Experimental and numerical investigation on a novel support system for controlling roadway deformation in underground coal mines

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Abstract
Roadway stability in extremely soft coal mass is a typical challenge in deep underground mines, as the most widely adopted support structure such as rock bolting, compound support system normally fails. This paper proposed a novel prereinforcement method for coal roadway, that is, jet grouting (JG) technique, to improve the quality of surrounding soft coal mass and form a stable support structure namely jet grouted coalcrete. The field and laboratory tests were conducted for evaluating the applicability of JG and the mechanical parameters of coalcrete. A numerical model was verified by comparing the calculated results with field measurements. According to the confirmed model, three typical JG support schemes were performed to assess the roadway stability after JG. The results showed that the proposed JG schemes can reduce the deformation and failure zone of the roadway and optimize the stress states around the roadway. The mechanism related to these advantages was investigated. This study provides a promising idea for supporting soft coal roadway in deep underground coal mines, which can promote the JG application in the field.

KEYWORDS
coalcrete, jet grouting technique, numerical modeling, roadway stability, soft coal mass

1 | INTRODUCTION

In the underground coal mines, roadway stability is vital for underground coal mining, which attracts constant concerns there years, as it is tightly related to coal production and the safety of personnel. Some control methods were presented for keeping roadway stable such as steel arch, rock bolts, rock anchor cables.¹ ² In some cases, these methods were effective to control the deformation of the roadway. However, with the increase in mining depth, such conventional support systems normally failed as high stress and complex conditions such as faults, soft rock mass, etc.³ ⁶ Therefore, some compound support technologies were further applied to reduce the large convergence of roadway. For example, some scholars utilized composite support systems including “bolts-cables-shotcrete-square confined arch” and “bolts-cables-U-shaped steel set-shotcrete” for stabilizing deep roadway in coal mines.⁷ ⁸

Considering the rheological properties of soft coal mass, it is quite challenging for maintaining roadway stability by such conventional compound support techniques. Thus, the grouting technique was normally used for reinforcing coal mass around the roadway as it can improve the physical and mechanical properties of soft coal mass, especially in integrity and cohesion.⁹ ¹⁰ Pregrouting and delayed grouting are the main approaches used in underground coal mines.¹¹ The pregrouting technique can increase the overall quality of soft
coal mass before tunneling, which decreases the risk of collapse. Recently, some successful cases can be found in roadway reinforcement by pregrouting.\textsuperscript{12,13} However, in practice, this method is normally limited by grout diffusion radius, the permeability of surrounding coal mass.

To address this issue in pregrouting, a new grouting method called jet grouting (JG) was first present in Japan, which was employed in tunnel reinforcement.\textsuperscript{14} In general, the soil and fractured rock mass were reinforced by JG, forming stable jet grouted columns. The columns have a special performance with higher strength and lower deformability, which was called soilcrete or sandcrete.\textsuperscript{15-18} The physical and mechanical properties of these materials were studied by many scholars. Recently, the JG technique was tried in soft coal mass to form a stable “coalcrete” column in the underground coal roadway.\textsuperscript{19} The high-pressure cement grout was injected into coal mass and mixed with coal particles cut by high-velocity jet. With the withdraw of drill stem, a coalcrete column was generated and finally more such columns created a stable coalcrete arch around roadway profile.\textsuperscript{20} Therefore, this can be seen as a presupport structure, which can be further enhanced by steel sets or rock bolts.

2 \hspace{1em} \textbf{RESEARCH SIGNIFICANCE}

As described above, the JG technique is very promising in underground coal mines, but relevant reports about the control effect and mechanism were limited as this technique is a relatively new support design. Moreover, the size effect widely exists in heterogeneous materials such as concrete, rock, geomaterials, etc.\textsuperscript{21,22} Similarly, coalcrete made up of different materials, that is, coal particles and cement particles are also influenced by the size effect. Coalcrete plays a key role in the JG support system, and therefore, it is necessary to thoroughly understand the size effect on coalcrete and select reasonable parameters for numerical simulation. To the authors’ knowledge, there is no relative research about the mechanical properties considering size effect.

This paper concentrated on the control effect and mechanism of coalcrete on the roadway. A field test of JG was examined, and some tests in the laboratory were designed and conducted for obtaining the mechanical parameters of coalcrete considering size effect. A novel numerical model was constructed and verified by field monitoring data. Furthermore, three JG support schemes were analyzed for revealing the mechanism of controlling effect by coalcrete. The deformation, plastic zone, and stress of roadway were compared and further explained. This work provides a new idea for addressing deformed roadway in deep underground coal mines.

3 \hspace{1em} \textbf{EXPERIMENTAL TESTS OF JET GROUTING}

3.1 \hspace{1em} \textbf{Field evaluation of JG}

A field evaluation was performed before JG application to examine its applicability and availability in an underground soft coal seam. When driving in the coal seam, the collapse and spalling in the tunnel frequently occurred (shown in Figure 1A). The used support system, that is, U-shaped shed, shotcrete, and rock bolts cannot resist the large deformation of roadway effectively. Consequently, the JG technique was first tried in the soft coal mass to construct a reinforcement structure, namely, compound coalcrete columns. Figure 1B showed the trial process of JG in the coal seam. The cement grout (P.O 325) with a water–cement ratio of 0.8 was used for JG. With the drill stem withdrawing in the drilling hole (reverse speed of 20 cm/min), the high-pressure cement grout (23 MPa) with high jet velocity rotated and cut coal mass (rotating speed of 18 r/min), then mixed with coal particles, and finally, a coalcrete column was formed. The excavation profile of the jet grouted coalcrete section showed that the diameter of formed coalcrete is normally around 400-600 mm. This meets the requirements of a roadway support system, demonstrating that the JG technique in soft coal mass is practicable.

3.2 \hspace{1em} \textbf{The size effect of coalcrete}

The function of coalcrete columns is to increase the shear strength of coal mass and form a stable support structure.\textsuperscript{20} Considering the size effect of coalcrete, it is necessary to test the mechanical properties of that. A series of shear tests and compressive tests were performed. The coalcrete...
mix was designed according to the field application. For example, the water–cement ratio of 0.8 and the coal–grout ratio of 1.3 were prepared. The coalcrete slurry was cast into molds with different sizes. Finally, the standard sizes of the specimen were 50-mm, 100-mm, 150-mm, 200-mm cube (shown in Figure 2), and these specimens were used for direct shear tests and compressive tests. All calculations have been done based on the standard test methods (ASTM D5607 and ASTM C39) for performing these laboratory tests.

According to the results of direct shear tests of coalcrete, the failure of that obeyed Mohr–Coulomb failure criteria well. The calculated mechanical results of coalcretes with various sizes were given in Table 1. After compressive tests, the uniaxial compressive strength (UCS) and deformation modulus of coalcrete were summarized in Table 1. The typical failure patterns of coalcrete under different tests were shown in Figure 3. As can be seen, the failure normally occurred at the connections between coal particles and the cement matrix and some bigger coal particles were broken because of the stress.

Then all the mechanical parameters of coalcrete were plotted in Figure 4. It is clear that the larger specimen has a lower strength. With the increase in specimen size, the values of these parameters decreased with a different rate. Based on the suggestions from the literature, two different regression functions were used for fitting the data (ie \( y = a + bx \) for cohesion and friction angle, \( y = bx^2 \) for deformation modulus and UCS). The fitting results were graphed and shown in Figure 4A-D. The values of \( R^2 \) were larger than .99, demonstrating that the function had a good agreement with experimental results. The specific results of the fitting parameters were given in Table 2.

By the established empirical equations and corresponding coefficients in Table 2, it is reasonable to deduce the mechanical parameters of larger coalcrete (the diameter of 400, 600, and 800 mm). The results were summarized in Table 3. It should be mentioned that the tensile strength of coalcrete was determined as 0.3 times of compressive strength based on the experimental results of grouted materials. The test results of Poisson’s ratio varied from 0.21 to 0.26 with less regularity, and therefore, the value was set as 0.24 in this study.

### 3.3 | Rock mass properties

The rock mass properties were affected by geological conditions. In this study, the geological strength index (GSI) was used to calculate the mechanical parameters of different lithological units. Normally, the GSI value was calculated by a rock mass rating (RMR) classification system, as the RMR was not affected by subjective factors of different geological surveyors. Then, the intact rock properties, such as compressive strength (\( \sigma_{ci} \)), \( m \), constant, were tested in the laboratory. The rock mass properties (strength and deformation modulus, shown in Table 4) were calculated based on the empirical equations in the literature.

### 4 | NUMERICAL MODELING AND VERIFICATION

#### 4.1 | Numerical modeling

In this paper, the numerical model is to investigate the effect of jet grouted coalcrete columns on roadway stability. A 2D FEM program RS2 was applied to construct a model representing a cross section of the deeply buried roadway. The established numerical model was shown in Figure 5. The width and height of the arched roadway section are 5.6 m and 4.8 m, respectively. The model domain is 48 m \( \times \) 56 m, which can reduce the boundary effect. The 3-noded triangular elements are introduced in analysis models, and the accuracy and efficiency of such elements have been verified in the previous studies. The applied vertical stress (19.23 MPa) and horizontal stress (11.21 MPa) of the 2D model were transformed from the 3D global–2D local modeling method as presented in this coal mine.

Support systems were divided into two types, that is, conventional compound support (rock bolts + U-shaped shed + shotcrete) and JG prereinforced support system (coalcrete + shotcrete), which will be explained in detail in next parts. The Mohr–Coulomb (MC) model was utilized.
for modeling the rock mass and the coalcretes. Shotcrete and U-shaped shed support components were modeled by structural elements obeying linear elastic constitutive behavior based on the recommendations from the previous literature.33,34

### 4.2 Verification by the conventional support system

Normally, a 2D numerical model should take the three-dimensional face effect into account especially in the tunnel face.35-37 Therefore, in this study, a displacement release method was used, which was derived for analyzing the stress on the arbitrary tunnel section.38 The displacement release ratio \( \lambda \) is generally equal to the stress release ratio that was similarly defined in the literature.39 By this method, the real stress \( P_r \) acting on the tunnel periphery is expressed as a function of the in situ stress \( P \) as following:

\[
P_r = \lambda P
\]

\[
\lambda = \frac{U_r}{U_u}
\]

where \( \lambda \) is displacement release ratio, \( U_r \) represents the real displacement of the tunnel with support. \( U_u \) means the ultimate displacement in the case of no support.

As per this method, the displacement release ratio can be expressed as the function of time and successfully used in practical application for deep roadway and tunnel as shown in the literature.40 Hence, the monitoring data of a typical roadway cross section with traditional support was collected and compared with the results from the established 2D model using the displacement release method to verify the input parameters. The numerical model with a conventional support system was shown in Figure 6, and the properties of support materials were given in Table 5.

The sidewall convergence from in situ monitoring data corresponding to time (depicted in Figure 7 by the red solid line) was picked for calculating the displacement/stress release rate (shown in Figure 7 by the pink dashed line). Eight representative points (3, 7, 15, 30, 60, 90, 120, and 150d) were further selected from the curve of displacement release rate. Therefore, the established numerical model with conventional support contained eight stages of applied stresses according to the stress release rate. The sidewall convergence of these stages was monitored and shown in Figure 7 by the black symbols. It can be seen that with the increase in stress, the displacement of sidewall increased, while the growth rate decreased gradually to a relatively stable value. The calculated displacements from the numerical model were in good agreement with the in situ measured convergence, which confirms that the model and its input parameters of rock mass and support materials were reasonable and reliable. It should not neglect the effects of bedding, discontinuous, and rock joints in practice, the model used a relatively soft material to represent these conditions, which caused that there was a minor difference between modeling results and field measurement.

As can be seen from Figure 7, the roadway cannot provide service of transportation of coal as the large deformation occurred (approximately 800 mm). The roadway needs

| Specimen size (mm) | Cohesion (MPa) | Friction angle (°) | UCS (MPa) | Deformation modulus (GPa) |
|-------------------|---------------|-------------------|-----------|--------------------------|
| 50                | 5.21          | 36.1              | 14.01     | 10.77                    |
| 100               | 4.63          | 33.4              | 11.96     | 7.97                     |
| 150               | 4.31          | 32.3              | 10.9      | 6.81                     |
| 200               | 4.10          | 31.4              | 10.4      | 6.12                     |

**FIGURE 3** The failure patterns of coalcrete specimens, (A) under compressive tests, (B) under shear tests

**TABLE 1** The calculated cohesion and friction angle for different coalcrete specimen
to be maintained frequently, which is time- and money consuming. According to the experience in such conditions, the soft coal mass cannot resist the surrounding stress after excavating the roadway and failed in a large extent. Consequently, if the quality of soft coal mass is improved, its self-stabilization will be enhanced simultaneously. Hence,

![Figure 4](image)

**FIGURE 4** The size effect of coalcrete specimen on its mechanical parameters

| Fitting function | Mechanical parameters | 400 mm | 600 mm | 800 mm |
|------------------|-----------------------|--------|--------|--------|
| y = a + bx^c     | Cohesion (MPa)         | 3.71   | 3.50   | 3.36   |
|                  | Friction angle (°)     | 30.2   | 29.5   | 29.1   |
|                  | Deformation modulus (GPa) | 4.56 | 3.86   | 3.42   |
|                  | Uniaxial compressive strength (MPa) | 8.88 | 8.13   | 7.63   |
|                  | Tensile strength (MPa)  | 2.64   | 2.44   | 2.30   |
|                  | Poisson’s ratio        | 0.24   | 0.24   | 0.24   |

**TABLE 2** The fitting equations and their corresponding coefficients for different mechanical parameters of coalcrete

| Mechanical parameters | 400 mm | 600 mm | 800 mm |
|-----------------------|--------|--------|--------|
| Cohesion (MPa)        | 3.71   | 3.50   | 3.36   |
| Friction angle (°)    | 30.2   | 29.5   | 29.1   |
| Deformation modulus (GPa) | 4.56 | 3.86   | 3.42   |
| Uniaxial compressive strength (MPa) | 8.88 | 8.13   | 7.63   |
| Tensile strength (MPa) | 2.64   | 2.44   | 2.30   |
| Poisson’s ratio       | 0.24   | 0.24   | 0.24   |

**TABLE 3** The calculated mechanical results of the larger coalcrete column
the JG support system used for improving the strength of coal mass was designed.

5 | NUMERICAL INVESTIGATION ON JG SUPPORT SCHEMES

Considering the coalcrete column diameter of 400 mm, 600 mm, and 800 mm, three models with various coalcrete diameter were constructed to analyze the JG effect on roadway stability (shown in Figure 8). The rock mass properties, shotcrete properties, and the stress were the same as the original support scheme. The strength properties of coalcrete were based on Table 3. It should point out that the stress acting on the models was the maximum value because more concerns were about the final status of a roadway. Moreover, the deformation, failure zone, and stress conditions of different JG models were investigated.

5.1 | Deformation properties of JG schemes

According to the monitoring points set on the surface of the roadway, the monitored displacement results on the roof, floor, and side walls were comparatively shown in Figure 9. It is clear that the sidewall convergence of JG

| Rock unit | Density, kg/m³ | $\sigma_{ij}$ MPa | Poisson ratio, $\nu$ | $E_i$, GPa | RMR | GSI | $c$, MPa | $\phi$, ° | $\sigma_t$, MPa | $E_{mass}$ GPa |
|-----------|----------------|------------------|-------------------|--------|-----|-----|--------|-------|-----------|-------------|
| Sandstone | 2690           | 85.8             | 0.22              | 18.6   | 72  | 67  | 3.45   | 42    | 0.79      | 12.5        |
| Mudstone  | 2700           | 38.5             | 0.29              | 3.61   | 40  | 35  | 1.24   | 27    | 0.03      | 0.4         |
| Coal      | 1420           | 7.0              | 0.39              | 5.0    | 35  | 30  | 0.98   | 24    | 0.15      | 0.50        |

![FIGURE 5](image)

**FIGURE 5** The established 2D numerical model

| Parameters, unit                  | Rock bolt | U-shaped shed | Shotcrete |
|-----------------------------------|-----------|---------------|-----------|
| Elastic modulus, GPa              | 200       | 200           | 30        |
| Poisson's ratio                   | 0.3       | 0.25          | 0.15      |
| Diameter/thickness, mm            | 22        | 15            | 100       |
| Unit weight, kN/m³                | –         | –             | 24        |
| Length, mm                        | 2400      | –             | –         |
| Pretensioning, kN                 | 80        | –             | –         |

![FIGURE 6](image)

**FIGURE 6** The conventional support system used for model verification

![FIGURE 7](image)

**FIGURE 7** The deformation release rate based on measured data
support schemes was much smaller than the conventional support system. Scheme 1 had relatively larger roof subsidence and sidewall convergence, followed by scheme 2, scheme 3. Also, as for floor heave, scheme 1, scheme 2, and scheme 3 had similar value, which was much less than that of the original scheme. With the increase in the diameter of coalcrete column, the roof to floor convergence and sidewall convergence decreased. Overall, the comparison results indicated that the JG technique was more effective in controlling roadway deformation in soft coal mass. Based on the experience of managers in the coal mine, all the JG support schemes (schemes 1, 2, and 3) met the requirements of deformation for the serviceability of roadway (ie roof to floor convergence < 300 mm, sidewall convergence < 500 mm).

5.2 | Failure zone of JG schemes

Figure 10 illustrated the failure zone distribution of roadway under JG support schemes. Scheme 1 (Figure 10A) had a relatively larger extent of the failure zone, followed by scheme 2 (Figure 10B), scheme 3 (Figure 10C). As the diameter of the coalcrete column increased, the range of damage zone of roadway decreased gradually. Some measurement lines were defined as shown in Figure 10 by black dashed lines. L1 denotes the maximum failure zone distance from the tunnel shoulder; L2 represents the distance of failure zone from the middle sidewall; L3 is the maximum length of failure zone on the floor. The distance of the failure zone from the designed roadway boundary was given in Figure 10. The characteristic of “L1 > L2 > L3” indicated that the failure extent on roadway shoulder was much larger than other areas of the roadway. Also, there is no obvious failure zone on the roof of roadway. All JG support schemes had excellent control effect on decreasing damage zone and stabilizing roadway in the long-term.

Figure 10 also depicted the failure zone distribution with two failure patterns (shear and tension failures) around roadway under various schemes. It can be seen that tensile failure mainly appeared close to the roadway surface except for roof (by the enlarged areas in Figure 10), while shear failure developed not only in deep zones but also at the shallow surface. It should be noted that with the increase in the diameter of the coalcrete column, less tension failure occurred in coalcrete and most of them were at the two sides of contact interfaces, that is, coal–coalcrete interface and shotcrete–coalcrete interface. As for shear failure, there were some minor shear cracks at the vault of roadway in scheme 1, and the number of cracks decreased with the increase in the diameter of coalcrete column, until none cracks on the roof in scheme 3. Overall, the JG method can reduce the damage zone of roadway drastically, which means that the treated roadway by coalcrete would be stable with a low risk for major instability.

According to the above analysis of failure zone, some main reasons why the roadway had smaller deformation and failure zone after JG could be concluded as follows: (a) JG as a prereinforcement technique can improve the mechanical properties of surrounding coal mass significantly before roadway excavation. (b) In the JG scheme, the “coalcrete + shotcrete” system could provide sufficient support for the soft coal mass in time, and therefore improve the self-stabilization of soft coal mass.

5.3 | Stress distribution of JG schemes

It can be seen from Figure 11 that there were relaxation zones around the roadway, but the extent of them was different. By comparison of scheme 1 (Figure 11A), scheme 2 (Figure 11B) and scheme 3 (Figure 11C) had a relatively smaller stress relaxation zone with higher distributed stress on the roof of the roadway, indicating that there was no significant deterioration of coalcrete and coal mass on the roof. Furthermore, the stress above the vault of roadway in a certain extent increased with the increase in the diameter of coalcrete, which means that the more coalcrete possessed more sufficient load-bearing capacity.

For the stress distribution on the floor of the roadway, it can be seen that there was a large extent of stress relaxation zone for
all schemes due to no support on the floor. However, the stress easily concentrated around the two bottom corners of the roadway especially for JG schemes (black dashed circular shown in Figure 11). The reason is that the overlapped jet grouted coalcrete columns timely formed a stable support structure, which can optimize the stress state around the roadway by transferring high stress in the sidewall to the corner of the roadway.

A monitoring line in the sidewall was set to gain the maximum principal stress in the sidewall of roadway and monitored results were shown in Figure 11 by an enlarged view. The stresses near sidewall surface under JG supported schemes were much larger than the no support roadway (approximately 0 MPa on the sidewall surface), demonstrating that all support methods can enhance the
The stress in sidewall surface for all JG schemes increased with the diameter of coalcrete. In addition, as for the effect of coalcrete columns on deeper coal mass (4.5 m away from the roadway surface), it can increase the peak stress in coal mass and reduce the distance of maximum stress from the roadway surface. These phenomena can be regarded as the improvement of the loading-bearing capacity of deep coal mass by the JG method.

6 CONCLUSIONS AND SUGGESTIONS

This paper presented a novel JG method for improving the stability of roadway in underground coal mines. A series of experimental and numerical tests were conducted, and the results showed that the JG support system was effective and promising. The conclusions and suggestion are as follows:

1. The field trial of JG showed that JG method met the requirements for supporting roadway in underground coal mines. The size effect of coalcrete was examined, and the mechanical parameters of coalcrete were determined for further numerical models.

2. A numerical model was first established and verified by comparing the displacement of conventional support schemes and in situ monitoring data. The results showed that the numerical model and the input parameters were correct, reliable, and reasonable.

3. Three JG reinforcement models were constructed and compared. The results showed that with the increase in the diameter of the coalcrete column, the JG support system can reduce the deformation and the extent of failure zone of roadway significantly, and optimize the stress conditions around the roadway.

4. The mechanism of the JG support system on stabilizing roadway was revealed including improving the residual strength and self-bearing capacity of coal mass, creating the coalcrete with high mechanical performance, and forming a stable arch structure.

Considering some failure at bottom sidewalls, and stress concentration at the corner of the roadway, some suggestions were additionally proposed for the long-term stability of JG roadway. For example, the rock or cable bolts could be installed along the roadway shoulder and sidewalls to avoid the sudden collapse of the roadway surface. An inverted arch on the floor could be used for improving the stress state and providing a certain bearing capacity of the floor.

ACKNOWLEDGMENTS

The work was supported by the projects of the “National Key Research and Development Program (2016YFC0600901),” “National Natural Science Foundation of China (Grant No. 51574224, 51704277).” The authors are grateful to HuaiBei Mining (Group) Co. Ltd. Special thanks to Dr Wang Zuqi for her encouragement and help.
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How to cite this article: Sun Y, Li G, Zhang J, Qian D. Experimental and numerical investigation on a novel support system for controlling roadway deformation in underground coal mines. Energy Sci Eng. 2020;8:490–500. https://doi.org/10.1002/ese3.530