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A new effective method and new materials for high sealing performance of cross-measure CMM drainage boreholes

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ABSTRACT

This study focuses on improving the sealing performance of the cross-measure CMM (coal mine methane) drainage boreholes. The sealing of cross-measure CMM drainage boreholes is not only related to the gas emissions but also closely related to the CMM drainage efficiency and further affects the safety of the coal miners. However, the sealing performance of the traditional sealing method becomes increasingly poor with increasing mining depth. The three main shortcomings of the traditional sealing method were revealed based on the examination of the geomechanical factors and characteristics of the traditional sealing materials. To eliminate these shortcomings and obtain an effective sealing method, 10 groups of sealing materials were tested; an automatic grout pump and two types of rubber bottom subs were developed. Next, a new sealing method, which is characterized by performing grouting two or more times with high grouting pressure was developed and compared with the traditional sealing method in engineering. The cement grout with a cement-to-water ratio of 1:0.8 is a suitable sealing material from both engineering applicability and economic perspectives. The new sealing method has a better sealing performance of the cross-measure CMM drainage boreholes than that of the traditional sealing method based on the engineering test results.

1. Introduction

Sealing of boreholes and underground excavations has received a lot of engineering attentions in the past decades. The current engineering attentions mainly come from the industries of mine, petroleum, CBM (coal-bed methane), nuclear, construction, geotechnical and water well. The growing awareness of and sensitivity to environmental concerns of the engineering community as well as of the public at large has resulted in an increasing recognition of the fact that these geological penetrations may have an environmental impact (Fuenkajorn and Daemen, 1996). Sealing of CMM (coal mine methane) drainage boreholes is at an extreme situation because methane is not only a potentially valuable energy source but also a hazard in active coal mines (Flores, 1998). Degasing coal seams with drainage boreholes is an important method for mitigating this hazard, and the success of which is strongly influenced by the sealing performance.

With expanding economic development and the growing demand for energy, coal will remain the main energy source in China well into the future (Yuan, 2008). After 10 years of rapid development, the mining depths of some coal mines in central and east China now reach between 800 m and 1200 m, and the coal seams at the deep mining levels are characterized by high in-situ stress, high methane gas pressure and content, low strength and low permeability (Kang et al., 2010; Cheng et al., 2009). The sealing of drainage boreholes faces more difficulties in this increasingly extreme situation. Unlike the continuous tests of the sealing performance, which are difficult to perform in some other engineering activities, the sealing performance of drainage boreholes can be quantified by the methane concentration and the methane flux. According to an incomplete record, the methane concentrations of approximately 65% of the drainage boreholes in the coal face are less than 30% in Chinese coal mines, which is caused by the low sealing performance of CMM drainage boreholes (Zhao-feng, 2003; Cheng et al., 2006).

Recently, many researchers have made efforts to improve the sealing performance of drainage boreholes. Wang Zhaofeng

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reviewed and analyzed the major sealing method of CMM drainage boreholes in China (Wang and Wu, 2014). Zhou Fubao presented a new second borehole sealing method to improve the sealing performance of CMM drainage boreholes (Zhou et al., 2009, 2011). Zhai Cheng performed research on a new composite sealing material of CMM drainage boreholes and tested its sealing performance (Zhai et al., 2011, 2013). Li Guofa made a review of polyurethane used in the sealing of CMM drainage boreholes (Li et al., 2014). Fan Fuheng studied a new sealing device to improve the sealing performance of CMM drainage boreholes (Fan et al., 2013). Although there are some new sealing materials, such as expansive cement, expansion agent, high-water material, polymer and resin, that can eliminate one of the above-mentioned shortcomings, they have not been widely used in Chinese coal mines due to their high cost. Without a high sealing performance of CMM drainage boreholes, the concentration of the CMM is at a low level, resulting in inefficient degasing of the coal seams, thereby increasing the potential risk of an accident during coal mining. Most Chinese coal mines have no incentive to deal with low-concentration CMM, which is characterized by high difficulty in processing and low value (Cheng et al., 2008). The emission gas is also a source of pollution of the atmospheric environment.

There are many types of CMM drainage boreholes implemented in Chinese coal mines, including surface vertical well, inseam borehole and inclined cross-measure borehole. The use of inclined cross-measure boreholes in coal mines that are at high risk of coal and gas outburst dangers is the most important method to drain methane in China (Cheng et al., 2009, 2010a; Cheng and Yu, 2003). This study will focus on improving the sealing performance of inclined cross-measure CMM drainage boreholes. First, the geomechanical factors that affect the cross-measure CMM drainage borehole sealing and the shortcomings of the traditional sealing method are discussed. Second, the results of the tests of 10 groups of sealing materials conducted in a laboratory are presented. Next, a new sealing method and key sealing equipment including an automatic grout pump and two types of rubber bottom subs, is presented. Finally, the results of comparisons of the engineering performance between the new and the traditional sealing methods conducted in a coal mine in China are presented.

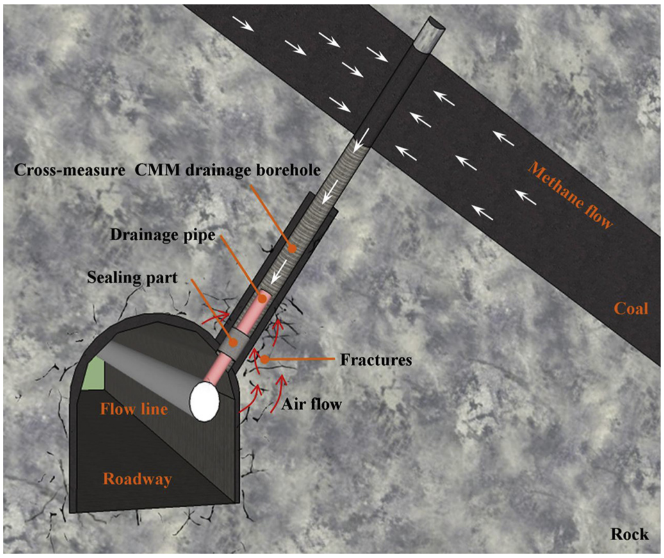

Fig. 1. Illustration of the CMM drainage via the inclined cross-measure borehole.

2. Geomechanical factors to be considered in cross-measure CMM drainage borehole sealing

As shown in Fig. 1, the cross-measure CMM drainage borehole is implemented in the roof (or floor) of the roadway. The execution cost of a cross-measure borehole is primarily determined by the cost of drilling the rock. The effect of the cross-measure CMM drainage boreholes on the CMM drainage is closely related to the sealing performance. A low sealing performance results in a low CMM drainage efficiency, leading to a waste of time and money.

The sealing performance is heavily influenced by the fracture distribution in the rock surrounding the roadway (Nong et al., 2009). The fracture distribution is mainly determined by its initial status and the in-situ stress condition (Wilson, 1983; Chang and Xie, 2009; Wan and Wang, 2013). The initial status of the fracture distribution is closely related to the geological conditions, and is mainly determined by the geological generated conditions and geological conformation movements. The underground rock is under triaxial stress condition at the initial state. Once the roadway is excavated, the stress state of the rock surrounding the roadway changes. The change from the tri-axial stress condition to the two-axial stress condition results in the breaking of the stress equilibrium (Liu et al., 2014; Liu and Lu, 2010). Fig. 2a shows the redistributed stress state of the rock surrounding the roadway, which is under hydrostatic pressure condition at the initial state. The hydrostatic pressure condition usually occurs in the deep mining level (Liu et al., 2014). The variables σ_r^p and σ_r^e denote the radial stress in the plastic state and in the elastic state, respectively. The variables σ_θ^p and σ_θ^e denote the tangential stress in the plastic state and in the elastic state, respectively. P_0 denotes the initial stress. r is the distance from the center of the roadway. The radial stress increases with increasing r and approaches the initial value. The tangential stress first increases and then decreases with increasing r, and it can be divided into four regions based on the comparison with the initial stress. In region I, the tangential stress is less than the initial stress, the rock in this region is in the residual strength state, and the fractures in the rock are fully extended, generated and connected, resulting in a high value of rock permeability, which is far greater than the initial permeability. In region II, the tangential stress is greater than the initial stress, and the rock is in the plastic state; the fractures are also extended and generated due to the effects of the compressive loading and unloading on the rock, but the connectivity is weaker than that of the fractures in region I. The rock permeability in region II is less than that in region I, but it is still greater than the initial permeability. In region III, the tangential stress is also greater than the initial stress, and the rock is in the elastic state; the fractures are mainly closed due to the effect of compressive loading on the rock. Therefore, the connectivity of the fractures is weaker than that of the initial fracture state, and the permeability is smaller than that of the initial state. The rock in region IV is hardly affected by the excavation of the roadway; therefore, the tangential stress, radial stress and permeability are almost equal to their initial values. The effective sealing of the fractures is the foundation to achieve a high sealing performance of cross-measure CMM drainage boreholes. Therefore, according to the fracture distribution characteristics of the rock surrounding the roadway, it can be concluded that the sealing length of a cross-measure CMM drainage borehole should be at least longer than the difference of R_p and r_a, where R_p is the plastic zone radius and r_a is the radius of the roadway, m.

The failure of the rock usually follows the Mohr–Coulomb criterion, which is one of the most commonly used failure criteria (Zhang et al., 2003). If the redistributed stress is greater than the yield stress of the rock surrounding the roadway, then further failure of the rock surrounding the roadway will occur. It is clear

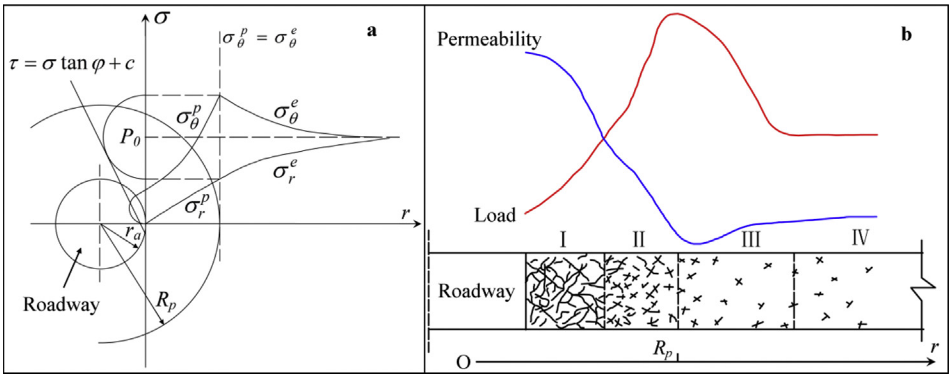

Fig. 2. Illustration of the elastic–plastic secondary stress and rock permeability distributions around a roadway.

that the rock surrounding the roadway is under the elastic–plastic redistributed stress condition based on the Mohr–Coulomb criterion. The plastic zone radius (R_p) can be calculated as follows (Yao et al., 2010; Wang et al., 2012a):

$$R_p = r_a \left[\frac{2}{\varepsilon+1} \frac{P_0(\varepsilon-1)+2c\sqrt{\varepsilon}}{P_i(\varepsilon-1)+2c\sqrt{\varepsilon}} \right]^{\frac{1}{(\varepsilon-1)}} \tag{1}$$

where ε is an intermediate variable, $\varepsilon = (1+sin\varphi)/\quad(1-sin\varphi)$. φ is the internal frictional angle, rad. c is the cohesion of rock, MPa. P_i denotes the braced pressure of the roadway, MPa. Many factors, including the rock strength characteristic, the in-situ stress, the braced pressure of the roadway and the radius of the roadway, influence the plastic zone distribution and its radius, and further influence the sealing performance of the cross-measure CMM drainage boreholes.

3. Traditional method and shortcomings

Fig. 3 shows the traditional sealing method of cross-measure CMM drainage boreholes that is widely used in Chinese coal mines (Cheng et al., 2010b; Wang et al., 2012b). Polyurethane and cement grout are the sealing materials. Polyurethane is set up and fixed at both ends of the sealing part, which is characterized by good expansibility, and then cement is injected into the middle of the sealing part. This sealing method has been successfully used at shallow mining depths in many Chinese coal mines because the advantages of both polyurethane and cement have been utilized. However, the performance of this sealing method becomes increasingly low with increasing mining depth in many Chinese coal mines. According to the status of the cross-measure CMM drainage borehole sealing engineering, the above-mentioned sealing method cannot meet the requirements of borehole sealing at the current mining depth any more (which now reaches between 800 m and 1200 m).

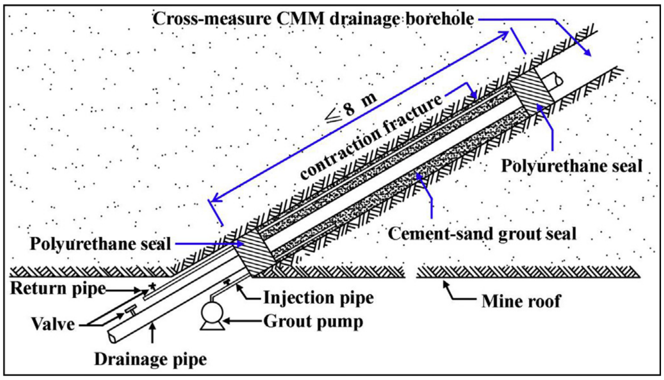

Fig. 3. Illustration of a CMM drainage borehole sealed by the traditional method.

The main shortcomings are as follows:

(1) Polyurethane is mainly sealed by the miners and is of low mechanization degree. The success of the polyurethane seal is closely related with the worker's proficiency; therefore, strong contingency exists. Due to the rapid chemical reaction of the polyurethane foam (within 4 min), the depth of polyurethane set up inlet in the borehole is usually shorter than 8 m, resulting in the sealing length being shorter than 8 m. However, the rock at the shallow levels is primarily in the elastic state and is characterized by stiffness and stability, while it is mostly in latent plastic or plastic state and is characterized by softness and stretchability at the deep mining level (Quansheng et al., 2004; He et al., 2005; Zhang et al., 2008). Based on the analysis in section 2, it can be concluded that the sealing length which is shorter than 8 m, may not meet the requirement of the cross-measure CMM drainage boreholes sealing at the deep mining level.

(2) The polyurethane seal at both ends of the sealing part is of low strength, and it cannot endure the required grouting pressure (Wang and Wu, 2014). The gravity of the cement primarily causes the cement to seep into the fractures in the rock surrounding the cross-measure CMM drainage boreholes. However, the cement is of low fluidity. The connected small fractures in the rock cannot be well sealed without suitable grouting pressure, even though the cross-measure CMM drainage borehole has a large dip angle. The sealing performance of the cross-measure CMM drainage borehole with a small dip angle is further reduced. Most of the fractures in the rock surrounding the cross-measure CMM drainage borehole cannot be well sealed using this traditional cross-measure CMM drainage borehole sealing method.

(3) The shrinkage of the cement paste with a cement-to-water ratio of 1:1 is significant after solidification. As a result, the cross-measure CMM drainage borehole wall and the sealing material easily separate, resulting in contraction fractures in the sealing part.

4. A new effective sealing method and materials

Determining whether a new sealing method and new materials can be accepted and widely used depends not only on the application effect but also on the economy and engineering applicability. The procedures of the new sealing technology to be implemented should be easy for the miners to learn. Based on these basic principles, a new sealing method and new sealing materials were developed and tested.

4.1. Laboratory performance of sealing materials

The shortcomings of the cement grout with a cement-to-water ratio of 1:1 and some new sealing materials were mentioned earlier. To find some better sealing materials without these shortcomings, the characteristics of the sealing materials that are typically used in Chinese coal mines will be tested: cement (P.O. 32.5), expansion agent (UEA-II) and expanding cement (JD-WFK-II). These sealing materials are mixed with water and divided into 10 groups based on the cement-to-water ratio. The shrinkage rate is one of the test items and evaluation indices because contraction fractures are caused by the shrinkage of the sealing material. The key point of the shrinkage tests of the ten groups of sealing materials is the accurate measurements of the initial volume and the solidification volume. Both The initial volumes and the solidification volumes can be easily obtained by reading the scale of the measuring cups. The underground openings (including roadway and cross-measure CMM drainage boreholes) face increasing numbers of stability problems because the in-situ stress increases with increasing mining depth (Kang et al., 2010; Liu et al., 2014; Liu and Lu, 2010). The deformation of the cross-measure CMM drainage borehole may lead to the damage of the sealing material; therefore, the uniaxial compressive strength, which is also a selected indicator of the sealing materials, was tested according to the ISRM Suggested Methods on rock mechanics tests (Ulusay and Hudson, 2007). The test results of the sealing materials are listed in Table 1. V_0 denotes the initial volume, L; V_s denotes the volume after solidification, L; Γ_s denotes the shrinkage rate, %; UCS denotes the uniaxial compressive strength, MPa.

The samples numbered No. 1, No. 2, No. 3, and No. 4 are composed of cement and water, and the cement-to-water ratios of the four samples are 1:0.8, 1:1, 1:1.2, and 1:15, respectively. The samples numbered No. 5, No. 6, No. 7, and No. 8 are composed of cement, expansion agent and water, and the mass ratios of the cement, expansion agent and water of the four samples are 1:0.1:0.8, 1:0.1:1, 1:0.1:1.2, and 1:0.1:15, respectively. The samples numbered No. 9 and No. 10 are composed of expanding cement and water, and the cement-to-water ratios of the two samples are 1:0.8 and 1:1, respectively. The maximum cement-to-water ratio is 1:0.8 because the liquidity of the cement grout is closely related to the cement-to-water ratio. A large cement-to-water ratio leads to high ropiness and low liquidly. When the cement-to-water ratio is higher than 1:0.8, the cement grout is not suitable to seal the small connected fractures, based on engineering experience.

For the sake of convenience, the test results (including Γs and UCS) of the 10 samples are presented in Fig. 4. The minimum shrinkage rate is 6.0%, which was measured in sample No. 9, and the maximum shrinkage rate is 41.4%, which was measured in sample No. 4. The shrinkage rates of samples No. 1 to No. 4 were found to be larger than those of samples No. 5 to No. 8 when the cement-to-water ratios are equal. The expansion agent played an important role in reducing the shrinkage rate of the cement grout. The shrinkage rates of the expanding cement are far lower than that of the cement. Moreover, the shrinkage rates of the samples increase with a decreasing cement-to-water ratio for all three groups of the samples composed of different sealing materials. The comparisons of the volumes of the samples with different cement-to-water ratios and sealing materials after solidification are illustrated in Fig. 5. The minimum uniaxial compressive strength is 2.89 MPa, which was measured for sample No. 8, and the maximum uniaxial compressive strength is 11.0 MPa, which was measured for sample No. 9. The uniaxial compressive strength of samples No. 1 to No. 4 is larger than those of samples No. 5 to No. 8 when the cement-to-water ratios are equal. The expansion agent causes the uniaxial compressive strength of the cement grout to decrease. The uniaxial compressive strength of the expanding cement is larger than that of the cement. The uniaxial compressive strength of the samples decreases with a decreasing cement-to-water ratio for all three groups of samples composed of different sealing materials. Therefore, based on the premise of guaranteeing the cement grout liquidity, the cement-to-water ratio should be as high as possible to reduce the shrinkage rate and to increase the UCS of the cement grout.

Based on the tests, the expanding cement with a cement-to-water ratio of 1:0.8 was found to have the lowest shrinkage rate and the largest UCS, and the expanding cement was found to be the best sealing material among the three groups of sealing materials. However, the price of expanding cement is 15 times the price of the cement under conditions of the same quality. In economic terms, the expanding cement is too expensive and is difficult to implement in Chinese coal mines. When the cement-to-water ratio is 1:0.8, the shrinkage rate and the UCS of cement are larger than those of the cement mixed expansion agent. However, the shrinkage rate of the cement can be decreased by performing

Table 1
Test results of 10 groups of sealing materials.

No	Sample components of sealing material/kg				V_0/L	V_s/L	Γ_s/%	UCS/ Mpa
	Cement	Expansion agent	Expanding cement	Water				
1	1.5	0	0	1.2	1.76	1.46	17.1	9.34
2	1.5	0	0	1.5	2.08	1.48	28.9	6.62
3	1.5	0	0	1.8	2.34	1.56	33.3	5.44
4	1.5	0	0	2.25	2.8	1.64	41.4	3.40
5	1.5	0.15	0	1.2	1.82	1.66	8.8	8.66
6	1.5	0.15	0	1.5	2.12	1.72	18.9	4.42
7	1.5	0.15	0	1.8	2.4	1.86	22.5	3.23
8	1.5	0.15	0	2.25	2.78	1.82	34.5	2.89
9	0	0	1.5	1.2	1.74	1.74	6.0	11.00
10	0	0	1.5	1.5	2.12	1.94	8.5	6.96

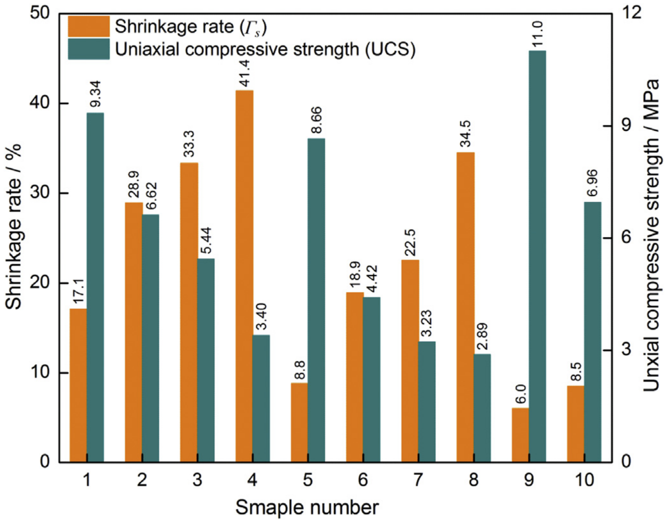

Fig. 4. Test results of the shrinkage rate and the UCS of 10 groups of sealing materials.

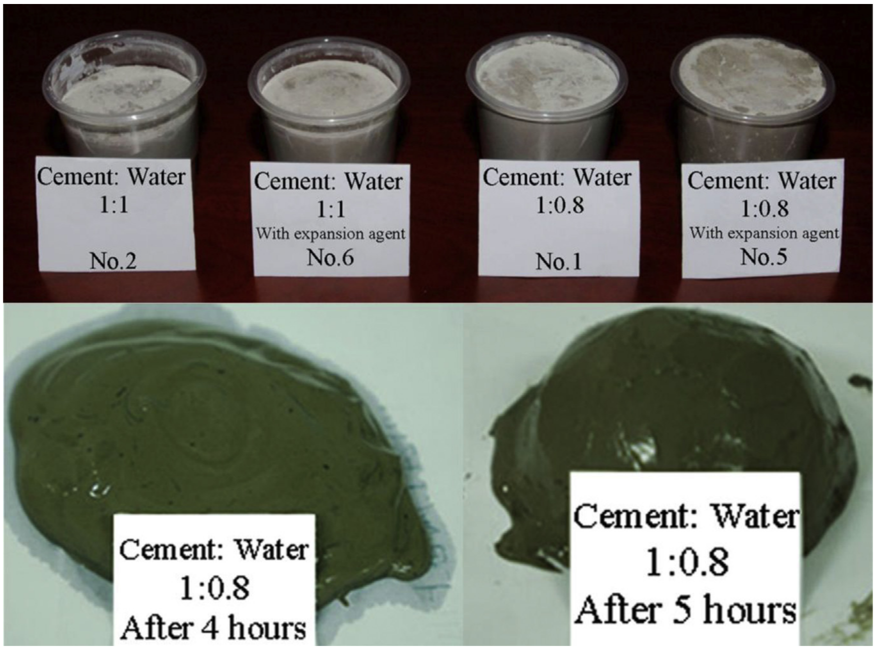

Fig. 5. Photographs of four types of cement grouts after solidification and the cement grout with a cement-to-water ratio of 1:0.8 during solidification.

grouting two or more times (the method will be discussed in section 4.2 in detail) and there is no environmental impact or additional cost with the use of an expansion agent. The UCS of the cement grout with a cement-to-water ratio of 1:0.8 is higher than that of many coals, and it can meet the strength requirement for the sealing materials. Overall, the cement grout with a cement-to-water ratio of 1:0.8 is the most suitable sealing material among the 10 groups of sealing materials considered, from both the engineering applicability and the economic perspectives.

The variation with time of the volume of the cement grout with a cement-to-water ratio of 1:0.8 was also tested. The test results indicate that the shrinkage of the cement grout after 2 h of solidification is almost equal to that of the cement grout after 24 h of solidification. As shown in Fig. 5, the cement grout enters the solidified state after 5 h of solidification. The characteristic of the volume variation with time is closely related to the grouting procedures, which will be discussed in section 4.2 in detail.

4.2. The new effective sealing method and equipment

The following section will focus on the new sealing method and the required equipment. To eliminate the main shortcomings of the traditional sealing method, the new sealing method should be improved regarding the following aspects:

(1) New material or equipment should be developed for the bottom sub to replace polyurethane. The new material or equipment should be easily set up in the cross-measure CMM drainage borehole and satisfy the requirement of the sealing length.
(2) Suitable grouting pressure other than that provided by only the use of gravity is required to ensure improved sealing of the fractures in the rock surrounding the cross-measure CMM drainage borehole. Thus, the bottom sub should be able to withstand a certain grouting pressure.
(3) The shrinkage rate of the cement grout with a cement-to-water ratio of 1:0.8 is 17.1%; as a result, there are still many risks of generating contraction fractures with performing grouting only one time. Performing grouting two or more times is required.
(4) The procedures of the new sealing method should be easy for the miners to learn, and mechanization should be improved to balance out the increased work caused by performing grouting two or more times.

As shown in Fig. 6, the new effective sealing method and equipment are developed based on the above-mentioned basic principles.

First, the key sealing equipment, including an automatic grout pump and two types of bottom subs, are introduced.

(1) There are two types of rubber bottom subs that are used at the bottom end and the top end. The rubber hose of the two bottom subs is 50 cm in length, with a diameter that is 8 cm before expansion and 13 cm after expansion. Generally, the diameter of the cross-measure CMM drainage borehole in most Chinese coal mines is 9.6 cm. The dimensions of the two types of rubber bottom subs are suitable for operation in this cross-measure CMM drainage borehole. The two types of rubber bottom subs function in the same manner: when liquid is injected through the inlet of the rubber bottom sub, the safety valve operates and the liquid is injected into the rubber hose through a one-way valve, which ensures that the liquid cannot outflow from the rubber hose; with continued injection of the liquid, the liquid pressure in the rubber hose increases, and when the internal liquid pressure is greater than 3 MPa, the safety valve breaks and the liquid can flow out through the outlet into the borehole. The internal liquid pressure is measured by the pressure gauge installed on the grout pump. The rubber bottom subs can endure at least 4 MPa of grouting pressure, and the rubber hose can endure at least 6 MPa of internal liquid pressure. The airtightness of the rubber hose is very good; the internal liquid pressure remained constant over 15 days of observations in the laboratory. The bottom subs can be easily connected to the

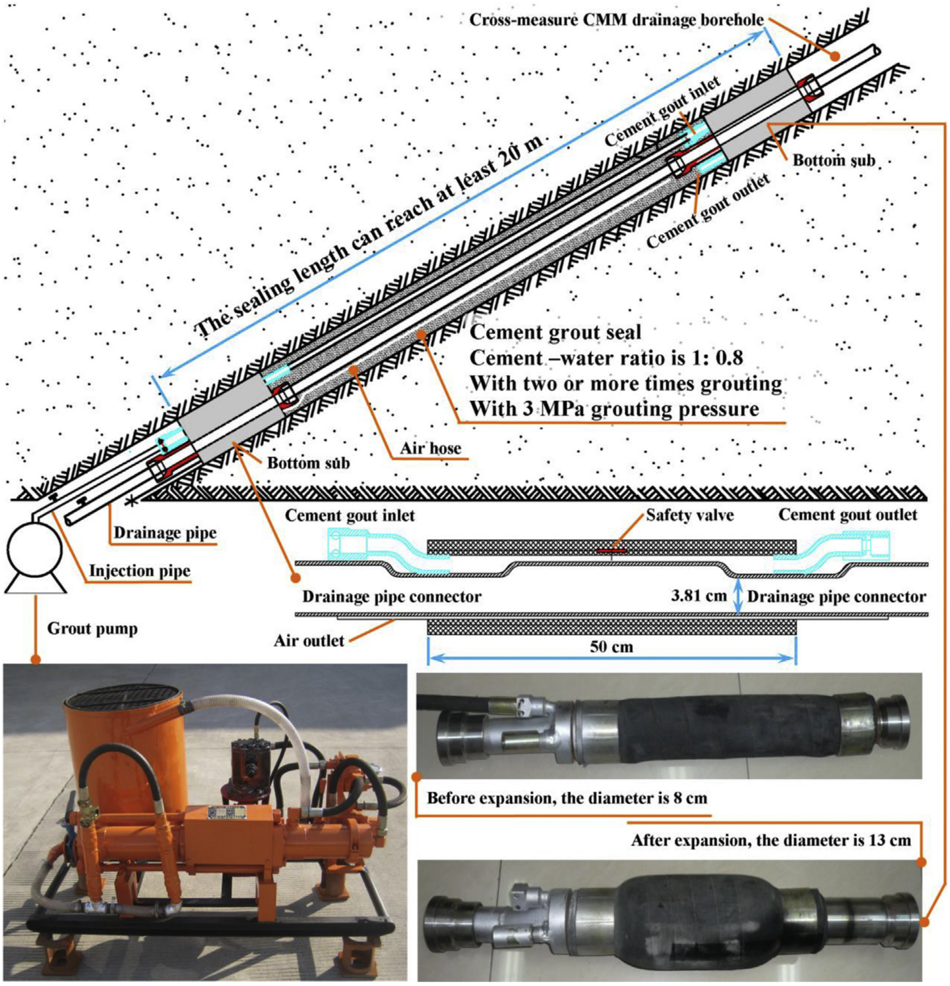

Fig. 6. Illustration of a CMM drainage borehole sealed by the new method and equipment.

drainage pipe and the injection pipe because all of the connectors are of the fast connector type.

(2) An automatic grout pump with a high degree of automation was developed to balance out the increased labor intensity of the miners using the proposed approach. The automatic grout pump integrates both blender and grout pump; as a result, it has both the mixing function and the grouting function. By introducing the cement and water into the blender in proportion, the machine can automatically mix them without artificial mixing. The cement grout, after being mixed uniformly, can be directly grouted into the borehole by the grout pump without an extra transfer. These automated operations greatly reduce the labor intensity of the miners. The hydraulic power of the drilling machine (ZDY series [33]) is the power source of the grout pump; thus, it can be safely used in the coal mines without using electricity. The automatic grout pump can provide a maximum of 6 MPa of grouting pressure, which can be measured by the pressure gauge installed on the grout pump. The automatic grout pump is easy to use because it is only half the weight of the electric grout pump of equal grouting ability. Again, all of the connectors in the automatic grout pump are of the fast connector type, which can be easily connected to the injection pipe and the drilling machine.

After the introduction of the key equipment, the following section will focus on the sealing procedures and the technology to perform grouting two or more times with high grouting pressure. The sealing procedures and the related critical values are gradually improved in the sealing engineering, and optimal ones are determined as follows:

(1) Design the sealing parameters (including the sealing length, the length of the injection pipe inside the borehole and the approximate cement amount) based on the geological conditions of the working location and the characteristics of the cross-measure CMM drainage borehole.
(2) Connect the rubber bottom sub, which is used at the top end with the drainage pipe and the injection pipe. Fix the air hose on the drainage pipe. Place the rubber bottom sub and the connected pipes into the borehole, and then carefully load the rubber bottom sub to the target depth using the drainage pipe. At the same time, connect the automatic grout pump with the drilling machine and prepare a certain amount of cement and water based on the design. Mix the cement and water with a mass ratio of 1:0.8 in the blender.
(3) Stop loading the rubber bottom sub at the location of 1 m in front of the target depth. Connect the drainage pipe, injection pipe, air hose and automatic grout pump with the rubber bottom sub, which is used at the bottom end. Then, load the two rubber bottom subs to the target depth.

(4) Inject the cement grout into the rubber bottom sub, which is used at the bottom end; when the grouting pressure is higher than 3 MPa, the expansion of this bottom sub is completed. Next, the cement grout flows through this bottom sub into the other bottom sub, which is used at the top end; again, when the grouting pressure is higher than 3 MPa, the expansion of this bottom sub is completed. At this point, the two bottom subs, which can endure high grouting pressure, are fixed in the cross-measure CMM drainage borehole.
(5) Continually inject the cement grout into the borehole between the two bottom subs, and then stop the first grouting process when the cement grout flows out from the air hose. Close the valves on the injection pipe and the air hose and wait for 2 h; the interval time is obtained based on the characteristic of the cement grout variation with time.
(6) Open the valve on the injection pipe and conduct the second grouting process. Stop the grouting when the grouting pressure reaches 3 MPa. If a long time or a large amount of cement grout is required for the grouting pressure to reach 3 MPa, then conduct the third grouting process. Repeat this judgment to determine whether to conduct the grouting process again. The interval time of 1 h is suitable for performing the grouting after the second grouting process, and all of the grouting should be completed within 5 h from the beginning of the first grouting process.

It is clear that the first grouting process is conducted without a required grouting pressure. The effect of the first grouting process is to seal the major fractures in the rock surrounding the borehole and to fill the borehole between the two bottom subs. At the same time, the first grouting process is performed to keep the fractures from extending without a high grouting pressure. The second and additional grouting processes with a grouting pressure of 3 MPa are performed to seal the contraction fractures induced by the shrinkage of the cement grout and to seal the minor fractures in the rock surrounding the borehole. The grouting pressure will not induce a wide range of fracture extension due to the resistance of the cement.

5. Engineering performance of the new sealing method

To check the engineering performance of the new sealing method, the sealing of 600 inclined cross-measure boreholes was conducted in the Panbei coal mine, Huainan coalfield, China. As shown in Fig. 7, the experimental site is located in the 1131(3) gas drainage roadway, and the inclined cross-measure boreholes were drilled for drainage of the methane of the No. 1131(3) working face. The mining depth of the No. 1131(3) working face is between 500 m and 660 m. The No. 1131(3) working face is 1350 m in length and 150 m in width. The average thickness of the coal seam of the No. 1131(3) working face is 5.0 m. The gas pressure and gas content are 0.4 MPa and 6.2 m^3/t, respectively. The inclined cross-measure borehole was between 30 m and 40 m in length and 96 mm in diameter. The space between the inclined cross-measure boreholes was 10 m × 5 m, which can be measured at the bottom of the boreholes.

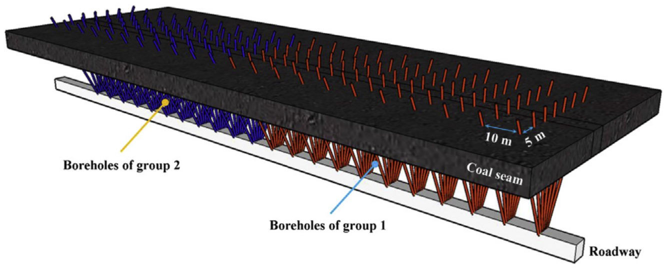

Fig. 7. Schematic view of the two groups of CMM drainage boreholes.

All of the 600 boreholes were divided into two groups, i.e., group 1 and group 2. The 300 boreholes in group 1 were sealed by the traditional method and materials, with the sealing length ranging between 6 m and 8 m. The 300 boreholes in group 2 were sealed by the new method and materials, and the sealing length was 16 m. The boreholes in group 1 connected to two drainage pumps, but the drainage pressure can only reach approximately 13 kPa. The boreholes in group 2 connected to only one drainage pump, and the drainage pressure can reach approximately 35 kPa. All three drainage pumps are the same. The differences between the drainage pressures of group 1 and group 2 were induced by the sealing performance; a high sealing performance leads to a high drainage pressure, and a low sealing performance leads to a low drainage pressure.

For further comparison between the new sealing method and the traditional sealing method, a comparison of the statistics of the methane concentrations and the methane fluxes of group 1 and group 2 was also performed. The methane concentrations of four CMM drainage boreholes are illustrated in Fig. 8. The No. 1-100 and No. 1-200 boreholes were randomly selected from group 1, and the other two boreholes were randomly selected from group 2. It is clear that the methane concentrations of the boreholes selected from group 2 are significantly higher than those of the boreholes selected from group 1. At the beginning of the drainage, the methane concentrations of all the No. 2-100 and No. 2-100 boreholes approach 100%; however, the methane concentrations of the other two boreholes are only approximately 40% and 50%. The methane concentrations of all of the No. 1-100 and No. 1-100 boreholes decrease more quickly than those of the other two boreholes. The methane concentrations of all of the No. 1-100 and No. 1-100 boreholes decrease below 30% after drainage for 16 days and decrease to approximately 2% after drainage for 45 days. The methane concentrations of all of the No. 1-100 and No. 1-100 boreholes decrease more slowly; after drainage for 60 days, the

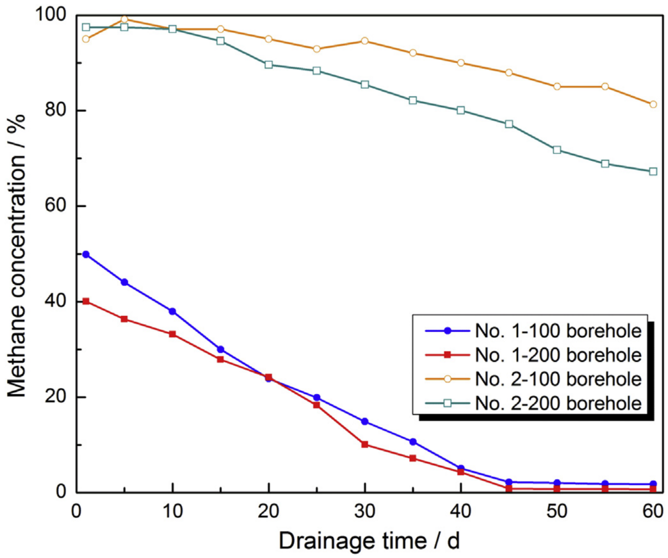

Fig. 8. Comparisons of the methane concentration among the four CMM drainage boreholes.

methane concentration of the No. 2-100 borehole is still higher than 80%, and the methane concentration of the No. 2-200 borehole is still higher than 70%.

The methane concentrations and methane fluxes of the two groups of boreholes are illustrated in Fig. 9. First, it is clear that both the methane concentration and methane flux of group 2 are significantly higher than those of group 1. The maximum methane concentration of group 1 measured when the drainage proceeded for 10 days is approximately 33%, which is approximately 82% of the concentration measured when the drainage proceeded for 25 days for group 2. The methane concentration of group 1 decreases very rapidly with time and decreases below 15% after drainage for 30 days and approaches 2% after drainage for 50 days. On the contrary, the methane concentration of group 2 decreases slowly with time; the concentration remains higher than 55% after drainage for 60 days. Moreover, the methane concentration of group 2 is higher than 60% during most of the measurement period. It can be concluded that a large amount of air in the roadway will be drained into the CMM drainage boreholes without a high sealing performance. The maximum methane flux of group 1 is approximately 1.3 m^3/min, measured after drainage for 30 days, which is approximately 2.5 m^3/min, measured after drainage for 25 days for group 2. The average methane flux of group 2 is approximately 2.3 m^3/min, which is approximately 2.5 times that of group 1 (the average methane flux of group 1 is approximately 0.9 m^3/min). The sealing performance of the CMM drainage boreholes not only affects the methane concentration but also affects the CMM drainage efficiency. In summary, it can be concluded that the sealing performance of the new sealing method is significantly higher than that of the traditional sealing method, based on comparisons of the drainage pressures, methane concentrations and methane fluxes of the group 1 and group 2 boreholes.

6. Conclusions

In this study, a new sealing method and new materials for cross-measure CMM drainage borehole sealing were developed. The geomechanical factors that affect the cross-measure CMM drainage borehole sealing were discussed; in addition, discussions of the shortcomings of the traditional sealing materials were presented, and the three main shortcomings of the traditional sealing technology were identified. Next, 10 groups of sealing materials were tested, and four basic principles of an effective sealing method were proposed. Finally, the key sealing equipment, including the grout pump and the two types of bottom subs, and the new sealing method were proposed. Moreover, the new sealing method was also tested by comparing the performance with that of the traditional sealing method in the Panbei coal mine. Based on the work completed, the following conclusions are made:

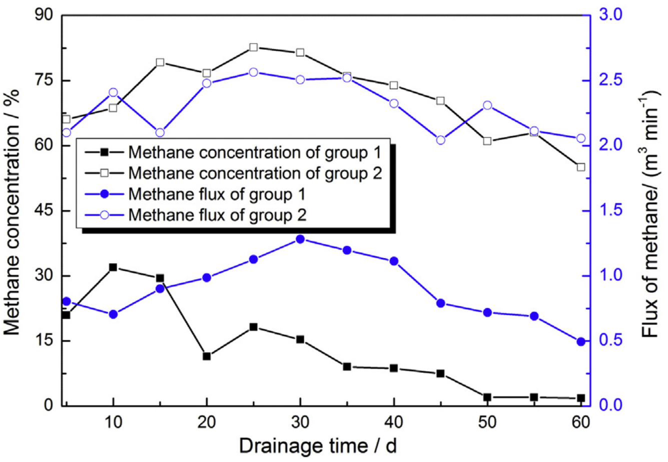

Fig. 9. Comparisons of the methane concentration and flux between the two groups of CMM drainage boreholes.

(1) The effective sealing of the fractures in the rock surrounding the cross-measure CMM drainage borehole is the foundation for high sealing performance. Based on the distribution characteristics of the fractures in the rock surrounding the roadway, the sealing length of a cross-measure CMM drainage borehole should be at least longer than the difference between R_p and r_a.

(2) There are three main shortcomings of the traditional sealing method: short sealing length, poor sealing performance of fractures with low grouting pressure and contraction fractures induced by large shrinkage of cement grout with a cement-to-water ratio of 1:1.

(3) The cement grout with a cement-to-water ratio of 1:0.8 is the most suitable sealing material among the 10 tested sealing materials from both the engineering applicability and the economic perspectives. The shrinkage rate and the UCS of this cement grout are 17.1% and 9.34 MPa, respectively.

(4) The new sealing method is characterized by performing grouting two or more times with high grouting pressure. The high grouting pressure was realized by using the two types of rubber bottom subs, which can endure at least 4 MPa of grouting pressure. The new sealing method has a significantly better sealing performance of the cross-measure CMM drainage boreholes than that of the traditional sealing method, based on engineering test results. With the new sealing method, the CMM drainage performance will be more efficient and result in a high concentration of methane. The new sealing method and the sealing materials are effective for providing high sealing performance of cross-measure CMM drainage boreholes and can be widely used in coal mines.

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