Study on the influence of sliding structural zone on grouting reinforcement effect of limestone aquifer in coal mine

Yujun Zhou*

School of Energy Science and Engineering, Henan Polytechnic University, Jiaozuo, 454003, China
Henan College of Industry Information Technology Resources and environment department, Jiaozuo, 454000, China

Abstract. In this paper, the influence of sliding structural zone on grouting reinforcement effect of limestone aquifer in coal mine is studied. The study area is located in a large coal field in North China, China, with complex geological structure and widely distributed sliding structural zones, which destroyed the integrity of rock strata and increased the risk of water disaster. In this study, ordinary portland cement and polyurethane chemical slurry are selected as grouting materials, and their performance parameters are determined through experiments. The grouting pressure is controlled at 2-4MPa, and the arrangement of grouting holes varies according to different regions. The experimental results show that grouting reinforcement significantly improves the characteristics of limestone aquifer. The permeability is reduced by 75% from 5.2×10-5m/s, and the fluctuation of water level is reduced to 0.1m/d, which proves that the water-blocking curtain is effectively formed and the water-rich property and water conductivity are reduced. At the same time, the compressive strength of rock stratum increased from 25MPa to 38MPa, an increase of 52%, which enhanced the stability and strength of stratum. However, the characteristics of the sliding structural zone affect the reinforcement effect. In the fractured zone, although the grouting material spreads widely, the curing effect is poor, and the compressive strength of the added solid is 32MPa. However, in the stress concentration area of the fold shaft, the curing effect is good, and the average compressive strength reaches 39MPa. The characteristics of rock surface, such as scratches and mirror surface, also affect the adhesion and curing effect. The former has strong adhesion, while the latter has poor adhesion due to smooth surface. In addition, moderate grouting pressure (2-3MPa) and selective use of polyurethane chemical slurry improve the permeability and curing effect in specially developed cracks, while excessive pressure or poor permeability will limit the diffusion and curing effect of grouting materials.

Keywords: sliding structural zone; grouting reinforcement; limestone aquifer; coal mine.

1. Introduction

In the process of coal mining, water disaster has always been one of the major hidden dangers threatening mine safety production. Limestone aquifer is a common aquifer type in coal mine, and its water abundance and water conductivity pose a serious threat to the safety production of mine. As a common form of geological structure, the existence of sliding structural zone will often aggravate the water hazard risk of limestone aquifer. Grouting reinforcement technology, as an effective means to prevent and control water disasters, has been widely used in coal mines. By injecting grouting material into limestone aquifer, a water plugging curtain can be formed, which reduces the water abundance and water conductivity of aquifer, thus ensuring the safe production of mine [1]. However, the existence of sliding structural belt may have a certain impact on the grouting reinforcement effect, reduce the strength and stability of the added solid, and then affect the effect of preventing water disasters.

In the process of coal mining, grouting reinforcement of floor limestone aquifer is an important measure to prevent mine water inrush. However, in the sliding structure zone, due to the influence of faults and sliding structures, the integrity of rock strata is destroyed and cracks increase [2], which may lead to the diffusion and solidification effect of grouting materials being affected [3]. Geological structure analysis studies the stratigraphic structure and hydrogeological conditions of the mining area, and analyzes the characteristics of the sliding structural zone and its influence on the coal seam floor [4]. Selection of grouting materials Explore grouting materials suitable for sliding structural zones, such as cement-sodium silicate (C-S), and study its mechanical properties and curing characteristics through experiments [5]. Study on the optimization of grouting technology The optimization design of grouting borehole includes the determination of

* Corresponding author: hpuzhouyujun@163.com

grouting pressure, grouting speed and grouting diffusion radius [6]. The grouting effect was evaluated using techniques such as wave velocity exploration and borehole seismic wave detection to assess the condition of the floor rock post-reinforcement [7]. The research shows that the sliding structural zone has certain influence on the grouting reinforcement effect. While grouting generally improves the strength and toughness of the rock mass, the effectiveness of the consolidation is highly dependent on pre-existing fracture geometry. The degree of improvement diminishes as the length of the original cracks increases. In addition, the permeability of grouting plus solid decreases after grouting, especially in the linear elastic stage of stress-strain curve [8].

This paper studies the influence of sliding structural zone on grouting reinforcement effect of limestone aquifer in coal mine, and provides theoretical guidance and technical support for preventing and controlling water disasters in coal mine through in-depth analysis of the characteristics of sliding structural zone and its action mechanism on the diffusion and solidification effect of grouting materials.

2. Study area and geological conditions

The research area is located in a large coal field in North China, which is one of the important coal production bases in China, with a long mining history and rich coal resources. The study area is located at the junction of mountainous areas and plains, with large topographic relief and diverse landform types, including mountains, hills and plains. The climate belongs to temperate monsoon climate with four distinct seasons and concentrated precipitation, which poses a certain hydrogeological threat to coal mining.

Geologically, the study area is located in the core of a large syncline, surrounded by a series of faults. The syncline exhibits a complex geological structure, characterized by numerous secondary folds and faults. This complex geological structural background provides favorable conditions for the formation of sliding structural belts.

In the study area, slip structural zones are widely distributed, mainly along fault zones, fold axes and weak planes of strata (Figure 1). These sliding structural belts have obvious sliding surfaces, and the sliding structural signs such as scratches, mirrors and steps are common on the sliding surfaces. The width of the sliding structural zone varies, some are only a few meters wide, while others can reach tens or even hundreds of meters. The tendency of the sliding tectonic belt is roughly consistent with the direction of the regional tectonic line, but some parts are deflected due to the influence of the late tectonic movement.

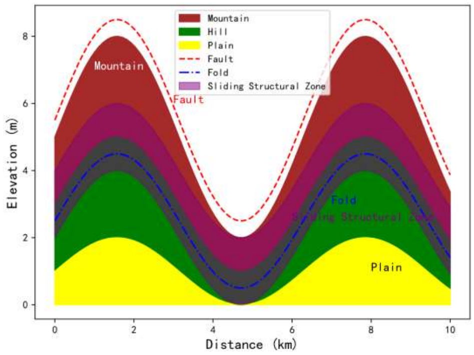

Figure 1 Distribution profile of sliding structural zone

The existence of the sliding structural belt destroys the integrity of the rock stratum, making the rock stratum become broken and loose, and easy to be weathered and eroded. At the same time, the sliding structural zone is also a good channel for groundwater activity, which provides favorable conditions for groundwater seepage and enrichment.

The limestone aquifer in the study area is one of the main aquifers in the process of coal mining. The aquifer is mainly composed of thick limestone with uniform lithology, developed pores and fractures, and has good water storage and conductivity. The thickness of limestone aquifer varies, generally ranging from tens to hundreds of meters, and some areas can reach thousands of meters.

Hydrogeological conditions, limestone aquifers are replenished by atmospheric precipitation, surface water and overlying aquifers, and the recharge sources are sufficient. Groundwater flows along pores and cracks in limestone aquifer, with fast velocity and close hydraulic connection. In the process of mining, once the limestone aquifer is exposed, a large amount of groundwater will flood into the mine, posing a serious threat to mine safety production.

3. Grouting reinforcement scheme

3.1 Selection of grouting materials

In the study area with complex geological structure and loose rock strata, ordinary portland cement is selected as the main grouting material, because of its high strength and stability, it can effectively fill cracks and pores and enhance the strength of rock strata; The cement grade is 42.5R, and the water-cement ratio is set between 0.8 and 1.2 to ensure good fluidity and strength after solidification. For the area where cracks are particularly developed, polyurethane chemical grout is supplemented. With its excellent permeability, this kind of material can penetrate into tiny cracks, and keep its elasticity after curing to adapt to the deformation of rock strata and prevent the generation of new cracks[9]. The performance parameters of grouting materials are shown in Table 1.

Table 1 Performance parameters of grouting material

Grouting material type	fineness	initial setting time	Final setting time	Compressive strength (3 days /28 days)	Bending strength (3 days /28 days)	SO3 content	MgO content	loss on ignition
Portland cement	Specific surface area ≥300 m2/kg	≥45 minutes	≤390 minutes	22.0/42.5 MPa	4.0/6.5 MPa	≤3.5%	≤5.0%	≤3.0%
Portland cement	0.080mm square hole sieve residue 10% or less.	≥45 minutes	≤10 hours	12.0/32.5 MPa	2.5/5.5 MPa	≤3.5%	≤5.0%	≤3.5%
Slag portland cement	0.080mm square hole sieve residue 10% or less.	≥45 minutes	≤10 hours	Make no provision	Make no provision	≤4.0%	≤5.0%	Loss on ignition ≤50%

3.2 Grouting pressure control

Grouting pressure control is divided into two stages: initial detection and normal grouting (as shown in Figure 2). In the area far away from the sliding structural zone and limestone aquifer, the initial pressure of 0.5-1MPa is detected through the test grouting hole. If the pressure rises rapidly, it is necessary to check whether there is poor formation permeability or blockage and adjust the grouting hole. After entering the normal grouting stage, keep the pressure at 2-3MPa in the area close to the sliding structural zone to ensure the effective diffusion of materials without destroying the rock stratum; In the vicinity of limestone aquifer, the grouting pressure can be increased to 3-4MPa because of the well-developed pores and fractures and close contact with groundwater, so as to ensure the grouting material to be fully filled and reduce groundwater seepage.

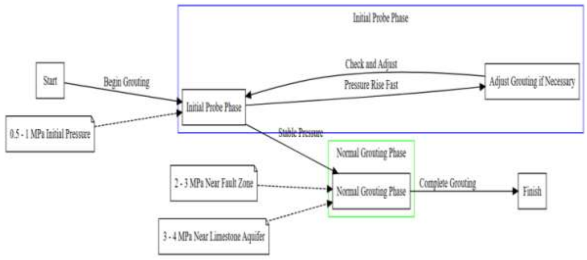

Figure 2 Grouting pressure control process

3.3 Grouting hole arrangement

The arrangement of grouting holes varies according to different regions. In the sliding structural zone, grouting holes are set every 5-10m along the strike. For the structural zone with smaller width, a row of holes is set in the center, while for the structural zone with larger width, multiple rows are arranged, the row spacing is 3-5m, and the depth of holes should reach 2-3m below the bottom to ensure the reinforcement effect. Above the limestone aquifer, plum blossom-shaped holes are arranged with the hole spacing of 8-12m, and the grouting holes need to penetrate the upper water-resisting layer and penetrate into the aquifer for 3-5m, thus effectively covering and strengthening the aquifer and reducing its water storage and water conductivity. Layout parameters of grouting holes are shown in Table 2, and layout of drilling holes is shown in Figure 2.

Table 2 Layout parameters of grouting holes

Region type	Grouting hole spacing	Row spacing of grouting holes	Depth of grouting hole	remarks
Sliding tectonic belt	5 - 10m	3 - 5m	2-3m below the bottom	According to the structural belt width adjustment
Above limestone aquifer	8 - 12m	/	Penetrate the upper aquiclude and go deep into the aquifer for 3-5m	Effectively cover and reinforce the aquifer

4. Data acquisition method

4.1 Geological survey

Surface surveying adopts a scale of 1:1000 to 1:5000, with observation points set every 20-50m along the planned route to record information such as lithology, layer thickness, and attitude, and accurately measure parameters of faults and fold structures. The drilling holes are arranged in a grid pattern with a spacing of 100-200m, and the depth depends on the geological unit, with a maximum depth of 1000m. During the process, core samples are collected every 2-5m, with a required recovery rate of over 80%. The collected core samples are analyzed in the laboratory for their mechanical parameters, such as compressive strength, tensile strength, and elastic modulus, with testing accuracy controlled within ± 5MPa and ± 1GPa.

4.2 Hydrogeological observation

Water level observation holes with a spacing of 200-500m are set up in the research area, and automatic monitoring devices are used to monitor the water level once per hour. The wellhead is 0.5-1m above the ground and equipped with protective devices. The flow observation points are located at the inflow and outflow points, springs, and runoff channels of surface water. For high flow points, flow meters (with an accuracy of ± 0.01m3/s) are used for measurement, while for low flow points, volumetric methods (with accuracies of ± 0.001 and ± 0.005m3/s, respectively) are used. In terms of water quality analysis, no less than 1 liter of water samples are collected from different aquifers and bodies of water every month, and all indicators such as ions, pH value (accuracy ± 0.01), and total dissolved solids (TDS, accuracy ± 1 mg/L) are fully analyzed in the laboratory.

4.3 Grouting process monitoring

Each grouting hole is equipped with a high-precision pressure sensor with a measurement accuracy of ± 0.05MPa, which monitors and transmits data in real-time to the ground system for analysis at a frequency of once per second. An electromagnetic flowmeter with a measurement accuracy of ± 0.1 liters per minute is equipped on the grouting pipeline, and flow data is collected every minute to adjust grouting parameters in a timely manner. In order to monitor the diffusion of grout, geophysical methods such as seismic wave CT were used to scan at intervals of 0.5-1m. By comparing the velocity and attenuation changes of seismic waves before and after grouting, the diffusion and effectiveness of grout in rock layers were evaluated.

4.4 Reinforcement effect evaluation

Ground penetrating radar (GPR) is used to detect the grouting reinforcement area, with a detection depth of 10-50m and a resolution of 0.1-0.5m, and the characteristics of reflected waves are analyzed to evaluate the change of rock integrity and compactness. To evaluate the reinforcement effect, core samples were obtained by re-drilling at 200-300m intervals within the treated area. Laboratory mechanical tests were then conducted on these samples, comparing the compressive strength, tensile strength, and elastic modulus to pre-reinforcement values. This comparison determined whether the reinforcement met the target objectives, with testing accuracy maintained consistent with the initial geological survey, so as to judge whether the reinforcement effect meets the expected goal, and the test accuracy is consistent with the previous geological survey.

5. Experimental results and analysis

5.1 Evaluation of grouting reinforcement effect

Before grouting reinforcement, the average permeability of limestone aquifer was 5.2×10-5m/s, with a decrease of 75%, and the fluctuation range of water level was reduced to 0.1m/d, which indicated that grouting reinforcement effectively formed a water plugging curtain and significantly reduced the water abundance and hydraulic conductivity of aquifer.

In terms of formation stability, before grouting reinforcement, due to the development of cracks and groundwater activities, the integrity of the rock stratum is poor, and the average compressive strength is 25MPa. After grouting reinforcement, the average compressive strength of rock stratum is increased to 38MPa, with an increase of 52%, which shows that grouting reinforcement significantly enhances the strength and stability of rock stratum.

5.2 Influence of sliding structural zone on grouting reinforcement effect

The different characteristics of the sliding structural zone have a significant impact on the grouting reinforcement effect. In the region of structural fracture zone, due to severe rock fracture and numerous cracks, grouting materials spread widely, but the curing effect is poor and the strength of added solid is relatively low. The experimental data show that the average compressive strength of the added solid in this area is 32MPa, which is lower than the 42MPa of the intact rock and solid[10].

Within folded rock strata, the diffusion of grouting material can be limited by the bending deformation. However, in stress concentration areas like the fold axis, the grout that does penetrate achieves a superior cure, resulting in a grouted mass with higher compressive strength. The experimental results show that the average compressive strength of the reinforced body in the folded area is 39MPa, which is close to the reinforcement effect of the intact rock stratum.

Physical and chemical characteristics of rock surface, such as scratches and mirrors, have certain influence on the adhesion and solidification of grouting materials. In the area where scratches are developed, the bonding force between grouting materials and rock strata is strong and the curing effect is good; However, in the area where the mirror surface is developed, the adhesion of grouting material is poor and the curing effect is relatively weak because of the smooth surface of rock stratum.

5.3 Discussion on influencing factors

In addition to the characteristics of sliding structural zone, grouting pressure, grouting material properties and stratum permeability also have a significant impact on grouting reinforcement effect.

In terms of grouting pressure, the experimental data show that when the grouting pressure is kept at 2-3MPa near the sliding structure zone, the diffusion range of grouting materials is moderate and the curing effect is good; However, near the limestone aquifer, when the grouting pressure is increased to 3-4MPa, the grouting material can fully fill the pores and cracks, forming a more dense water plugging curtain. However, too high grouting pressure may lead to rock fracture and affect the reinforcement effect.

In terms of grouting material performance, the experimental results show that portland cement, as the main grouting material, its high strength and stability play an important role in grouting reinforcement. Especially in the area where cracks are particularly developed, the supplementary use of polyurethane chemical grout can significantly improve the permeability and curing effect of grouting materials. However, the performance of different grouting materials is quite different, so the selection should be considered comprehensively according to the specific geological conditions.

In the aspect of stratum permeability, the experimental data show that grouting materials can spread and solidify more easily in the stratum with good permeability. However, in the rock stratum with poor permeability, the diffusion of grouting materials is limited and the curing effect is poor. In addition, stratum permeability also interacts with grouting pressure, grouting material properties and other factors, which jointly affect the grouting reinforcement effect.

The application effect of grouting reinforcement technology in limestone aquifer of coal mine is remarkable, but it is influenced by many factors such as the characteristics of sliding structural zone, grouting pressure, grouting material properties and stratum permeability. In practical application, it is necessary to comprehensively consider and optimize the design according to the specific geological conditions in order to achieve the best grouting reinforcement effect.

6. Conclusion

The existence of sliding structural zone significantly affects the diffusion and solidification effect of grouting materials. In the region of structural fracture zone, due to severe rock fracture and numerous cracks, grouting materials spread widely, but the curing effect is poor, resulting in relatively low strength of reinforcement. However, in the area of rock folds, although the diffusion of grouting materials is limited to some extent, the curing effect of grouting materials is better and the strength of added solid is higher in the stress concentration area such as the axis of folds.

Grouting pressure is one of the key factors affecting grouting reinforcement effect. In the area close to the slip structure zone, maintaining moderate grouting pressure (such as 2-3MPa) can ensure the effective diffusion and solidification of grouting materials; In the vicinity of limestone aquifer, increasing the grouting pressure to 3-4MPa is helpful to form a more dense water plugging curtain. However, too high grouting pressure may lead to rock fracture, which will weaken the reinforcement effect.

Portland cement, as the main grouting material, its high strength and stability play an important role in grouting reinforcement. Especially in the area where cracks are particularly developed, the supplementary use of polyurethane chemical grout can significantly improve the permeability and curing effect of grouting materials. The performance of different grouting materials is quite different, so the selection should be considered comprehensively according to the specific geological conditions.

Formation permeability has an important influence on grouting reinforcement effect. In the rock stratum with good permeability, the grouting material can spread and solidify more easily; However, in the rock stratum with poor permeability, the diffusion of grouting materials is limited and the curing effect is poor. In addition, stratum permeability also interacts with grouting pressure, grouting material properties and other factors, which jointly affect the grouting reinforcement effect.

Acknowledgments

1 Key Research Projects of Higher Education Institutions in Henan Province, China (No:24B440002).

2 Project supported by the Key Science and Technology Program of Henan Province, China (No:242102320356).

References

1. Liu Shiqi, Xu Yanchun, Fei Yu, Xie Xiaofeng, & Wang Ren. (2018). Application of acoustic detection technology in quality inspection of grouting reinforcement for fractured rock mass. Journal of Xi'an University of Science and Technology, 38(3), 7. DOI: 10.13800/j.cnki.xakjdxxb.2018.0308
2. Hu Weiyue, Zhao Chunhu, & Lü Hanjiang. (2022). Analysis of influencing factors of grouting control in coal seam floor water hazard area and efficient hole layout method. Coal Geology & Exploration, 50(11), 10.
3. Dong Shuning, Fan Min, Guo Xiaoming, Liu Yingfeng, Guo Kang, & Ji Zhongkui, et al. (2024). Characteristics and control technology of typical water disaster hazards in Shaanxi Province coal mines. Journal of China Coal Society, 49(2), 902. DOI: 10.13225/j.cnki.jccs.YH23.1493
4. Du Hailong, He Molí, Luo Xiaobin, Bin Bin, & Zhao Tiejun. (2019). Design and new technology of reinforcing and strengthening bored piles foundation in karst area. China Karst, 038(004), 600-606.
5. Liu Guangchao. (2018). Joint grouting reinforcement technology of large fault structure above and below the well. Coal Mine Safety, 49(10), 5. DOI: 10.13347/j.cnki.mkaq.2018.10.042

https://doi.org/10.1051/e3sconf/202566601015

6. Xu Guosheng, Zhou Shaoxi, Wang Yanlong, & Chen Shanle. (2018). Comprehensive geophysical exploration technology and engineering verification of coal mining under pressurized aquifer. Coal Technology, 37(11), 4.
7. Sun Qinghua, Lou Jie, Hu Xin, Gu Chao, Sun Qiang, & Zhang Weiqiang. (2024). Study on the effect of fly ash grouting in fractured rock mass based on resistivity response. China Coal, 50(10), 33-39. DOI: 10.19880/j.cnki.ccm.2024.10.005
8. Sun Xiaoyu. (2018). Research on technology and equipment of ground L-type drilling grouting reinforcement for coal seam floor. Coal Engineering, 050(003), 53-56.
9. Zhang, R., Wang, H., & Li, G. (2022). Grouting diffusion mechanism in fractured rock masses under structural plane control. Tunnelling and Underground Space Technology, 130, 104742.
10. Chen, X., Liu, B., & Yang, J. (2023). Experimental study on polyurethane-modified cement grout for sealing water inrush in karst limestone aquifers. Journal of Rock Mechanics and Geotechnical Engineering, 15(4), 1021–1034.