Structural design and experimental study on mechanical properties of sand column support

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Abstract: In order to solve the problem of insufficient support strength caused by unreasonable structure design of roadway side retaining roadway along goaf in Zhubai Coal Mine, and by means of preliminary test of bearing capacity, theoretical calculation and mechanical experiment of sand pillar, the optimization design of supporting structure of gob-side entry retaining was carried out. The results show that when the ratio of sand and stone material filled with sand column is 1:1 and the filling material is vibrated by adding water, the density of filling material reaches the maximum and the stability of sand column is optimal; When the pressure gauge reading is 32 MPa, the lower part of the sand column is in the basic fracture state and the water-sand column can bear more ultimate load than the water-sand column. It is proved that the optimized sand pillar support body can meet the support strength requirements of gob-side entry retaining and improve the production efficiency.

1. Introduction

As China's economy develops, the demand for coal energy is growing, thus the necessity of efficient extraction of existing coal resources, which can be realized through the roadway technique along the Zhubai Coal Mine, in which the roadside support is very important as it plays the role of cutting and supporting in the design [1-2]. But a certain requirements should be met, such as fast increase resistance, high support resistance, and economy [3], etc. However, there are certain deficiencies in the previous design [4-8]: for example, large work load, long time and large requirements for amount of auxiliary transportation when using concrete for wall-laying; the resistance of rafts and dense supports is small, leading to poor sealing and a large consumption of material and labor; the meteorite belt and the stone sarcophagus is largely compressed and have serious air leakage problems; the overall casting roadside filling technology that is being widely applied is complicated and costly, requiring for longer demoulding time with lower strength of the support body in the initial stage; what's worse, the existing roadway construction technology is slow in operation, and is not compatible with the fully mechanized mining face [9-10].

It can be seen that the roadside support in gob-side entry retaining is very important. Jia Min et al. [11-15] have proposed the pier-column gob-side entry retaining and studied the feasibility of the roadside support structure based on the law of rock movement. Based on the existing research, this paper explores and analysis the structure of the new type of roadside support body and the filling material using theoretical calculation, and sand column mechanics experiment so as improve the filed conditions of Zhubai Coal Mine.
2. Pre-test of bearing capacity of sand column

In the design of the gob-side entry retaining road, it is necessary to make corresponding technical and technological adjustments to adapt to the design the sand column support roadway technology at the site based on the actual geological conditions of Zhubai Coal Mine. The process is mainly about retaining, and it is necessary to conduct pre-test due to that the process adjustment is quite large.

1. The specification of steel pipe is Φ450×9 mm, Φ426×10 mm, with the net clearance of pipe wall of 6 mm, therefore ensuring the free expansion and contraction of steel pipe and no sand leakage. The steel pipe nesting must be ≥20 cm to ensure that the thick and thin pipes are not bent or unstable.

2. In the sand column down-hole test, the corresponding countermeasures against poor roof conditions such as padding waste belt on the roof, overlaying W-shaped steel belt can effectively solves the problems of uneven and broken roof and popping sand column.

3. The top plate has a tuck net phenomenon, which is solved using the I-beam; the roof of the goaf is not well cut, which is solved by the combination of the I-beam and the single hydraulic prop.

4. After pressing, the head of the sand column is inclined to the goaf, while its leg stretches to the roadway. Therefore, the construction is carried out when making the sand column vertical to the bottom plate.

5. When observing the shrinkage of the sand column, it is found that its compactness is a direct factor affecting its size while water adding and vibration of sand and gravel materials greatly influence the compactness. Therefore, it is necessary to determine a reasonable filling material ratio based on experiments.

3. Design of sand column structure

According to the sand column bearing capacity test, in order to ensure the considerable shrinkage and support resistance of the sand-column roadside support body, the new one should be composed of filled sandstone and two seamless steel pipes, as shown in figure 1.

3.1. Calculation of wall thickness of sand column

3.1.1. Theoretical calculation. The working face is buried at a depth of 650-700 m with the average rock density ρ of 2500 kg/m³. The maximum compressive stress is the total gravity of the overlying strata:

\[ \sigma_{max} = \rho gh = 2500 \times 9.8 \times 675 \times 10^{-6} \text{MPa} = 16.54 \text{MPa} \]  \hspace{1cm} (1)

Where g refers to gravity constant q and H the depth of the working surface.

3.1.2. Field measurement. In the 12302 fully mechanized mining face, 120 m roadway is retained which the stress of one of the four corners of the supporting raft is measured to be 19 MPa.

The roof controlled by the raft is carried by all four fulcrums, and the average stress is:

\[ \sigma_{ping} \times S_{duo} = 19 \times S_{fang} \times 4 \]  \hspace{1cm} (2)

Where \( S_{duo} = 1.2 \times 1.2 \text{m}^2 \), \( S_{fang} = 0.15 \times 0.15 \text{m}^2 \).

It can be gained from the above: (3)

\[ \sigma_{ping} = \frac{19 \times 0.15 \times 0.15 \times 4}{1.2 \times 1.2} = 1.2 \text{MPa} \]  \hspace{1cm} (3)

3.1.3. Resistance calculation of the work face bracket. The maximum compressive stress of the bracket is 50 MPa; the diameter of the hydraulic support column is Φ230 mm; the bearing area is 3.24×1.50 m²; the average stress of the bracket is \( \sigma_{pingjia} \):

\[ \sigma_{pingjia} = \frac{50 \times \pi D^2}{4 \times \frac{3.24 \times 1.5}{2}} = 0.854 \text{MPa} \]  \hspace{1cm} (4)
3.1.4. Calculation of wall thickness of steel pipe. According to the rock stress formula $\sigma_z = \lambda \sigma_z$ and the wall tensile stress formula $\sigma = \frac{pD}{2t}$, we have:

$$\sigma = \frac{pD}{2t} = \frac{\lambda \sigma_z D}{2t} \leq [\sigma]$$

$$t \geq \frac{\lambda \sigma_z D}{2(\sigma + \lambda \sigma_z)} = 0.0046m$$

Where $\sigma_z$ is internal pressure, or the pressure at the sand column side, which is taken as the maximum stress P: 16.54 MPa. $D'$ is the inner diameter of the steel pipe, 0.426 m. $t$ is the wall thickness of the steel pipe; $\lambda$ is the lateral pressure coefficient, which is generally 0.18 ~ 0.43 (0.5 here). $[\sigma]$ is the tensile strength of A3 steel, 375 MPa.

It can be obtained that the wall thickness of the steel pipe is 0.0046 m. This paper takes 10mm thick steel pipe because of the factors such as corrosion of the steel pipe.

![Figure 1. The sand column structure](image)

3.2. Design of sand column structure

The construction work of sand column support should follow the requirements listed below:

1. The sand column should be tightly attached to the top plate to ensure that it can provide some initial support. To this end, place the support seats of the two symmetrical single-pillar struts above the upper mold, I about 400 mm away from the roof to ensure the initial support force.

2. During construction, ensure that the sand column is stable and balanced in the direction perpendicular to the bottom plate. Meantime, cleaning should reach the hard rock area, which should also be smoothed to ensure that the bottom can be parallel to the center of the roadway. The sand column must be fixed before the next step. Therefore, two pairs of lifting ears should be vertically placed on the upper and lower molds to fix the sand column and the top metal mesh.
(3) The sand column construction procedure must be simple and convenient. In order to make material filling to the sand column more convenient, it is necessary to place a filling port on the upper of the sand column near the top, the size of which shall be determined based on the diameter of the concrete spray gun. When the filling port is not arranged, a small opening is required in the top plate. However, the roof are relatively hard, making it difficult to carry out this work; the roof is seriously damaged, affecting the stability of the sand column.

(4) Ensure the recyclability of the sand column mold material. To achieve this, a water leakage hole should be drilled at the bottom of the lower part of the mold, so that the moisture of the filling material can be oozing along the hole. When the next working surface has been quarried, open the hole and the sand and take the stone out at the same time to complete the recycle process so as to reduce the maintenance cost of the roadway.

With the above requirements taken into consideration, this paper sets the structural design parameters of the sand column: the sand column is made of seamless steel pipe; the mold is divided into upper and lower parts to adapt to the height change of the roadway with the specifications of the upper section being Φ426×10 mm and 1.2 m long, while the lower Φ450×9 mm and 1.0 m long. The two are nested and form a sand column after sand filling. The length of the upper and lower joints should exceed 500 mm. The filling port and the single support of the upper part should be vertically arranged; the lifting ring and the single support seat must be firmly welded and can not be arranged in the same straight line. The lifting rings of the upper and lower parts are made of Φ12 steel bars; the single support is made with a Φ34 scraper chain; the ribs are made of Φ20 mm bolts. The welding must be firm and reliable with the sanding port made of 3 mm steel plate to ensure flexible drawing.

4. Selection of filling material ratio
The density of the filling material is greatly affected by the ratio of the sandstone material, water adding, and vibration. In order to select reasonable and reliable filling material ratio, this section analyzes the physical properties of sandstone materials under different mixing conditions (table 1) and under different experimental conditions (table 2) through experiments.

| Table 1. Different mixing conditions |
|-------------------------------------|
| Proportion | 2:1 | 1.8:1 | 1.6:1 | 1.4:1 | 1.2:1 |
| 1:2        | 1:1 |

| Table 2. Different experimental conditions |
|--------------------------------------------|
| Vibration | Water | No | Yes |
| Condition 1 | Condition 2 | Condition 3 | Condition 4 |

4.1. Effect of water on the density of filling materials
By analyzing the data of Condition 1 and Condition 2, the curve of the sinking amount of the filling material can be obtained, as shown in figure 2. It can be seen that the material fluidity is increased due to the water. Water motivates the small-sized sand to flow toward the voids between the larger ones, which leads to the improvement of the compactness of the filling material and the bearing capacity.

4.2. Effect of vibration on the density of filling materials
By analyzing the results of the experimental Conditions 2 and 4, the density curve of the filling material can be obtained, as shown in figure 3. It can be seen that when there is no vibration, although water produces a certain dynamic effect, the compactness is still poor under the cohesive force of the material itself; vibration reduces the cohesion between the materials, thus promoting the flowing performance and the compactness of the material.
4.3. Effect of water and vibration on the density of filling materials
By analyzing the data of under Conditions 3 and 4, the density curve of the filling material can be obtained, as shown in figure 4. The density of the filling material is greatly affected by water under different sandstone materials ratios. When the ratio is 1:1, the vibration density reaches the top, 2220 kg/m³.

In summary, when the ratio is 1:1 with both water and vibration, the density of the filling material reaches the top, which is beneficial to the stability of the sand column.

5. Mechanics experiment of sand column support body
In order to analyze the actual bearing capacity of the sand column, two loading experiments were carried out on the sand column through the pressing machine. In the first experiment, no water was added, which is different from the second experiment, the results were showed in the table 3 and 4. The specification of the pressing machine is 3000 t with the nominal pressure of 24 MPa, the total power of 160 kw, and the maximum stroke of 1.5m. By analyzing the experimental results, it can be concluded that:

(1) When the pressure gauge read 22.7 MPa (the pressure was 28.5 t), deformation occurred at the bottom of the sand column, and gradually increased as the pressure increased. When the pressure gauge read 32 MPa (the pressure was 400 t), the lower part of the sand column was basically ruptured.

(2) When the pressure reached a certain value, the weakest area on the barrel wall of the sand column (near the sand outlet of the lower section) raptured, and further damage will occur after continued force.
(3) It is found that when a certain pressure value was reached, the amount of shrinkage was significantly reduced after adding water. As shown in the table 3, when the pressure was 232 t, the amount of shrinkage without water was 151 mm, and that after adding water was reduced to 112 mm, a decrease of 39 mm. Therefore, the limiting load of the sand column with water is larger than that of the sand column without water.

| stress (t) | shrinkage (mm) | state of the sand column |
|------------|----------------|--------------------------|
| 130        | 45             | normal                   |
| 200        | 110            | normal                   |
| 232        | 151            | normal                   |
| 285        | 178            | the upper part deforms and gradually increases |
| 400        | —              | upper deformation, the bottom of the sand mouth at the cylinder wall fracture |

Table 4. The relationship between stress and shrinkage of sand column with water

| stress (t) | shrinkage (mm) | state of the sand column |
|------------|----------------|--------------------------|
| 165        | 48             | normal                   |
| 232        | 112            | lower slightly deformed   |
| 380        | 242            | the lower deformation is larger |
| 530        | —              | The lower part of the column is basically broken |

6. Conclusion

A new sand column type roadside support structure has been designed through the preloading test and theoretical calculation of sand column. On the basis of experimental research, it is found that under different experimental conditions and the ratios of sand and gravel materials, the 1:1 ratio plus water and vibration can deliver the maximum density of filling materials, which is conducive to the stability of the sand column.

Through the loading test of the sand column using the pressing machine, it is found that when the pressure gauge reading reaches 22.7 MPa, deformation occurs at the bottom of the column and gradually increases with the increase of the pressure. When the gauge reading is 32 MPa, the lower region of the sand column is substantially ruptured. The water-added sand column can withstand larger load than the sand column without water. Meanwhile, the sand column can meet the requirements of strength and deformation of gob-side entry retaining.

Reference

[1] Wen ZJ, Jiang YJ, Song ZQ, et al. (2011) Study on Mechanical Model and Surrounding Rock Catastrophe System of Gob-Side Retaining Entry[J]. Journal of Hunan University of Science and Technology, 26(3):12-16.
[2] Zhang C, Wen ZJ, Hu SC. (2011) Application of Stope Roof Control Theory in Gob-side Entry Retaining[J]. Safety in Coal Mines, 42(4):119-122.
[3] Jin XH. (2017) Design and Economic Evaluation of Gob-Side Entry Retaining[J]. Inner Mongolia Coal Economy, (10):153-153.
[4] Bai JB, Zhou HQ, Hou CJ, et al. (2004) Development of Support Technology Beside Roadway in Goaf-Side Entry Retaining for Next Sublevel[J]. Journal of China University of Mining & Technology, 33(2):183-186.
[5] Tang JQ, Song WJ, Song LB, et al. (2016) Cutting Seam Design and Study of Gob-side Entry Retaining by Roof Cutting and Pressure Relief[J]. Safety in Coal Mines, 47(9):53-55.

[6] Zhang S, Liu Y, Liu HF, et al. (2018) Optimal Design of Laneway’s Side Support for Gob-side Entry Retaining with Solid Cemented Backfilling[J]. Safety in Coal Mines, 49(3): 48-51.

[7] Kan JG. (2009) Study on Rock Structural Analysis and Control Technique for Gob-side Entry Retaining under Typical Roof Conditions, Doctoral Dissertation, China University of Mining & Technology.

[8] Liang JZ, Cheng YH. (2011) Application of Gangue Filling and Gob-side Entry Retaining[J]. Shandong Coal Science and Technology, (5):33-34.

[9] Yang B, Chai J, Wang MH. (2018) Study on Roadside Support Method of Gob-side Entry Retaining in Condition of Overlying and Thick-hard Roof[J]. Safety in Coal Mines, (7): 220-223.

[10] Yang WH, Wei FS. (2012) Discussion on Fully Mechanized Mining Working Face Gob Roof Support[J]. Coal Technology, 31(8):238-239.

[11] Jia M, Bai JB, Tian T, et al. (2014) Research on Pier Column Gob-side Entry Retaining Technology[J]. Coal Science and Technology, 42(1):18-22.

[12] Chen D. (2014) Technology of Gob Side Entry Retraining Support by Steel Tube Concrete Pier Column[J]. Coal Science and Technology, (S1):1-3.

[13] Fu ZB, Wang ZT, Wang JH, et al. (2016) Research on Properties of Roadside Support with Pier Column and High Water Material[J]. Coal Technology, 35(3): 74-76.

[14] Shi GY. (2014) Gateway Retained Along Goaf Technology with Pier Pillar Backfilled with High Water Material in High Gassy Mine[J]. Coal Science and Technology, 42(7): 30-32.

[15] Guo DM, Fan LF, Gao J, et al. (2018) Study on Sidewall Support Technology of Pier Pillar Type Gateway Retained along Goaf in Wutongzhuang Mine[J]. Coal Science and Technology, 46(1): 81-87.