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ORIGINAL PAPER

Deep-hole water injection technology of strong impact tendency coal seam—a case study in Tangkou coal mine

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Abstract
The implementation of coal-seam water injection can change the physical and mechanical properties of coal, can improve the coal storage limit, prevent and control rock burst, prevent coal and gas outburst, and reduce dust concentration in underground operations. However, there are still many shortcomings such as the poor sealing effect and the lack of coal seam permeability. In order to study coal softening through water injection and its effect of reducing the coal's impact tendency, we examine the impact tendency, coal seam injection, water injection additive, water injection hole sealing, and coal seam stress-relief effect of coal seam on LW5304 experimentally and through engineering application. The results show that this method can be used to reduce the coal's impact tendency, if the samples are soaked. Triton X-100 additive can effectively reduce the polarity of water and the surface tension, while improving the coupling effect of water and coal and the wettability of coal. The "pure polyurethane + cement slurry + cement mortar" sealing process can be used to avoid water injection leaking. The water content of LW5304 coal seam is 3.2~4.2% after water injection, and the average increase of moisture content is 1~2.5%. In addition, the number of coal-stress early warning is reduced, and micro-seismic monitoring shows that the average energy is reduced as well. Therefore, water injection in coal seam is considered a good method for relieving stress.

Keywords Coal seam water infusion · Water injection additive · Stress relief of water injection · Water injection parameters · Rock burst

Introduction

China is a major coal-producing country. In 2015, despite a year-on-year reduction of 3.3%, China's coal production still reached 37.5 billion tons. However, the geological conditions at most of the coal mines are complex in China (Mazaira and Konicek 2015), and the rock burst issue is serious (Cao et al. 2015). Especially in recent years, with the development of deep mining, the intensity and frequency of rock burst incidents in coal mines are increasing in China. According to incomplete statistics, as of 2015, in China's 177 mines, rock burst failures occurred in 20 provinces and cities.

As one of the most destructive coal mine dynamic disasters, rock burst has become one of the most important research subjects in the field of mining engineering. In particular, numerous studies have been implemented on the technology for its treatment and control methods (e.g., He et al. 2010; Yan et al. 2015). These have indicated that the coal-seam infusion relieving stress technology is an effective method for the treatment of rock burst.

Research and practice shows that the implementation of coal-seam water injection can change the physical and mechanical properties of coal, improve the coal storage limit, prevent and control rock burst, prevent coal and

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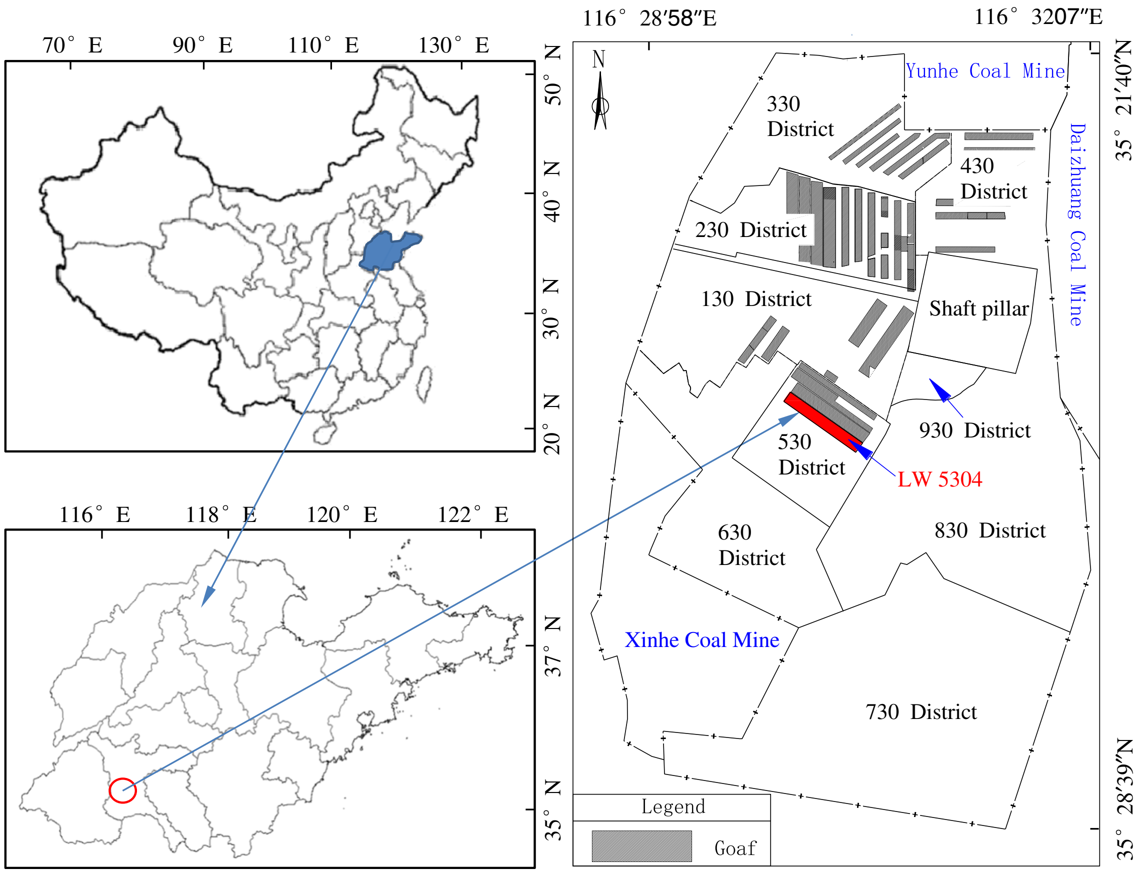

Fig. 1 Map showing the study area and a planar graph of the Tangkou coal mine

gas outburst (Zhou et al. 2017a), and reduce dust concentration in underground operations (e.g., Wold et al. 2008; Zhou et al. 2017b). At present, water injection systems usually adopt static-pressure or high-pressure water injection. Static-pressure water injection uses an underground static-pressure water pipe to inject water at a pressure of 1.5~5 MPa in general, and it can achieve better results for high-permeability coal seam. In high-pressure water injection, high-pressure water (> 20 MPa) is injected into the coal seam and changes the original fracture structure of coal, expands the pressure relief range, and softens the coal body, thus preventing rock burst or reducing its intensity.

By mathematical modeling, Zhang et al. (2003) described the mechanism of coal-seam water injection in the prevention and control of rock burst. By analyzing the pore characteristics of several kinds of coal seams, Qin and Zhang (2000) obtained the general expression of the relationship between the distribution of coal porosity and the increment of coal-seam water injection. The influence of water injection on the mechanical properties of coal and the stress distribution of the coal seam was analyzed by Xiao and Wang (2009), who believed that coal-seam water injection can change the physical and mechanical properties of coal and realize stress transferring. Jiang et al. (2015) and Li et al. (2012) also discussed the problem of stress transfer caused by water injection.

Fig. 2 Working face location

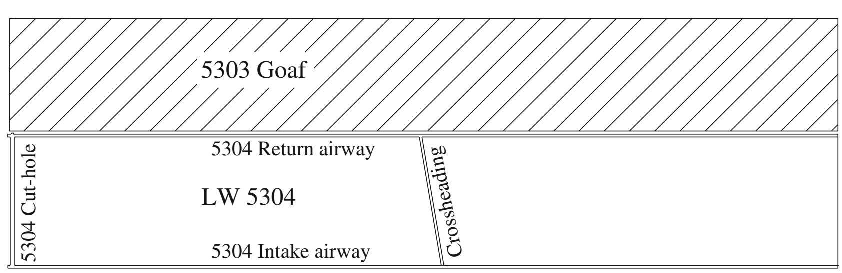

Table 1 Index determination of rock burst tendency of coal samples

Coal sample		Dynamic failure time/ms	Impact energy index	Elastic energy index	Uniaxial compressive strength/MPa
3# Coal seam	1	75	4.31	4.28	15.66
	2	124	3.03	5.11	23.75
	3	135	2.31	5.08	14.15
	4	58	3.73	9.12	24.76
	5	58	2.54	2.74	13.64
	Average value	90	3.18	5.27	18.39

Scientific research experts and engineers have made extensive research on coal-seam water injection, significantly improving the technology and its application. However, there are still many shortcomings such as the poor sealing effect and the lack of coal seam permeability. Based on previous studies, here, we select the deep strong burst tendency of the working face to carry out the coal-seam water injection test, through the analysis of the injection of coal seam and different parameters. In addition, we conduct site inspection in order to investigate the water-injection stress-relief effect.

Coal seams injection analysis

General situation of the test site

As shown in Fig. 1, the engineering practice LW5304 is applied at the Tangkou coal mine, Jining City, Shandong Province, China (Zhang et al. 2017). The mine is buried at a depth of about 963 m and has a width of 230 m, a recoverable length of 1565 m, and a coal-seam thickness of 1.2~5.7 m (average = 4.3 m). The working face is arranged as shown in Fig. 2.

The coal seam 3#, as the main mining coal seam of LW5304, exhibits a strong rock burst tendency, as shown in Table 1.

Analysis of the effect of coal-seam water injection in reducing the rock burst tendency

Table 2 shows the results for coal samples under natural conditions and different immersion times. Indeed, soaking affects the rock burst tendency of the coal samples (Zhou et al. 2015); the rock burst tendency changes with the soaking time. For 10 days soaking, the coal sample still exhibits a strong rock burst tendency (Xu et al. 2017). When the coal sample is immersed in water for 20 days, the rock burst tendency is significantly reduced to weak rock burst tendency. After 30 days, the rock burst tendency decreases even further, and the coal sample has weak rock burst tendency (Zhou et al. 2014). The test results show that under certain conditions, water injection can effectively reduce the rock burst tendency of coal.

Coal seams wettability analysis

Coal porosity is mainly determined using the mercury intrusion method, the density analysis method, NMR spin-relaxation method, and the isothermal adsorption method. The density analysis method is adopted in this paper (Manshad et al. 2017). The porosity of coal is calculated by measuring the true density and the apparent density of coal samples; the results are shown in Table 3.

The results for all coal samples satisfy the conditions: moisture $\leq 4\%$, porosity $\geq 4\%$, water absorption $\geq 1\%$, and hardness ≥ 0.4. Therefore, it is concluded that the 3# coal seam can be injected, but its permeability is low.

Table 2 The rock burst tendency of coal samples with different soaking time

Water immersion time	Dynamic failure time/ms	Impact energy index	Elastic energy index	Uniaxial compressive strength/MPa	Rock burst tendency
Natural state	90	3.18	5.27	18.39	Strong
10 days	30	6.48	3.38	13.97	Strong
20 days	134	1.42	3.09	13.50	Weak
30 days	160	1.51	2.62	10.36	Weak

Table 3 Coal sample test results

Sampling spot		20#	30#	50#	60#	70#	80#	100#
Hardness		1.31	1.11	1.55	1.44	1.77	1.14	1.65
Volatile	V_{ad} (%)	25.80	38.13	35.77	31.00	36.39	37.64	36.26
	V_{daf} (%)	30.55	43.02	39.88	36.22	40.36	41.66	39.85
Moisture (%)		2.64	2.50	2.24	2.17	2.11	2.49	2.34
Ash content (%)		12.93	8.88	8.06	12.23	7.72	7.17	8.24
True density		1.37	1.37	1.47	1.43	1.36	1.35	1.36
Apparent density		1.31	1.31	1.41	1.36	1.30	1.29	1.31
Porosity (%)		4.38	4.38	4.08	4.90	4.41	4.44	4.31
Water absorption (%)		3.86	3.19	3.57	4.83	3.70	4.49	3.89

Coal seam water injection process

Measures to improve the effect of coal seam water injection

The average buried depth of coal seam #3 is about 963 m; this large buried depth results in reduced porosity and permeability of the coal-seam, the moisture content of the coal seam is not high, and the water injection effect is not good. Through the above analysis of the factors resulting in low permeability of coal-seam water injection in deep coal mines, the measures to improve the effect of coal-seam water injection mainly include the following:

(1) Choosing reasonable water injection timing. After the start of working face mining, the coal in front of the coal wall produces a fracture zone due to lead stress. Thus, the water injection hole cannot be sealed sufficiently. Therefore, coal-seam water injection should be completed before working face mining.
(2) Water injection parameter optimization. Optimize the water injection pressure and the injection time, control the injection speed, and ensure the water injection rate of coal. The water injection rate determines whether rock burst due to high-pressure water injection in the coal seam is prevented or not.
(3) Additive in water injection. The use of an additive in coal-seam water injection can effectively reduce the polarity of the water and the surface tension, improve the coupling effect of water and coal, and enhance the wettability of coal.
(4) Reliable hole-sealing technology. Coal-seam water-injection hole-sealing technology is very important for the water injection effect. In the process of water injection, orifice running water and leaking means that water cannot be injected into coal-seam appropriately, and thus high-pressure water cannot fill coal cracks.

Coal-seam water injection parameters design

Coal-seam water injection pathway

The injection hole in LW5304 is constructed during the roadway excavation. After drilling, water injection facilities for bidirectional long-hole static/high-pressure water injection are installed (Hu et al. 2014), and the intake airflow roadway is injected with high-pressure

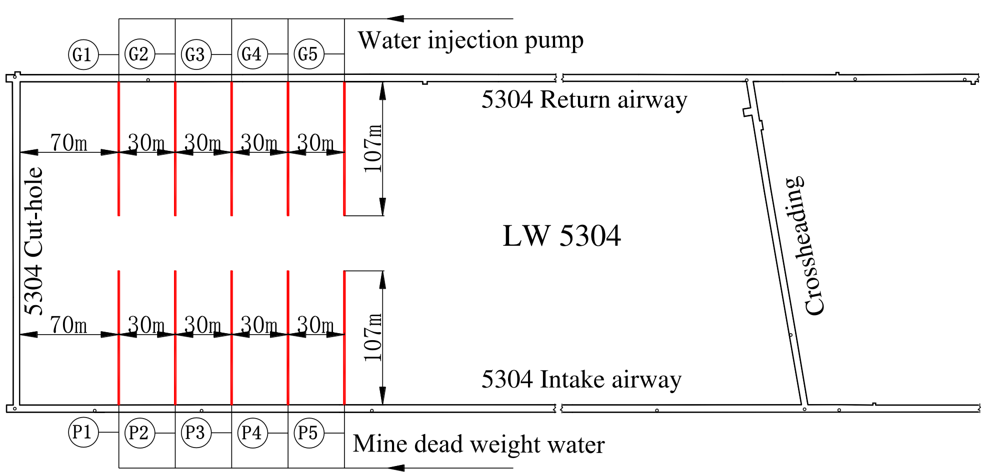

Fig. 3 Water injection hole layout

water via an injection pump. The return airway uses the static pressure water system to inject water, as shown in Fig. 3.

Design of water injection hole parameters

The construction drill model is a ZQJ-360 frame pillar-type drill, the diameter of the water injection hole is 76 mm, the space between the boreholes is 30 m, and the holes are located 1.8 m from the bottom of roadway, as shown in Fig. 3.

According to relevant requirements in "MT 501-1996," the length of bidirectional drilling should be shorter by 5~8 m than the 1/2 working face length, as described in Eq. (1).

$$l = L/2 - B, \quad (1)$$

where l is the length of the water injection hole, B is the accommodation coefficient (5~8 m, here 8 m), and L is the width of the workface (230 m).

Thus $l = 230/2 - 8 = 107$ m.

The depth of the water injection hole in LW5304 is 107 m.

Design of water injection amount

(1) Water injection amount in single hole

Water injection amount in the hole is the main factor that affects the coal wetting degree, the water injection amount should be designed according to the wet coal volume of the hole and its increased moisture value, and it can be calculated through Eq. (2).

$$Q = k \times M \times l_j \times \rho \times \delta, \quad (2)$$

where Q is the water injection amount of single hole, k is the wet coefficient of coal (1.1~1.3, here 1.1), M is the thickness

Table 4 Determination of surface tension of additive solution

Additive	Critical concentration (‰)	Surface tension (mN/m)	
		Pure water	30% inorganic solution
Aliphatic alcohol amide	1	38.63	65.21
0π-15	0.5	33.86	36.05
JFC	0.5	29.75	34.54
Triton X-100	0.1	29.43	32.32
Triethanolamine oleate	1	46.07	75.62
Abstergent	0.5	36.78	48.59
AQAS	3	40.32	83.43
SR-1	3	32.76	77.61
FC-1	1	35.43	38.72
Washing powder	1	37.58	42.54

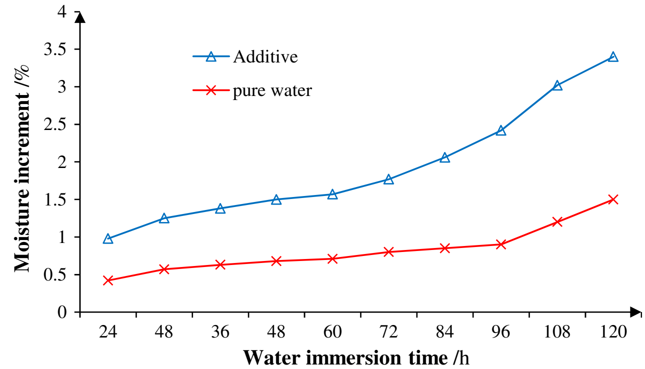

Fig. 4 Test results of coal sample infiltration

of the coal seam (4.26 m), l_j is the space between the boreholes (30 m), l is the hole length (107 m), ρ is the coal density (1.38 t/m^3), and δ is the water injection amount per ton of coal (0.02~0.04 m^3/t, here 0.02 m^3/t).

Thus, $Q = 1.1 \times 4.26 \times 24 \times 107 \times 1.38 \times 0.02 \approx 333$ m^3.

(2) Number of concurrently water-injected drilling holes

The number of concurrently water-injected drilling holes is determined by the advancing speed of the LW5304, the water injection time, and the space between the boreholes, as described in Eq. (3).

$$n = TV/l_j, \quad (3)$$

where n is the number of concurrently water-injected drilling holes, T is the water injection days ($T = 30$ days), V is the advancing speed of the LW5304 (m/day, $V = 5.4$ m/day), and l_j is the space between the boreholes (30 m).

Thus, $n = 30 \times 5.4/30 \approx 6$, that is, the number of drilling holes concurrently injected with water is 6.

Additive in water injection selection

The surface tension of the water can be greatly reduced by adding a surface-active agent in pure water, thus improving the coal wettability. It can prevent coal-injection water evaporation, increasing the moisture absorption and adding moisture materials in the water, and it is very good for improving the dustproof effect of water injection (Li et al. 2015). By testing different additives for water injection, we choose the additives suiting the coal properties of LW5304, as shown in Table 4.

Furthermore, we choose the Triton X-100 type additive for water injection, in order to improve the activity of the water

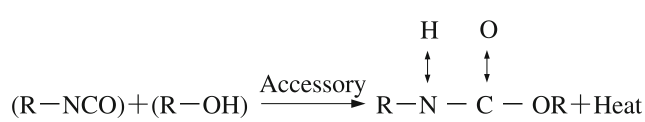

Fig. 5 Polyurethane reaction type

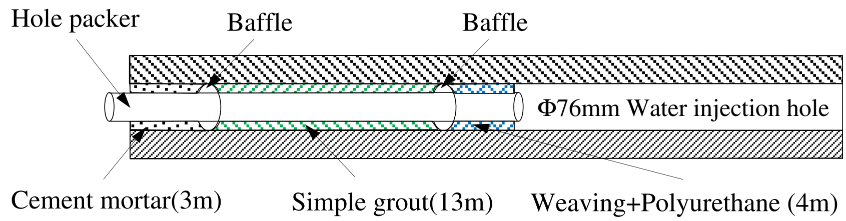

Fig. 6 Schematic diagram of combined sealing device

surface, shorten the time of water injection, increase the capillary force of the water when it permeates the coal seam fracture, reinforce permeation, effectively reduce the rock burst tendency of the coal seam, and decrease the dust concentration. An additive in water injection can significantly improve the coal seam permeability and wettability, and strengthen the coal seam injection. After water injection, the moisture content of the coal seam is not less than 4%.

The water absorption of coal samples in pure water and in the additive solution is tested, and the results are shown in Fig. 4.

As show in Fig. 4, use of an additive can obviously increase the moisture increment of the coal sample; the average moisture increment is 0.80% in pure water and 0.97% in the additive solution.

Design of sealing process

The sealing quality is the main factor affecting deep-hole water injection (Huang et al. 2010). The water injection hole should be sealed before single-hole injection meets the design requirement, because water seepage should not occur near the hole, nor should coal wall leakage or running water between adjacent water injection holes.

Design of sealing depth

The sealing depth affects the sealing quality, and the main factors determining the sealing depth include the coal fracture, the water injection pressure, the fracture zone width of the roadway surrounding rock, and the parameters of the water injection hole. Generally, the sealing depth of an up-dipping water injection hole should be larger when water injection pressure is high, for greater coal fracture and stronger injected coal seam (Liu et al. 2017). In addition, the sealing depth should exceed the scope of the roadway fracture zone. The field-monitoring results show that the high-stress area is generally in the range from 13 to 16 m in the side of the roadway, and the maximum stress concentration coefficient $K_{max} \approx 2$. Through field testing, we found that hole leakage during water injection can be effectively avoided using the above parameters, in order to seal in accordance with the 20 m depth.

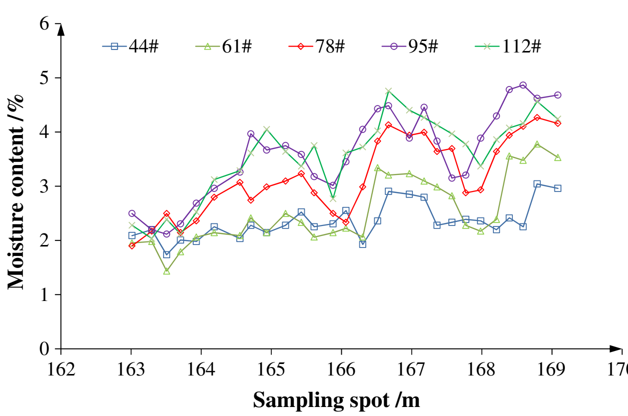

Fig. 7 The layout of moisture content of coal

Design of sealing methods

The main sealing methods used in the present study include compacted cement mortar sealing, polyurethane sealing, high-pressure rubber capsule sealing, and resin anchoring agent sealing.

Because LW5304 is nearly kilometers underground, the permeability of the coal seams is relatively low. Therefore, when injecting high-pressure water (more than 10 MPa), we developed a combined sealing technology with compacted cement mortar, polyurethane, and pure cement slurry, considering safety and cost; the reactive polyurethane is shown in Fig. 5.

The combined sealing section consists of three parts, from the inside out: polyurethane (about 4 m), pure cement slurry (about 13 m), and compacted cement mortar (about 3 m). The sealing process is shown in Fig. 6.

Validation of site effect after water injection

Analysis of water content and moisture content after water injection

Sampling was conducted three times a day, in six sampling positions, at the borehole distances of 1, 2, 3, 4, 5, and 7.5 m, in the workface along the hole's length direction. Coal samples were obtained from three water-wet areas in the 112#, 95#, and 78# bracket, and from two water-injection micro-wet or humid areas, which are respectively in the 61# and in the

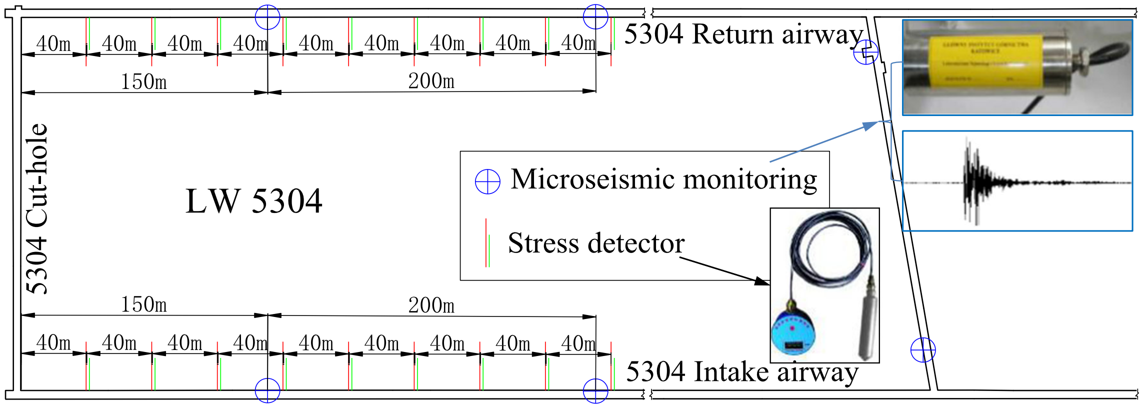

Fig. 8 Working face system layout

44# bracket. Each coal sample was classified, marked to indicate the sampling position, and sealed with plastic film. Moreover, we measured the moisture content of the coal samples, and then determined the wetting radius of the water injection test, which provides a reliable basis for the optimization and improvement of the water injection scheme. The coal moisture content results are shown in Fig. 7.

Through the above analysis, the average moisture content of the coal at point 165 is 3.21%, and the incremental water is 1.03%; the average moisture content of the coal at point 167 is 3.99%, and the incremental water is 1.81%; the average moisture content of the coal at point 169 is 4.16%, and the incremental water is 1.97%.

Based on the results for the samples from the six locations along the direction of the coal seam and the five zones along the length of the borehole layout, when the average moisture content of the coal is 3.2~4.2%, and the average increment of the water content is in the range of 1~2.5%, the water injection effect is good.

Early warning analysis of coal stress after water injection

As shown in Fig. 8, the stress measuring points (18 groups in total) are arranged on the roadway of LW5304 (Cai et al. 2014). The space between two adjacent stress measuring point groups is 40 m, there are two stress points in each group with hole depths of 10 and 15 m, and the distance between the holes is 1 m.

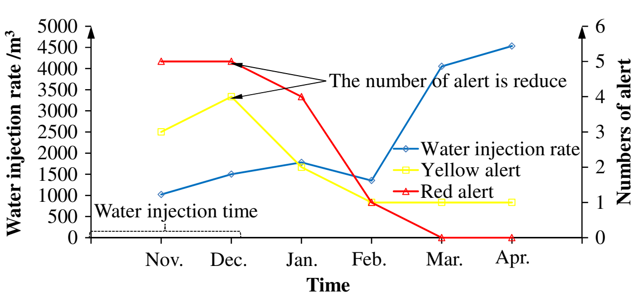

Fig. 9 The curve of water injection amount and the number of early warning of coal stress

Statistical analysis of the coal stress early warning after water injection is shown in Fig. 9. We observe that with increasing water injection amount, the number of coal stress early warnings decreases obviously, and when the monthly cumulative water injection amount exceeds 4000 m^3, no longer appearing as red warning. The initial coal-stress warning value is shown in Table 5.

Analysis of microseismic activity after water injection

The measuring points are arranged along the roadway on the contact lane of LW5304 (Fig. 8) to monitor the microseismic events before and after water injection (e.g., Lu et al. 2016; He et al. 2017). In Fig. 10, the curve shows the change in the frequency of microseismic events at LW5304. As show in Fig. 10, the frequency and the energy of the microseismic events begin to fall sharply 20 days after water injection, reaching a relatively low level. By comparing the average energy change before and after water injection, it can be seen that the average energy is reduced by 86%, the LW5304 advance 1 m, and the released microseism energy decreases from 403 to 205 J. These results show that the coal seam and the bottom plate are softened obviously through water injection.

Table 5 Early warning of coal stress

Depth	Alarm level	Alarm value (MPa)
10 m	Safe	< 10
	Yellow alert	10–12
	Red alert	> 12
15 m	Safe	< 13
	Yellow alert	13–15
	Red alert	> 15

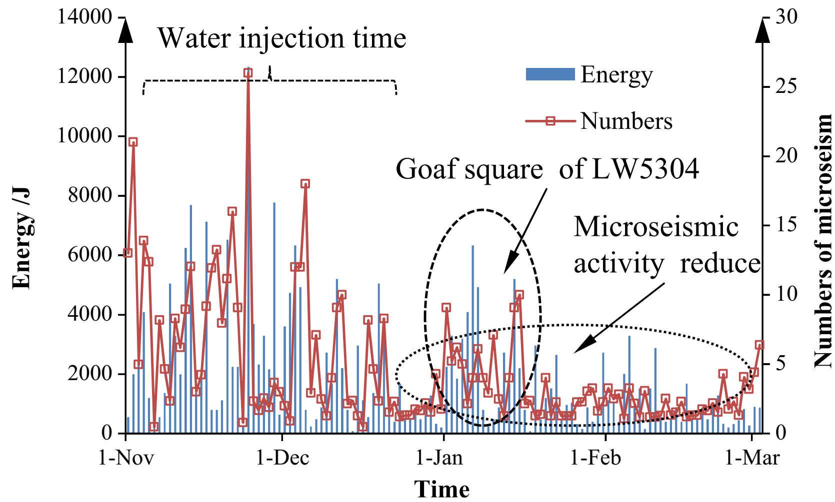

Fig. 10 The change curve of microseismic events

Conclusions

(1) Through testing, we found that the rock burst tendency differs with different soaking time; for 10 days soaking time, the coal sample still exhibits a strong rock burst tendency. When the coal sample is immersed in water for 20 days, the rock burst tendency is significantly reduced to become weak. For 30 days, the rock burst tendency continues to decrease, and the coal sample has weak rock burst tendency. The test results show that, under certain conditions, water injection can effectively reduce the rock burst tendency of coal.

(2) The inorganic solution surface tension reached 32.32 mN/m when 30% concentrated Triton X-100 was added with the critical concentration of Triton X-100 additive being 0.1%.

(3) Sealing a hole with polyurethane, cement slurry, and cement mortar, combined, the sealing depth is 20 m, which includes, from inside out, polyurethane (about 4 m), cement slurry (about 13 m), and thick cement mortar (about 3 m). As a result, water leakage during water injection to the hole can be avoided effectively.

(4) Based on analysis of the coal moisture content, the coal stress, and the frequency of microseismic events after water injection, we can see that, when the average moisture content of coal is 3.2~4.2% and the average increment of the water content is in the range of 1~2.5%, with increasing coal-seam water injection, the coal stress warning number decreases, and the average energy of the microseismic events is reduced by 86%. Thus, water injection achieves good results.

Coal-seam stress-relief technology through deep-hole water injection is an effective way to achieve strong impact coal seam softening, by reducing the rock burst and dust. Here, we studied the initial effect of coal-seam water injection from the point of view of field application. Nevertheless, many technical details require further improvement.

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References

Cai W, Dou LM, Cao AY, Gong SY, Li ZL (2014) Application of seismic velocity tomography in underground coal mines: a case study of Yima mining area Henan China. J Appl Geophys 109:140–149. https://doi.org/10.1016/j.jappgeo.2014.07.021

Cao AY, Dou LM, Cai W, Gong SY, Liu S, Jing GH (2015) Case study of seismic hazard assessment in underground coal mining using passive tomography. Int J Rock Mech Min Sci 78:1–9

He J, Dou LM, Gong SY, Li J, Ma ZQ (2017) Rock burst assessment and prediction by dynamic and static stress analysis based on microseismic monitoring. Int J Rock Mech Min Sci 93:46–53. https://doi.org/10.1016/j.ijrmms.2017.01.005

He MC, Nie W, Han LQ, Ling LJ (2010) Microcrack analysis of Sanya grantite fragments from rockburst tests. Int J Min Sci Technol 20:238–243

Hu GZ, Xu JL, Ren T, Dong YW, Qin W, Shan ZJ (2014) Field investigation of using water injection through inseam gas drainage boreholes to control coal dust from the longwall face during the influence of abutment pressure. Int J Min Reclam Environ 30:1–16

Huang, Z.A., Zhang, E.M., Zhang, Y.H., and Gao, Y.K., 2010, Development of a new hole packer used for both gas drainage and coal seam water infusion, Proceedings of the 4th International Conference on Bioinformatics and Biomedical Engineering, June 18–20, 7, pp. 1–5

Jiang FX, Wang B, Zhai MH, Guo XS, Huang GW, Huang JR (2015) Field tests on fixed-point hydraulic fracture with extra-high pressure in coal seam for rock burst prevention. Chin J Geotech Eng 37:526–531 (in Chinese with English abstract)

Li JB, Chen XX, Wang XM (2012) Mechanism analysis on concentrated stress in front of mining face moving forward occurred by water injection in seam. Coal Sci Technol 4:56–59 (in Chinese with English abstract)

Li J, Zhou F, Liu H (2015) The selection and application of a compound wetting agent to the coal seam water infusion for dust control. Int J Coal Prep Util 36:192–206

Liu ZG, Cao AY, Zhu GA, Wang CB (2017) Numerical simulation and engineering practice for optimal parameters of deep-hole blasting in sidewalls of roadway. Arab J Sci Eng 42(9):3809–3818. https://doi.org/10.1007/s13369-017-2501-7

Lu Y, Zuo SG, Ge ZL, Xiao SQ, Cheng YG (2016) Experimental study of crack initiation and extension induced by hydraulic fracturing in a tree-type borehole array. Energies 9(7):514. https://doi.org/10.3390/en9070514

Mazaira A, Konicek P (2015) Intense rockburst impacts in deep underground construction and their prevention. Can Geotech J 52(10): 1426–1439. https://doi.org/10.1139/cgj-2014-0359

Manshad AK, Nowrouzi I, Mohammadi AH (2017) Effects of water soluble ions on wettability alteration and contact angle in smart and carbonated smart water injection process in oil reservoirs. J Mol Liq 244:440–452. https://doi.org/10.1016/j.molliq.2017.09.011

Qin WG, Zhang YS (2000) Relation of pore distribution of coal with water infusion increment in seams. J China Coal Soc 5:514–517 (in Chinese with English abstract)

Wold MB, Connell LD, Choi SK (2008) The role of spatial variability in coal seam parameters on gas outburst behaviour during coal mining. Int J Coal Geol 75(1):1–14. https://doi.org/10.1016/j.coal.2008.01.006

Xiao ZG, Wang ZF (2009) Status and progress of studies on mechanism of preventing coal and gas outburst by coal seam infusion. China Saf Sci J 10:150–158 (in Chinese with English abstract)

Xu J, Jiang JD, Xu N, Liu QS, Gao YF (2017) A new energy index for evaluating the tendency of rockburst and its engineering application. Eng Geol 230:46–54. https://doi.org/10.1016/j.enggeo.2017.09.015

Yan P, Zhao ZG, Lu WB, Fan Y, Chen XR, Shan ZG (2015) Mitigation of rock burst events by blasting techniques during deep-tunnel excavation. Eng Geol 188:126–136. https://doi.org/10.1016/j.enggeo.2015.01.011

Zhang MT, Song WY, Pan YS (2003) Study on water pouring into coal seam to prevent rock-burst. China Saf Sci J 10:73–76 (in Chinese with English abstract)

Zhang ZB, Wang EY, Li N (2017) Temporal and spatial characteristics of coal-mine microseism based on single-link cluster. Geosci J 2:1–11

Zhou AT, Wang LP, Kiryaeva TA (2017a) Gas-solid coupling laws for deep high-gas coal seams. Int J Min Sci Technol 27(4):675–679. https://doi.org/10.1016/j.ijmst.2017.05.016

Zhou, G., Yu, Y., Wen, J., Nie, W., and Wang, H., 2015, Numerical simulation of seepage pressure field of coal seam water-injection in high and low pressure with one-way and bi-directional drilling holes. Proceedings of the 5th International Conference on Industrial Electronics and Engineering, October 25–27, 47(4), p. 155–162

Zhou PL, Zhang YH, Huang ZA, Gao YK, Wang H, Luo Q (2017b) Coal and gas outburst prevention using new high water content cement slurry for injection into the coal seam. Int J Min Sci Technol 27(4): 669–673. https://doi.org/10.1016/j.ijmst.2017.05.003

Zhou XH, Xu K, Qi QJ, Wu X (2014) Fuzzy clustering analysis and application of the degree of difficulty of coal seam water injection. Adv Mater Res 962–965:939–945