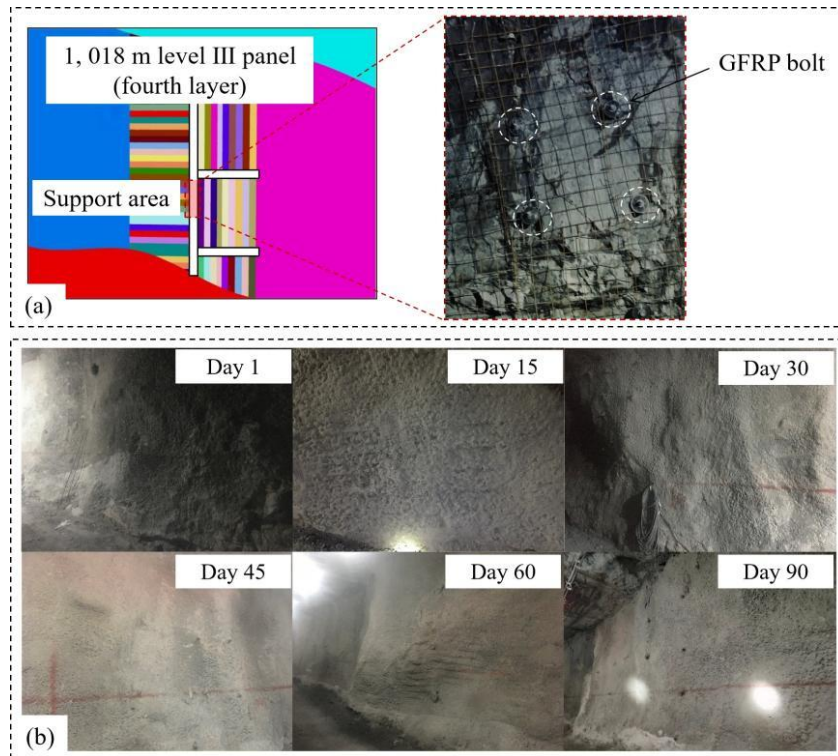


Fig. 6. (a) Field trial of GFRP bolt support; (b) condition of the test area

After support installation, the test area was monitored for three months. The main monitoring contents included roadway stability and the damage and deformation of the support structures on both sidewalls. As shown in Fig. 6(b), the stope roadway remained stable during the test. No significant deformation or failure occurred. No cracking or spalling was observed in the support structures on either sidewall. The support system satisfied the strength and stability requirements of stope roadway support.

5. Conclusions

This study was conducted based on Jinchuan No. 2 Mine. Field anchorage force tests, numerical analysis, and field trials were combined to evaluate the feasibility of GFRP bolts for stope roadway support during cemented backfill drift mining. The main conclusions are as follows.

(1) Under the rock mass conditions and support parameters of Jinchuan No. 2 Mine, the average anchorage force of GFRP bolts reached 103.53 kN under full length anchorage. This value was 74.65% of that of rebar bolts and satisfied the anchorage force requirement for stope roadway support in this mining area.

(2) The anchorage forces of both GFRP bolts and rebar bolts decreased as anchorage length decreased. However, GFRP bolts were more sensitive to changes in anchorage length. Under the same anchorage length, the anchorage force of GFRP bolts was consistently lower than that of rebar bolts. Sufficient anchorage length is an important prerequisite for the engineering application of GFRP bolts.

(3) GFRP bolt support effectively reduced the stress concentration range, deformation, and plastic zone volume of the surrounding rock. Under the same support parameters, its overall control effect was close to that of rebar bolt support. GFRP bolts showed good applicability for stope roadway support.

(4) Under the single layer support system of GFRP bolts, steel mesh, and shotcrete, the test roadway remained stable, and no obvious cracking, spalling, or large deformation was observed. Under the rock mass conditions and support parameters considered in this study, GFRP bolts can serve as a feasible support option for stope roadways during cemented backfill drift mining. They also offer engineering advantages in reducing underground labor intensity, lowering support cost, and improving corrosion resistance.

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