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Effect of silica sol on the sealing mechanism of a coalbed methane reservoir: New insights into enhancing the methane concentration and utilization rate

Congmeng Hao[a,b,c], Yuanping Cheng[a,b,c,*], Jun Dong[a,b,c], Hongyong Liu[a,b,c], Zhaonan Jiang[a,b,c], Qingyi Tu[a,b,c]

[a] Key Laboratory of Coal Methane and Fire Control, Ministry of Education, China University of Mining and Technology, Xuzhou, Jiangsu 221116, China
[b] National Engineering Research Center for Coal Gas Control, China University of Mining and Technology, Xuzhou, Jiangsu 221116, China
[c] School of Safety Engineering, China University of Mining and Technology, Xuzhou, Jiangsu 221116, China

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ABSTRACT

The low efficiency of coalbed methane (CBM) extraction not only causes a great waste of energy resources and environmental pollution but also poses potential safety risks during coal mining. The main reasons for these issues are the weak borehole sealing effect and serious air leakage that occur during CBM extraction. Seeking an effective sealing material is the key to improve the efficiency of CBM extraction and to protect the environment. In this paper, to explore ways to break through this bottleneck, the feasibility of silica sol (S.G325) as a sealing material for the boreholes used in CBM extraction was theoretically demonstrated. Scanning electron microscopy (SEM) was used to compare the surface morphological characteristics of S.G325 and some commonly used sealing materials. The performance of these materials after sealing the pores/fractures in the methane reservoir was also evaluated using mercury intrusion, an helium porosimeter and methane seepage tests. The experimental results indicate that S.G325 has obvious advantages over other materials because of its greater compactness, stability and performance after sealing. Evaluation of the effects of enhancing CBM extraction showed that S.G325 increased the initial concentration of CBM from 60% to 73.5%–82.9%, the amount of time the CBM that can be utilized from 54 d to 99 d - 132 d, the volume of utilizable CBM from 3421 m^3 to 4951 m^3 - 5773 m^3, and the utilization rate of CBM increased by 44.7%–62.8% compared with the original utilizable methane volume. In this paper, new insights into the improvement of energy resource utilization and protection of the environment are shown.

1. Introduction

As a byproduct of coal, coalbed methane (CBM) is a clean and high-efficiency fuel. The energy released in the combustion of 1 m^3 of methane is 35.9 million Joules, which is equivalent to the combustion of 1.2 kg of standard coal (Karacan, 2013). On the other hand, gas disasters are one of the most serious disasters that can occur. China is a big coal-producing country that has experienced the worst gas disasters (Tu et al., 2016). High gassy seams make up 50%–70% of Chinese coal mines. At present, the coal mines extend downward at a mining rate of 10–20 m per year. With increased mining depth, the gas content and pressure in seams increase gradually, which makes coal mine gas accidents more likely to occur (Li et al., 2013; Pan et al., 2014). Emitted methane is a greenhouse gas and an environmental pollutant (Yuan et al., 2017). CBM drainage is the most direct and effective measure for controlling gas disasters, and is also an effective way to make full use of energy resources and reduce pollution (Cheng et al., 2009). Therefore, extraction and utilization of CBM is an important measure of the "three major benefits" of "safety, energy savings and environmental protection". In 2016, China drained 17.3 billion cubic meters (bm^3) of CBM, and the amount utilized was only 9.0 bm^3, which is a utilization rate of merely 52.0%. In addition, 12.8 bm^3 of CBM was drained from the underground coal mine, accounting for 74% of the total drained CBM, but the utilization amount was only 4.8 bm^3, which is a utilization rate of only 37.5%; this means that 8.0 bm^3 of the methane drained from the underground was released into the atmosphere and caused a serious waste of resources (Shao, 2017). In addition, the released CBM was equivalent to the greenhouse effect caused by approximately 80 bm^3 of carbon dioxide, which resulted in serious environmental pollution (Cheng et al., 2011). The fundamental reason for the low utilization rate of underground CBM drainage is that the methane concentration is extremely low, especially during the late period of CBM extraction. Thus, a high amount of low-concentration CBM was released into the atmosphere because it is difficult or not economical to utilize (Xia et al.,

* Corresponding author. National Engineering Research Center for Coal and Gas Control, China University of Mining and Technology, Xuzhou, Jiangsu 221116, China.
E-mail address: ypcheng@cumt.edu.cn (Y. Cheng).

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2014). Increasing the concentration of CBM during extraction is the key to solving the low utilization rate.

Studies have shown that the low concentration of underground CBM drainage is mainly due to the poor performance of seals in boreholes, resulting in considerable air flow into the boreholes (Gao et al., 2015; Zhou et al., 2016a). According to an incomplete record, in China, a CBM extraction concentration of more than 80% of the bedding boreholes will attenuate to 6%–20% in a short time, with an average extraction rate of CBM of less than 23% (Andrzej and Olajossy, 2017; Xia et al., 2014). With an increasing methane extraction time, the volume of methane that flows into the borehole decreases, and the volume of air leakage increases. Thus, the concentration of the CBM attenuates rapidly over time, and improving the performance of seals in drainage boreholes is the key to improving the gas concentration and utilization rate (Hu et al., 2012; Wang et al., 2015).

Whether the concentration can be kept at an ideal level in the methane extraction process depends on whether the sealing material can fill the macrofractures and microfractures well around the borehole to achieve good anti-seepage (Zheng et al., 2016). At present, the commonly used sealing materials are polyurethane and cement-based materials. The former is convenient to use but has a pungent smell, and its liquidity and permeability are poor. Polyurethane can only fill the macrocracks near the borehole wall, which is unsatisfactory for methane extraction. The cement-based material has better liquidity and support capacity, but its minimum groutability width is over 0.1 mm. The large amount of unfilled microfractures are the main causes of the significant decrease in the concentration of CBM (Kuang et al., 2001; Zheng et al., 2016). Many researchers have done much work on traditional sealing technology and sealing materials to improve the sealing performance of drainage boreholes. Liu presented a new sealing method and associated sealing equipment and determined a new cement slurry water-cement ratio (Liu et al., 2014). Zhang developed a “strong-weak-strong" high-pressure sealing technology to improve the performance of the bedding drainage borehole (Zhang et al., 2013). Because the traditional materials cannot adapt to borehole deformation, Xiang proposed a flexible gel sealing material and associated a novel active sealing method (Xiang et al., 2015). Considering the difficulty in blocking the microfractures around the boreholes, Zhou used powder particles to conduct secondary sealing for methane extraction boreholes (Zhou et al., 2009).

In general, the large particle size of cement-based materials limits its sealing effect for microfractures, and the flexible polymer material has a weak mobility in that the sealing ability is limited. Although the powder particles can be deposited along the air flow in the air leakage channel to achieve the effect of increasing resistance, this is a passive and random blocking method and is still invalid for microfractures. Some scholars have suggested that the mucous seal can be a good way to block microfractures, but keeping it in the fractures for a long time is still a difficult engineering problem (Li et al., 2017; Xiang et al., 2015). Therefore, it is significant to seek a high-efficiency material to block the microfractures around the borehole.

Silica sol is an environmentally friendly, nanoscale grout with a good sealing ability for microfractures. Some studies have shown that the silica sol can penetrate well into tiny pores and fractures (Axelsson, 2004; Funehag, 2004, 2005; 2007; Funehag and Gustafson, 2008). In recent decades, the use of silica sol in geotechnical fields has gradually been increasing in Sweden, the United States, South Korea, Japan, China and other countries. Persoff investigated the use of silica sol to build a barrier to block the flow of pollutants in soil (Persoff et al., 1996). McCartney designed a secondary containment system using silica sol to prevent oil leakage (Mccartney et al., 2011). Saito proposed that silica sol could be used to maintain the stability of gravel-sized soil during shield tunneling (Saito, 1999). Pan has studied the modification of coal mudstones by silica sol (Pan et al., 2016). J. Funehag studied the penetration length of silica sol as a Newtonian fluid under certain grouting pressure conditions (Funehag and Fransson, 2006; Funehag and Gustafson, 2008).

At present, there is no research on the application of silica sol in the field of CBM extraction. As a new groutability material, silica sol has great potential for sealing microfractures. Based on the understanding of the good permeability of silica sol and the current situation of CBM drainage borehole sealing, we attempted to evaluate the efficiency of applying the silica sol to seal microfractures around the borehole to improve the quality of CBM extraction. To investigate the sealing performance of silica sol on microfractures in coal, we mainly study the characteristics of silica sol and its ability to plug the pores/fractures in coal and to predict the extraction effect. In addition, we also provide a scientific basis for its popularized application in the field of CBM extraction.

The particle size, viscosity and rheology characteristics of silica sol were investigated, showing that it is an effective sealing material. Additionally, we studied the effect of the sealing performance of silica sol on coal pores/fractures. Based on the relationships of methane extraction and air leakage, the effect of silica sol on methane extraction was also evaluated. The validity of silica sol provides a scientific basis for popularizing its application in the field of CBM extraction.

2. Theoretical feasibility of sealing of silica sol

2.1. The particle size and viscosity of silica sol

The silica sol, known as S.G325 in this paper, is a milky, white sol solution formed by amorphous SiO_2 aggregated particles dispersing in water, without any unpleasant smell. Its molecular formula can be expressed as $mSiO_2{\cdot}nH_2O$, and the size of the colloidal particles is in the range of 1–100 nm. There are many methods used to prepare silica sol, such as the ion exchange method, silane hydrolysis method, silicon dioxide powder solution separation by one-step hydrolysis, etc. (Gilliland et al., 2005; Iler, 1972). Under the action of the catalyst, the viscosity of S.G325 gradually increases and finally forms a solid, and this process is called gelling (Fig. 1). The saline solution can be used as the catalyst to accelerate silica sol gelling. The gelling time can be

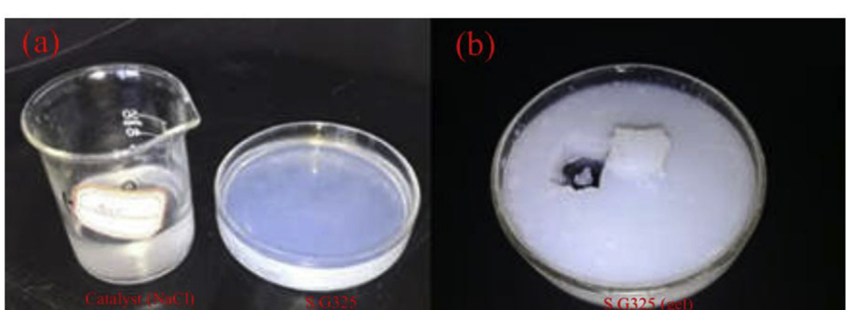

Fig. 1. Photographs of real situation: (a) S.G325 and catalyst before reaction; and (b) S.G325 became gel under the action of catalyst.

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