Nat Hazards (2014) 73:531–546
DOI 10.1007/s11069-014-1086-7

ORIGINAL PAPER

Effect of bedding structural diversity of coal on permeability evolution and gas disasters control with coal mining

Rongkun Pan · Yuanping Cheng · Liang Yuan · Minggao Yu · Jun Dong

Received: 6 January 2014 / Accepted: 8 February 2014 /

Abstract Bedding structure has affected gas flow in coal seam greatly, which also controls gas permeation direction and gas extraction results, and finally it has tremendous influence on prevention and control of gas disaster accidents. Combined with engineering practice of gas disaster prevention and control in China, in this paper, permeability evolution of nature coal in different bedding directions in the condition of loading is studied, and the results showed that in three directions of bedding fractures, permeability of coal which is parallel to bedding planes is the highest; it would be much easier for gas percolation along the bedding planes than other directions. In the unloading process, tension–shear destruction appears in coal sample which is oblique to bedding along the bedding planes, with a sudden increase in permeability. It is difficult for the crack damage from loading process to recover in unloading process, that is, permeability of unloading isn't just a simple reverse process of loading. Combined with the permeability evolution of the three coal samples in the whole process, three permeability evolution models which include elasticity, plasticity and fracture are proposed. Based on the experimental results, gas extraction using boreholes along coal seam and through coal seam is compared during depressurized mining. Due to the bedding structure of coal seam, a large area of fracture network of "boreholes–bedding fractures" is formed among boreholes through coal seam and bedding structure, which makes the good effect of gas extraction using boreholes through coal seam. Research results will be of important guiding significance for choosing the best gas extraction scheme, layout of setting parameters of drilling boreholes and gas disaster prevention in the underground coal mine.

R. Pan · Y. Cheng (✉) · L. Yuan · J. Dong
National Engineering Research Center for Coal Gas Control, China University of Mining and Technology, Xuzhou 221008, Jiangsu, China
e-mail: pprrk2011@126.com

R. Pan · M. Yu
Department of Safety and Science Engineering, Henan Polytechnic University, Jiaozuo 454000, Henan, China

L. Yuan
Huainan Mining (Group) Co. Ltd, Huainan 232001, China

Keywords Gas disasters · Coalmine accidents · Bedding planes · Structure diversity · Permeability evolution

1 Introduction

In the long geological age, the coal seam has shown the characteristics of sorted bedding planes due to the diversity of composition of coal-forming material, particle size, cement, texture and structure etc., which also has a decisive effect on the stability, producibility and fluid flow of coal (Laubach et al. 1998). The effects are mainly embodied in the following aspects: the presence of bedding planes destroys the continuity and integrality of coal and changes the stress distribution in coal seam, which easily causes the development, evolution, connection of bedding fracture and even deformation and destruction of coal after mining. The presence of bedding planes also influences the adsorption, desorption, diffusion and permeation of gas which directly controls the direction of gas flow and concentration distribution, and thus greatly affects coal seam gas extraction (Mazumder et al. 2006).

There is a huge demand for coal because of the rapid economic development of China, and the output of coal is increasing rapidly with the average annual growth rate of 10 % in the last decade, as shown in Fig. 1. Though China's coal output has been growing, the mortality rate of million ton, accidents number and death toll are all decreasing continuously, as shown in Fig. 2, which indicates the great achievements in coal mine safety made by Chinese scientific researcher. With the increase in mining depth and mining intensity, various accidents still occur frequently, especially the gas accident which has become the most prominent disaster. Figure 3 is the proportion of all kinds of accidents in 2012, and the gas disaster accidents account for 50.8 %. Therefore, the gas accident is one of the key problems that need to be solved urgently in coal mine development process. In China, the gas extraction is an important technical measure for controlling gas disaster. As is known, bedding structure is the main factor of controlling the permeability of coal and gas flow (Cheng et al. 2009; Yuan et al. 2013), and permeability is one of the most important basic parameters for controlling gas disaster in coal mine.

There are many factors that affect the permeability of coal during mining. Previous studies have focused primarily on factors involving changes in effective stress and coal matrix swelling and deformation by gas adsorption and desorption. For example, Jasinge et al. (2011), Korsnes et al. (2006) and Somerton et al. (1975) studied the relationship between permeability and stress. Harpalani (1985) did research on the variation of permeability along with the changes of gas pressure inside of the pore under various stress states. Durucan and Edwards (1986) found that the permeability decreases along with the increase in the effective stress. Yin and Wang (2006) concluded that pore pressure and effective stress have important effects on the permeability characteristics of rocks. Connell et al. (2010) considered that both the microstructure and the effective stress have obvious effect on the permeability of coal. Berryman (2011) proposed that the effective stress could affect the permeability by changing the structure of porous media. Gas adsorption and desorption which causes the swelling and shrinkage of coal matrix also affect the permeability directly in the process of gas percolation (Fu et al. 2002; Karacan and Mitchell 2003; Majewska et al. 2013; Zharikov et al. 2003). Zhou et al. (2009) developed a theoretical model based on the effective stress. Many valuable results in this field were obtained in the last decades.

Except for effective stress, pore pressure and coal matrix, only the bedding structure of coal seam is the internal factor that influences the anisotropy characteristic of permeation

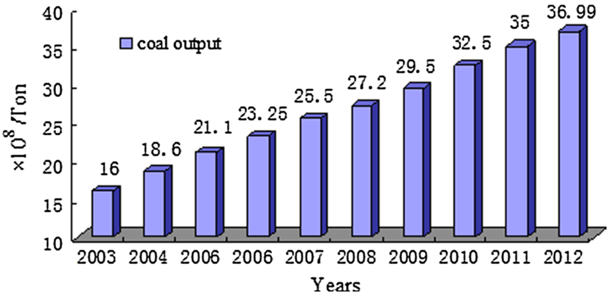

Fig. 1 Output of coal in China during past 10 years

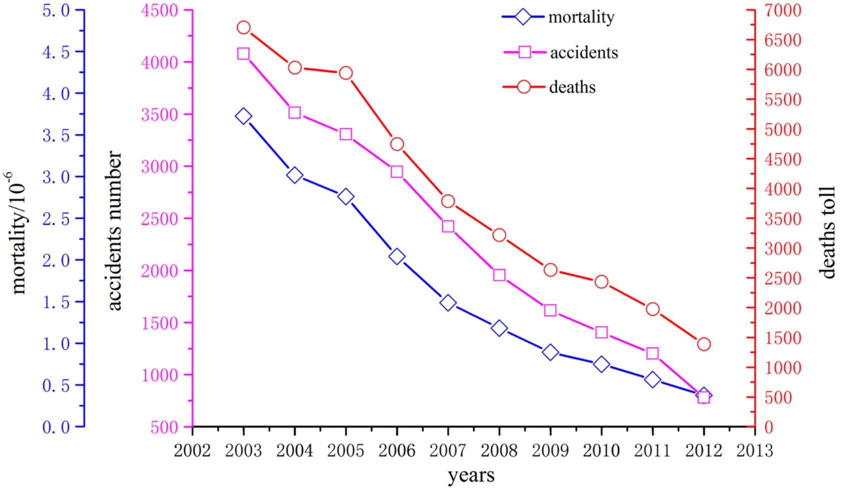

Fig. 2 Mortality rate of million ton, accidents number and deaths toll in China coal mines during past 10 years

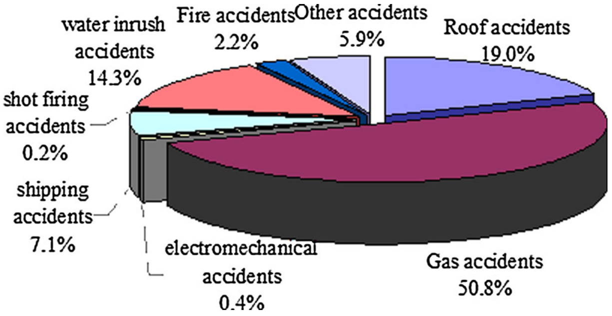

Fig. 3 Proportion of larger accidents in China coal mining in 2012

in coal-forming process (Kuila et al. 2011; Law 1993; Rose and Foh 1984). However, studies of the relationship between the bedding structure and permeability are presently scattered. Huang (2012) took into account the effect of the structural anisotropy on coal permeability. Yu et al. (2008) researched the impact on coal strength from the perspective of bedding. Pomeroy and Robinson (1967) conducted experiments and found that the flow of water (equivalent to permeability) changed obviously when the confining pressure was perpendicular to bedding planes of the specimens. Koenig and Stubbs (1986)considered that permeability characteristics of gas were influenced significantly by bedding. Gash et al. (1992) investigated that the permeability parallel to bedding was much higher than that of perpendicular to bedding in the conditions of loading confining pressures on coal samples. Palmer (2009), Li et al. (2013) and Liu et al. (2012) summarized an analysis model of gas permeability evolution in coal seam on the basis of CO_2 displacement. Some previous studies (Li et al. 2003, 2004; Perera et al. 2013) focused on the permeability of coal joint under vertical stress.

Based on the above, the structural characteristic of coal has great influence on gas permeability and also directly affects the behaviour of gas permeation and gas extraction (Dawson and Esterle 2010; Ryan and Branch 2002). Therefore, in this study, experiments were conducted using cylindrical samples of coal with three directions relative to bedding planes, shown as follows: (1) sample C1 was oriented perpendicular to bedding; (2) sample P1 was oriented parallel to bedding; (3) sample X1 was oriented oblique (45°) to bedding. We attempted to explore the evolution law of permeability and deformation characteristics of nature coal, as well as the influence of bedding structure on permeability under various loading conditions.

2 Experiment part

2.1 Coal samples preparation

A large block of coal was collected from No. 3 coal seam of Si-He coal mine in Jincheng, Shanxi province. The sample displayed distinct bedding structure. Properties of coal are summarised in Table 1. Standard cylinders of 50 mm in diameter and 100 mm in length were cut from the coal block at three different bedding orientations. Coal samples are shown in Fig. 4, and the schematic diagram of bedding distribution in each sample is shown in Fig. 5.

2.2 Experimental apparatus

Firstly, the length, diameter and weight of the nature coal samples were measured and recorded. Then, the samples were packed in hot pyrocondensation pipe to avoid gas leakage. Experiments were performed using self-regulating coupling characteristic determinator of adsorption–permeation mechanics. A schematic diagram of this apparatus is shown in Fig. 6, which consists of loading module, fluid module and data acquisition module.

2.3 Experimental scheme and procedure

The scheme of this experiment is presented as follows: a constant pore pressure of 1 MPa is set using methane as the gas source. Firstly, the axial and confining pressure should be raised to 12 MPa simultaneously. Next, the confining pressure is released, while the axial pressure is kept constantly. The detailed experimental scheme is shown as Table 2.

Table 1 Summary of the properties of the coal

Proximate analysis and gas parameters

Ash yield (%)	Volatile matter (%)	Fixed carbon (%)	Vitrinite reflectance (%)	Adsorption constant		Sturdiness coefficient
				a (m^3/t)	*b* (MPa^{-1})	
25.00	7.83	64.24	2.49	61	0.94	2.087

Sample physical properties

Sample	Length (mm)	Diameter (mm)	Weight (g)	Porosity (%)	Compressive strength (MPa)
C1	103.56	50.06	300.29	2.0	40.81
P1	102.92	50.00	297.44	3.4	44.35
X1	103.08	49.98	295.51	2.7	32.57

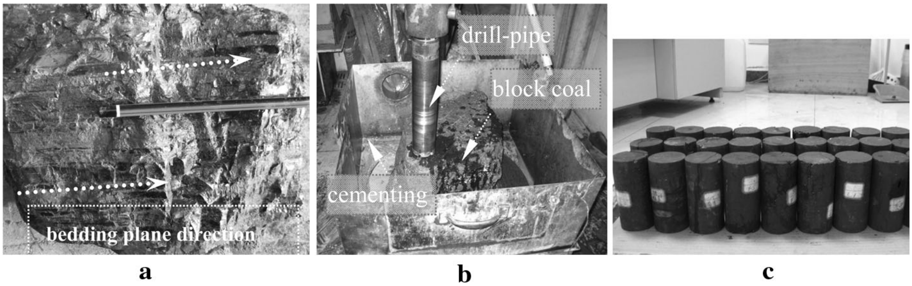

Fig. 4 Coal sample preparation. **a** A large block of coal; **b** sample preparation and processing; **c** experimental coal samples

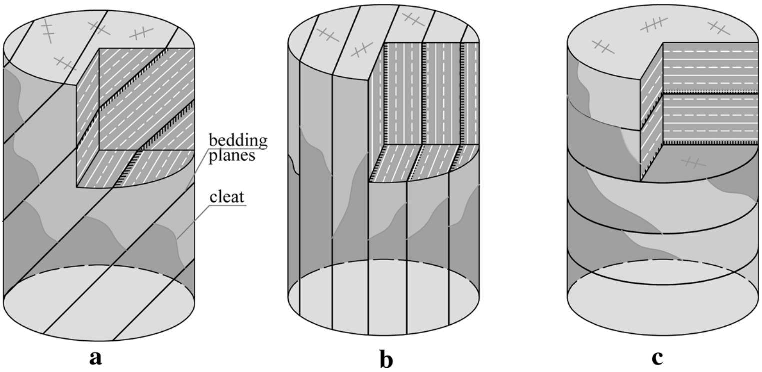

Fig. 5 Sketch of coal samples, showing various orientations of bedding planes. **a** Perpendicular to bedding planes (sample C1); **b** parallel to bedding planes (sample P1); **c** oblique to bedding planes (sample X1)

The transient pulse technique is used in this experiment. Its testing principle is to balance the pressure on both ends of the sample for a time and then increase the pressure on one end, which gives the sample a transient pulse pressure difference, thus one-dimensional percolation is formed inside of the sample. As time goes on, the upstream pressure gradually decreases, and the downstream pressure gradually increases until the sample reaches a new pressure balance state. The formula of the pressure gradient in the upstream with time is (Wang et al. 2011):

$$\delta P(t) = \delta P(t_0) e^{-\alpha t} \tag{1}$$

where $\delta P(t)$ is the pressure difference between the upstream and downstream at time t, $\delta P(t_0)$ is the initial pressure difference between the upstream and downstream, t is the time and α is defined as below:

$$\alpha = \frac{kA}{\mu L}\left(\frac{1}{S_u} + \frac{1}{S_d}\right) \tag{2}$$

where k is permeability, μ is the viscosity of the fluid, A is the sample cross-sectional area, L is the sample length and S_u and S_d are the storage coefficient of the upstream and downstream. The permeability is obtained from Eq. (2).

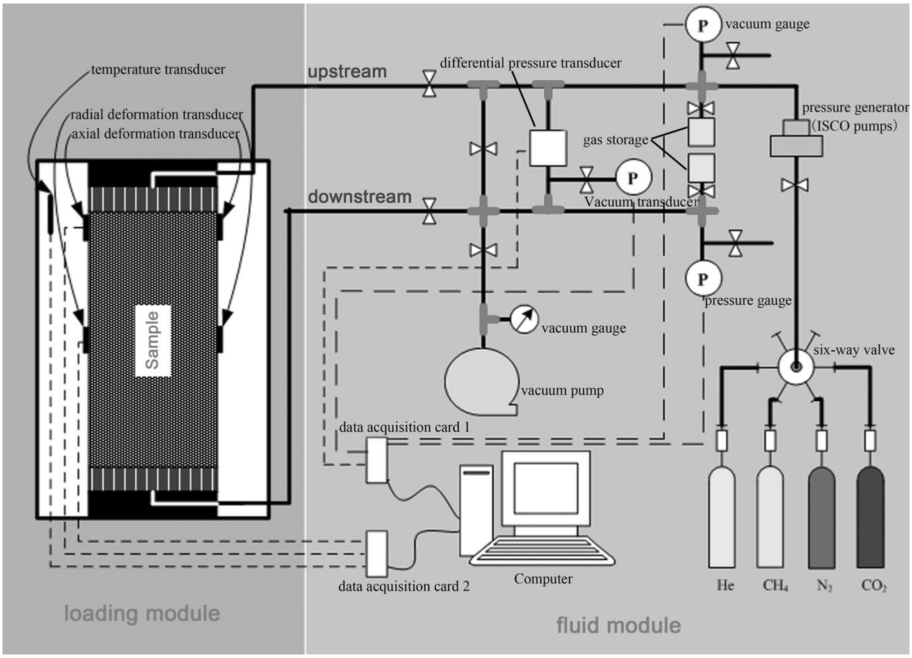

Fig. 6 Schematic diagram of the experimental apparatus

3 Results and discussion

Based on the conditions and methods of the experiment, the permeability of coal in three different bedding directions is tested. Experimental results are shown in Table 3, and the entire process of permeability evolution under loading and unloading is shown in Figs. 7, 8 and 9.

The permeability of coal in three bedding directions was analysed. In the loading process, the permeability decreased along with the increase in effective stress. The change rate of permeability was the biggest in the initial loading period, and then, it became flat. The permeability parallel to bedding was always the highest, and it was 7.5 and 1.7 times higher than that perpendicular and oblique to bedding, respectively. It indicates that in the loading process, gas flow was easier along the direction which is parallel to bedding than other directions. However, gas flow was blocked among bedding planes with the result that permeability of sample which was perpendicular to bedding planes was the lowest, which was identical with the research results in literature (Li et al. 2004).

During the unloading process, the permeability of the sample in three directions increased along with the decrease in effective stress. When the effective stress decreased from 11 to 7 MPa, the permeability began to increase but the increasing extent was small, which indicated that the fractures of bedding planes were unable to quickly recover from their previous compressed state during loading. The permeability increased sharply when the effective stress decreased to <7 MPa. During this process, fractures of bedding planes were recovered, and new fractures were produced. Under the effect of corresponding effective stress, the permeability in the loading process was higher than that in the unloading process, which indicated that the unloading process is not a simple inverse

Table 2 Parameters of experimental scheme

Serial number	Axial pressure (MPa)	Confining pressure (MPa)	Pore pressure (MPa)	Remarks
Loading				
1	2	2	1	The rate of loading axial pressure and confining pressure are 10 N/s
2	4	4	1	
3	6	6	1	
4	8	8	1	
5	10	10	1	
6	12	12	1	
Unloading				
7	12	10	1	The rate of unloading axial pressure and confining pressure are 20 N/s
8	12	8	1	
9	12	6	1	
10	12	4	1	
11	12	2	1	

process of loading. Because fractures inside of coal incurred permanent damage during the loading process, these fractures deformed and closed such that they had difficulty in completely recovering during unloading. The final permeability in the three directions with respect to bedding recovered only 39.3, 14 and 28.7 % of their initial value. The recovery degree of permeability which was perpendicular to bedding is higher mainly because bedding planes were compressed in the axial direction and new fractures were then formed. Fractures among the bedding planes were cut through so that gas flow became much easier for permeation.

Seen from the testing results of a single coal sample, the variation range of permeability perpendicular to bedding was the lowest during loading from 1 to 3 MPa. Therefore, gas flow through the bedding planes was insensitive to the effective stress. The permeability parallel and oblique to bedding changed appreciably, as well as the widths of the bedding fractures. During the unloading process, the permeability recovery of the coal samples parallel to bedding became slowly. However, the sample that was oriented oblique to bedding displayed a phenomenon of mutations, namely the widths of original fractures suddenly recovered and new fractures rapidly developed. One reason to explain this unusual deformation when the confining pressure was decreased to 2 MPa was that the coal sample was ruptured along the bedding planes, and the strength of bedding planes was weaker than the coal body. The feature of the breakage of this coal sample was shown in Fig. 10. Slip and deformation appeared on weak bedding planes created separations along planes and fractures, which caused rapid increase in permeability. This is a good guidance of the boreholes drilling arrangement for gas extraction.

The relationship between permeability and unloading rate is established, as shown in Fig. 11. When the unloading rate is <24.5 %, the permeability increases slowly; when the unloading rate is more than 36.4 %, the permeability increases rapidly. The micro-cracks, joints and bedding fractures are gradually extended and connected. As their connectivity develops well in the coal, they form an extensive system of fractures, which then creates paths for gas flow gradually; thus the permeability of coal samples increases rapidly. The permeability among the coal samples varies by a factor of 7. This large variation in

Table 3 Permeability of coal samples in three different directions with respect to bedding

Serial number	Axial pressure (MPa)	Confining pressure (MPa)	Pore pressure (MPa)	Permeability of C1 (mD)	Permeability of P1 (mD)	Permeability of X1 (mD)
1	1.998	1.997	1	0.00346	0.02600	0.01500
2	3.999	3.998	1	0.00246	0.01101	0.00477
3	5.999	5.998	1	0.00150	0.00600	0.00320
4	7.998	7.997	1	0.00098	0.00336	0.00183
5	9.998	9.998	1	0.00080	0.00280	0.00130
6	12.003	12	1	0.00065	0.00062	0.00043
7	12.004	9.998	1	0.00065	0.00068	0.00040
8	12.002	7.998	1	0.00069	0.00084	0.00060
9	11.998	5.998	1	0.00071	0.00140	0.00090
10	12	3.998	1	0.00079	0.00241	0.00230
11	11.996	1.999	1	0.00137	0.00364	0.00530

deformation leads to the appearance of displacement and breakage along the bedding planes.

Because the bedding planes fractures in the coal that incurred permanent damage is different in loading, the permeability recovering is quite different. Finally, the permeability evolution will be concluded as three typical paths, which is shown in Fig. 12.

In process of loading, permeability changes along the path from 1 → 2. On the contrary, the permeability changes along the path from 2 → 1 in process of unloading, which creates a reversible process of loading. This indicates that fractures or pores were kept unchanged in the sample and new fractures also did not appear as well. This sample should be regarded as elastic material, and an elastic model could be used to explain its behaviour. If, after unloading, the permeability changes along the path from 2 → 3, then the permeability during unloading is lower than that of the loading process. In this case, the sample has incurred damage, and the fractures and pores have changed. Such a sample should be classified as plastic, and a plastic model may be used to explain its behaviour. If, after unloading, permeability changes along the path from 2 → 4 when the stress is released to some value, then the permeability suddenly rises with stress releasing to the value that is greater than that of the loading process. This behaviour indicates that fractures and pores have changed and new fractures have developed, and a fracture model is required to explain the behaviour. Such behaviour can be described using a cube permeability model by McKee et al. (1988), in the case of paths 2 → 1 and 2 → 3. However, in the case of path 2 → 4, such a model is not applicable, thus a new explanatory model is needed to be established. Based on the above analysis, we have summarized these three typical paths as elastic permeability model, plastic permeability model and fracture permeability model.

4 Bedding structure effect of gas extraction in coal mining

Gas extraction is an important technology for controlling gas disaster in underground coal mining. Meanwhile, the bedding in coal seam serves as the primary pathway of gas flow and enrichment place. In China engineering practice of gas control in coal mining, the

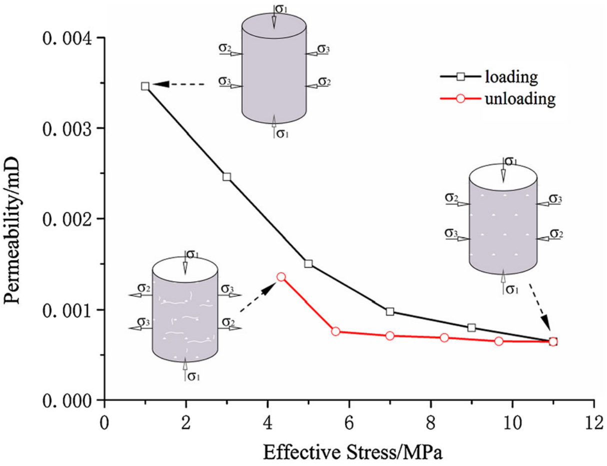

Fig. 7 Permeability–effective stress relationship perpendicular to bedding planes

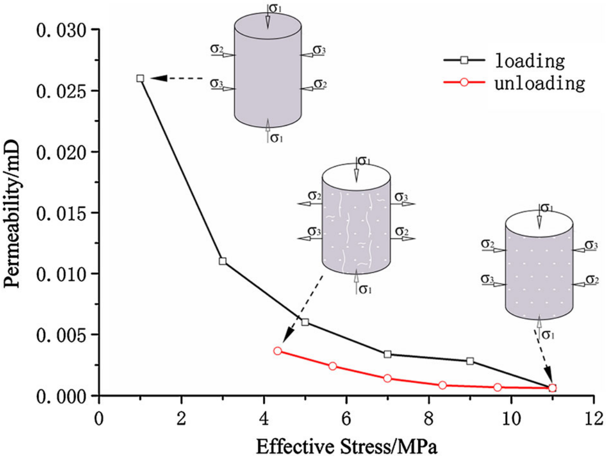

Fig. 8 Permeability–effective stress relationship parallel to bedding planes

boreholes drilled across coal seam and along coal seam for gas controlling has been used extensively. In this study, we applied the experimental results to working face 4401 in the Si-He coal mine. The bedding structure is clearly displayed and distributed widely in this coal seam. According to the experiment, the borehole is designed and shown in Figs. 13 and 14, the borehole perpendicular and parallel to coal seam bedding, respectively.

The hundred metres borehole of initial gas flow and the hundreds metres borehole of attenuation coefficient of gas flow, the average extraction flow and the total flow volume are taken as indexes for analysing the effects of gas extraction in the boreholes, as shown in Table 4. An average initial flow is 0.267 m^3/min in hundred metres of borehole, and it was measured in boreholes drilled 45° to the bedding planes. This value is 1.4 and 2.1 times bigger than that of the boreholes perpendicular and parallel to bedding, respectively. The minimum attenuation coefficient of gas flow in boreholes drilled 45° to bedding is 45 and 27 % lower than that of the other two boreholes. The average flow of extraction in the

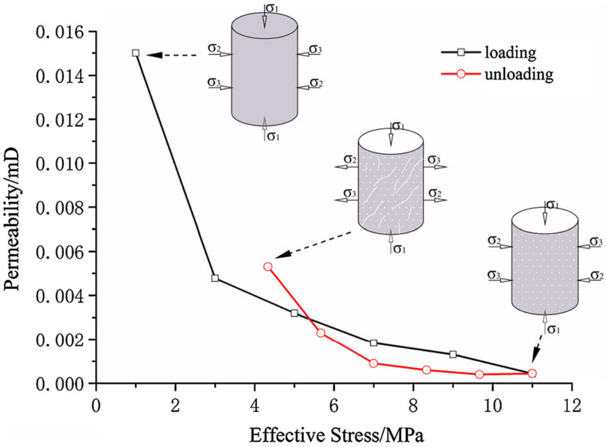

Fig. 9 Permeability–effective stress relationship oblique to bedding planes

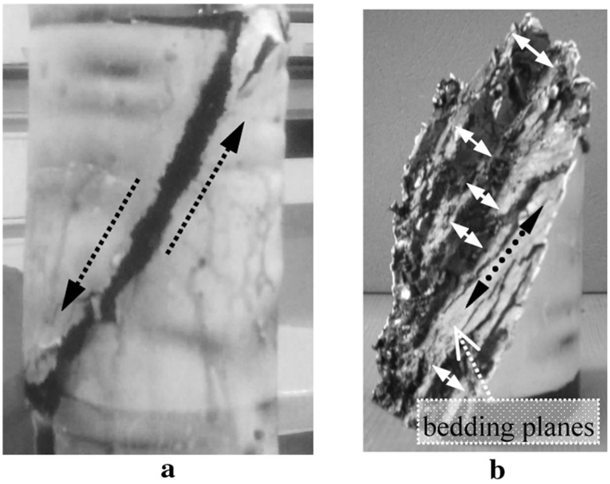

Fig. 10 Deformation in sample oriented 45° to bedding planes. **a** Broken of whole coal sample, **b** broken along bedding planes

boreholes is as follows: boreholes oblique to bedding > boreholes perpendicular to bedding > boreholes parallel to bedding. The total volume of gas extraction is also larger than that of the other boreholes. In the conditions of relatively stable gas extraction pressure, the rate of gas extraction is controlled by the initial flow of gas from the borehole and the attenuation coefficient. When the initial gas flow is larger, the attenuation coefficient of gas extraction is smaller, and the effect of gas extraction is better.

Therefore, effects of gas extraction is better from the boreholes drilled oblique and perpendicular to bedding than that from the boreholes drilled parallel to bedding, which matches with the results from the literature (Chen et al. 2003), and the experiment that the gas permeate easier when passing through along the bedding planes. During coal mining, bedding planes are easily broken through by the borehole wall as the drilled is cutting

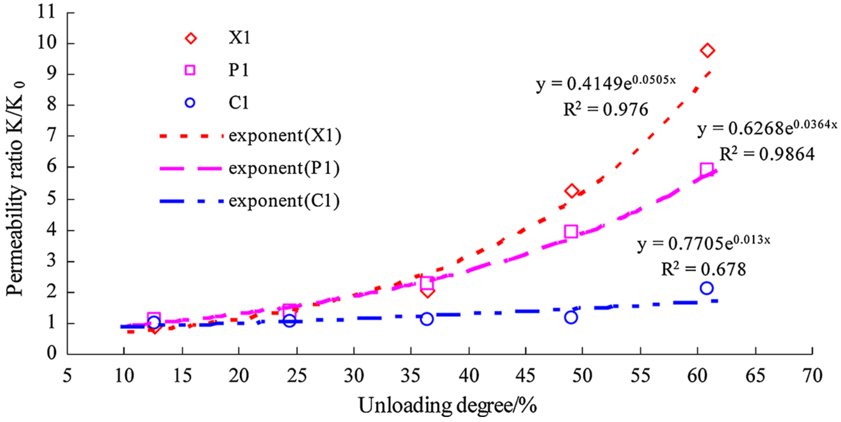

Fig. 11 Relationship between permeability and unloading rate in various orientations with respect to bedding planes

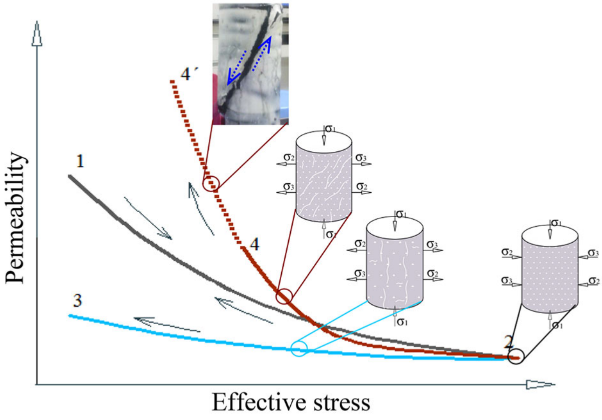

Fig. 12 Schematic diagram for permeability evolution path under loading

through the coal seam, and the borehole wall contact with bedding fractures in larger space, which have numerous intersections with the cut face. Then, gas is released from extensive areas of fracture surfaces. Ultimately, fractures form an extensive network of fracture–borehole intersections, and the gas flow through this network into the boreholes under extraction pressure. Thus, gas extraction is better as a result of this entire process.

According to the experimental results and project practice at site, when the boreholes are crossing the coal seam for gas extraction, gas flow has achieved better results along the bedding planes. In the case of borehole which is drilled parallel to bedding planes, gas seepage needs to pass through the coal bedding in order to enter into boreholes, and gas seepage is restrained, it turns out that the permeability and flow velocity are greatly decreased. Under such conditions, effects of gas extraction will not be ideal. Therefore, based on the results of experiment, the permeability of boreholes perpendicular to bedding is 2–10 times higher than that of boreholes parallel to bedding. It shows the fact that the gas flow smoothly from the bedding fractures to the boreholes, which also achieved good effects in engineering practice. Many coal mines in China use the method of drilling

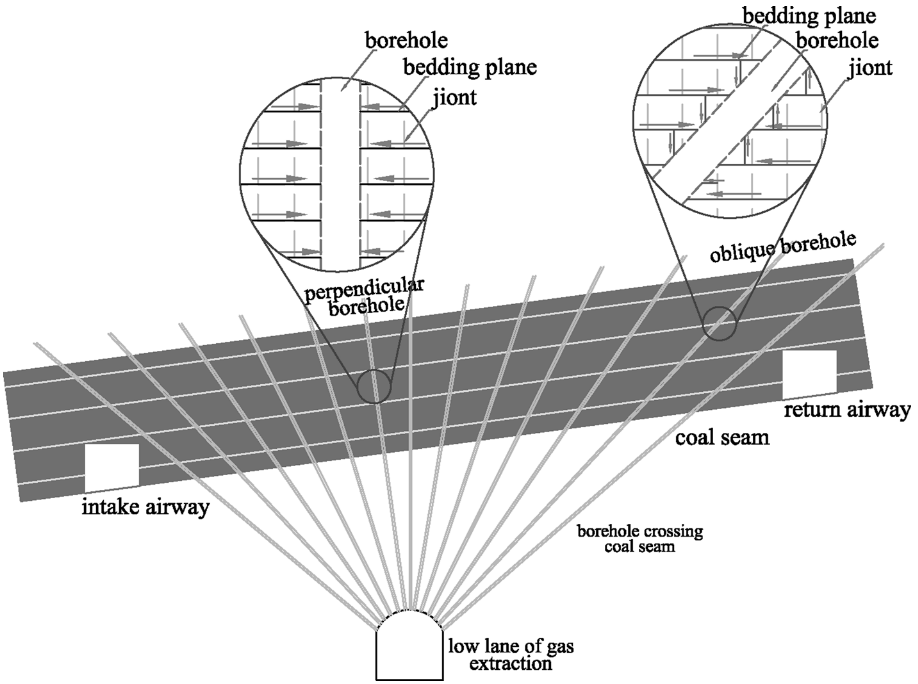

Fig. 13 Arrangement of boreholes crossing the coal seam

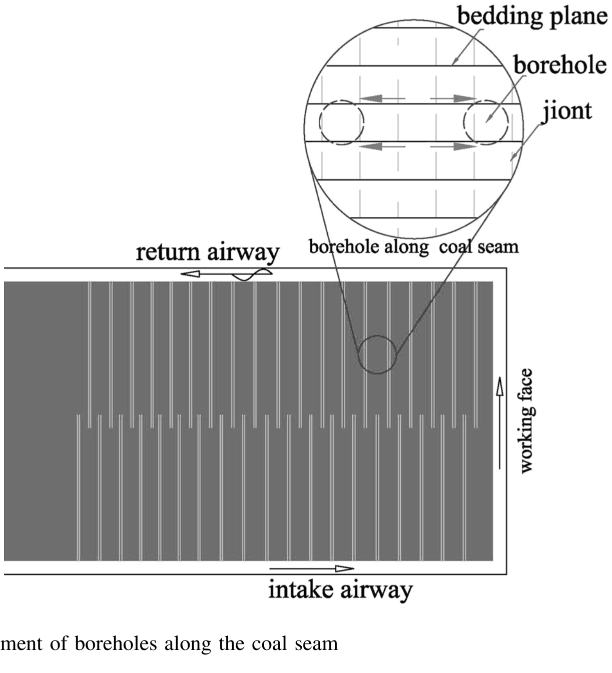

Fig. 14 Arrangement of boreholes along the coal seam

Table 4 Effect of gas extraction in various boreholes

Borehole characteristic	Initial flow of gas (m^3/min)	Attenuation coefficient	The average flow of extraction (m^3/min)	The total of gas extraction (m^3)
Borehole along to bedding planes	0.129	0.0136	0.072	9,250.7
Borehole perpendicular to bedding planes	0.185	0.0082	0.124	14,629.6
Borehole oblique to bedding planes	0.267	0.0037	0.180	17,382.5

boreholes through coal seam to control gas disaster. Many measures have been adopted, such as low-lane boreholes path through the coal seam for gas extraction, high-lane boreholes down through the coal seam for gas extraction and extensive fields of boreholes through the coal seam for gas extraction. All of these measures have been widely used in gas extraction, which have effectively controlled the gas disasters, and finally reaching the objective of reducing the amount of coal mining accidents.

5 Conclusions

The experiments were performed to study the variation in permeability along with various orientations with respect to bedding planes in the conditions of loading and unloading, and the objective was to optimize the effect of gas extraction according to the characteristics of the permeability. Based on the results obtained from the experiments, the following conclusions are drawn:

1. The permeability had a close relationship with bedding structure of coal seam. This study included a comparative analysis of three orientations of bedding planes, which indicated that the gas permeability in three directions with respect to bedding planes was quite different. The permeability of which the fluids conducting direction is parallel to bedding was the highest, followed by the permeability oblique to bedding and perpendicular to bedding, respectively, which showed that the gas seepage became much easier along the bedding planes than other orientation.
2. In the process of loading, the permeability of nature coal samples was approximately one order of magnitude at maximum in three different directions with respect to bedding planes, and the permeability decreases along with the increase in effective stress. In the process of unloading, the permeability increases along with the decrease in confining pressure. The unloading rate had greatly effect on the deformation sensitivity of the sample oblique to bedding planes. Under a certain extent of unloading, bedding fractures tended to open; when the unloading increased, new fractures led to a sudden increase in the permeability. Simultaneously, breakage developed along bedding, which indicated that the strength and stability of coal which was oblique to bedding were poor. Compared with the samples in other orientations, this sample was easier to deform, and the changes in pore structures, fractures and filling properties during structural deformation helped increase the permeability.
3. After comparing the permeability evolution process of the three coal samples, we have obtained three models of permeability evolution path, which are elastic permeability model, plastic permeability model and fracture permeability model.

4. The directionality of coal bedding led to the anisotropy of permeability, which also had a significant impact on the layout of gas extraction boreholes in coal mining. In this study, some parameters were used to compare the borehole extracting effects between drilling across bedding and drilling along bedding. Finally, due to the bedding structure of coal seam, a large area of fracture network of "boreholes–bedding fractures" is formed among boreholes through coal seam and bedding structure; the results showed that drilling across bedding planes for gas extraction achieved better effects, at last reduce gas release and gas disasters.

Acknowledgments This work was carried out with funding from the National Basic Research Development Program of China (Grant No. 2011CB201204); and National Natural Science Foundation of China (Grant Nos. 51304070, 51074160, U1361205, 51204173). The authors wish to thank these two organizations for the support provided. They also wish to thank there viewers and editors for their constructive comments and suggestions in improving the manuscript.

References

Berryman JG (2011) Mechanics of layered anisotropic poroelastic media with applications to effective stress for fluid permeability. Int J Eng Sci 49:122–139

Chen J, Qin Y, Song Q, Song Z (2003) Coupling relationship between direction of coalbed cleat and methane drainage effect and its prediction model. Zhongguo Kuangye Daxue Xuebao (J China Univ Min Technol) 32:223–226

Cheng Y, Fu J, Yu Q (2009) Development of gas extraction technology in coal mines of China. J Min Saf Eng 26:127–139

Connell LD, Lu M, Pan Z (2010) An analytical coal permeability model for tri-axial strain and stress conditions. Int J Coal Geol 84:103–114

Dawson G, Esterle J (2010) Controls on coal cleat spacing. Int J Coal Geol 82:213–218

Durucan S, Edwards JS (1986) The effects of stress and fracturing on permeability of coal. Min Sci Technol 3:205–216

Fu X, Li D, Qin Y (2002) Experimental research of influence of coal matrix shrinkage on permeability. J China Univ Min Technol 31:129–131

Gash BW, Volz RF, Potter G, Corgan JM (1992) The effects of cleat orientation and confining pressure on cleat porosity, permeability and relative permeability in coal. Paper 9321:17–21

Harpalani S (1985) Gas flow through stressed coal. California University, Berkeley

Huang X (2012) Experimental study on influence of structural anisotropy of coal upon gas permeability. Min Saf Environ Prot 39:1–3

Jasinge D, Ranjith PG, Choi SK (2011) Effects of effective stress changes on permeability of Latrobe Valley brown coal. Fuel 90:1292–1300

Karacan CÖ, Mitchell GD (2003) Behavior and effect of different coal microlithotypes during gas transport for carbon dioxide sequestration into coal seams. Int J Coal Geol 53:201–217

Koenig R, Stubbs P (1986) Interference testing of a coalbed methane reservoir. In: SPE unconventional gas technology symposium, Louisville, Kentucky

Korsnes R, Risnes R, Faldaas I, Norland T (2006) End effects on stress dependent permeability measurements. Tectonophysics 426:239–251

Kuila U, Dewhurst D, Siggins A, Raven M (2011) Stress anisotropy and velocity anisotropy in low porosity shale. Tectonophysics 503:34–44

Laubach S, Marrett R, Olson J, Scott A (1998) Characteristics and origins of coal cleat: a review. Int J Coal Geol 35:175–207

Law B (1993) The relationship between coal rank and cleat spacing: implications for the prediction of permeability in coal. In: Proceedings of the 1993 international coalbed methane symposium, University of ALabama, Twscaloosa, ALabma

Li H, Ogawa Y, Shimada S (2003) Mechanism of methane flow through sheared coals and its role on methane recovery. Fuel 82:1271–1279

Li H, Shimada S, Zhang M (2004) Anisotropy of gas permeability associated with cleat pattern in a coal seam of the Kushiro coalfield in Japan. Environ Geol 47:45–50

Li J, Liu D, Yao Y, Cai Y, Chen Y (2013) Evaluation and modeling of gas permeability changes in anthracite coals. Fuel 111:606–612

Liu S, Harpalani S, Pillalamarry M (2012) Laboratory measurement and modeling of coal permeability with continued methane production: part 2—modeling results. Fuel 94:117–124

Majewska Z, Majewski S, Ziętek J (2013) Swelling and acoustic emission behavior of unconfined and confined coal during sorption of CO_2. Int J Coal Geol 116–117:17–25

Mazumder S, Wolf KHAA, Elewaut K, Ephraim R (2006) Application of X-ray computed tomography for analyzing cleat spacing and cleat aperture in coal samples. Int J Coal Geol 68:205–222

McKee C, Bumb A, Koenig R (1988) Stress-dependent permeability and porosity of coal and other geologic formations. SPE Form Eval 3:81–91

Palmer I (2009) Permeability changes in coal: analytical modeling. Int J Coal Geol 77:119–126

Perera M, Ranjith P, Choi S (2013) Coal cleat permeability for gas movement under triaxial, non-zero lateral strain condition: a theoretical and experimental study. Fuel 109:389–399

Pomeroy C, Robinson DJ (1967) The effect of applied stresses on the permeability of a middle rank coal to water. Int J Rock Mech Min Sci Geomech Abstr. Elsevier, pp 329–343

Rose R, Foh S (1984) Liquid permeability of coal as a function of net stress. In: SPE unconventional gas recovery symposium, Pittsburgh, Pennsylvania

Ryan B, Branch NV (2002) Cleat development in some British Columbia coals. BC Minist Energy Mines 2003–2011

Somerton WH, Söylemezoḡlu IM, Dudley RC (1975) Effect of stress on permeability of coal. Int J Rock Mech Min Sci Geomech Abstr 12:129–145

Wang S, Elsworth D, Liu J (2011) Permeability evolution in fractured coal: the roles of fracture geometry and water-content. Int J Coal Geol 87:13–25

Yin S, Wang S (2006) Effect and mechanism of stresses on rock permeability at different scales. Sci China Ser D 49:714–723

Yu Y, Wang L, Li J (2008) Effect of impulse and bedding on impact toughness of coal. J Coal Sci Eng (China) 4:27–30

Yuan L, Qin Y, Cheng Y, Meng J, Shen J (2013) Scenario predication for medium–long term scale of coal mine methane drainage in China. J China Coal Soc 38:529–534

Zharikov A, Vitovtova V, Shmonov V, Grafchikov A (2003) Permeability of the rocks from the Kola superdeep borehole at high temperature and pressure: implication to fluid dynamics in the continental crust. Tectonophysics 370:177–191

Zhou J, Xian X, Jiang Y, Li X, Jiang D (2009) A permeability model considering the effective stress and coal matrix shrinking effect. J Southwest Pet Univ (Sci Technol Ed) 31:4–8