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Experimental study on permeability stress sensitivity of reconstituted granular coal with different lithotypes

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ABSTRACT

Coal permeability has been identified as one of the key factors affecting coalbed methane (CBM) extraction. CBM drainage and hydraulic fracturing usually lead to coal fines output. Some of these coal fines passed through wellbore discharged of coal bed, and some of them were compacted in fractures during the closing of fractures (or cleats) under the confining pressure. The pore distribution and seepage path of those compacted coal fines are different from natural coal. In this study we used reconstituted coal as a research material to study porosity and permeability characteristics of compacted coal fines in coal reservoir fractures. We use different macrolithotype coal particles with size of 0.2–0.4 mm, a heat-shrinkable tube and two guide blocks to make a reconstituted coal sample. In order to investigate the behavior of reconstituted coal permeability changing with effective stress and the influence of lithotype effect on permeability of reconstituted coal, reconstituted coal cores porosity and permeability test with helium gas in net confining stress were measured in laboratory. And pore distribution of different macrolithotype natural coals and reconstituted coals were analyzed by low-temperature nitrogen adsorption experiment and low-field nuclear magnetic resonance (NMR) measurement. Both porosity and permeability of reconstituted coal decrease exponentially with the increase of effective stress. Initial permeability and permeability damage rate of reconstituted coal have a negative correlation and a positive correlation with quality proportion of clarain and vitrain, respectively. The proportion of seepage channels of dull reconstituted coal is larger than that of bright reconstituted coal.

1. Introduction

Coalbed methane (CBM) is a natural gas that stored in pores and cleats of coal seams. Coal is structurally heterogeneous, porous, and amorphous. Coalbeds, unlike conventional natural gas reservoirs, are characterized by low mechanical strength, cleat development, and strong heterogeneity typically [1–5]. As a key parameter for reservoir, permeability is one of the main factors that affecting CBM production. Because of the low porosity and permeability of high-rank coal reservoir, most of the CBM wells production needs hydraulic fracturing. Cleat network and porosity of coal changed after hydraulic fracturing. High-rank coal reservoir permeability is generally less than 0.1 mD, but it can reach more than 5 mD after fracturing. Hydraulic fracturing and CBM production usually lead to coal fines output. Coal fines have a great influence on coal reservoir permeability. When coal is crushed under the effect of hydraulic fracturing, some of coal fines flow out of the wellbore with gas or fluid, whereas some settle and plug the natural cleats and hydraulic fractures because of the gravity and constraints of pore size or coal microstructures [6]. Those coal particles are compacted under the confining pressures with fractures close down. In addition, during gas production, coal permeability changes with the effective stress [7–12]. It is meaningful and necessary to study the porosity and permeability stress sensitivity of compacted coal fines whose pore distribution is much different from natural coal. Over the past several decades, coal reservoir permeability has been studied in many aspects. Fu et al. (2009), presented the relationship between coal structures and permeability of coal seams using geophysical logging technologies [13]. A significant decrease in coal reservoir permeability occurs in a well with a fast pressure drop or high dewatering rate, which generally causes a concomitant decrease in gas production [14,15]. Permeability of coal cylinders under triaxial compression tends to decrease with the increase of effective stress and is affected by the direction of loading stress and cleats [16,17]. Many researchers demonstrate

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that coal core permeability decreases exponentially with the increase of effective stress based on experimental measurement [18–21]. During CBM production, coal reservoir permeability decreases with the increase of effective overburden pressure on the coalbed framework. In the meantime, shrinkage of the coal matrix due to desorption of gas tends to open the cleat fractures leading to coal permeability improvement [22–24].

Laboratory physical simulation experiment often requires application of samples with repeatable properties. And a material which stands for coal and is characterized with properties similar to compacted coal fines is necessary in laboratory physical simulation experiment studies. The seepage path of compacted coal fines underground is different with the natural coals. The connected cleats and marcofractures are then main seepage paths of natural coals. But there is no cleat system in compacted coal fines, instead the space between the coal particles is the main seepage path of compacted coal fines, which is similar to reconstituted granular coals. Authors of this article suggest that reconstituted granular coal can be used as a research material to study porosity and permeability behavior of compacted coal fines filled in fractures. Reconstituted coal has already been used for studying coal sorption of CO_2/CH_4, swelling on permeability characteristics and compressive strength of altered coal [25–29]. The object of this paper was to investigate the stress sensitivity of compacted coal fines and lithotype influence on stress sensitivity based on porosity and permeability overburden pressure experiment on reconstituted coal. Considering the following four reasons, we use reconstituted coal cores as the experimental object:

(1) Characteristic of reconstituted coal made with a preparation pressure is similar to compacted coal fines filled in coal-seam fractures.
(2) Permeability of coal reservoir after fracking is generally thousands of times larger than that of coal cores. Permeability of reconstituted coal cores can be changed with different preparation pressure, which means we can get high permeability samples that we need.
(3) Reconstituted coal can be made of different marolithotype coal particles (clarain, vitrain and durain) to study the lithotype influence on porosity and permeability of compacted coal fines
(4) Reconstituted coal is the way of obtaining the repeatable research material for experimental study. According to our work, the relative error of permeability of reconstituted coals which were made with same coal particles under the same prepared pressure is less than 3%.

In this study, coal material was collected from the coal seam No. 3 in Shanxi Formation of Permian in Fanzhuang block. The Fanzhuang block is located in the southwest corner of the Qinshui basin in Shanxi Province, China, which is the major commercial CBM producing block in China (Fig. 1). Coal seam No. 3 in the Shanxi Formation is the main target zone for CBM development. The total gas-bearing area of the Fanzhuang Block is 398.23 km^2, and the total resource of CBM is 104.3 billion m^3, with 35.2 billion m^3 of proven reserves [30]. Up to now, more than 760 vertical wells for CBM development have been drilled in Fanzhuang Block, with an average daily gas production of 1420 m^3 and an accumulated gas production of 23.32×10^8 m^3.

2. Experimental

2.1. Research material

Coal material was collected from the coal seam No. 3 in Shanxi Formation of Permian in Fanzhuang block in southern Qinshui basin. The burial depth of the No. 3 coal seam in study area is from 300 to 1100 m. No. 3 coal seam is bright coal or semi-bright coal in macrolithotype and is banded or homogeneous in coal texture. Vitrinite reflectance relating to maceral maturity was determined: Ro, max = 3.02%. Proximate analysis of coal was as follows: volatile matter content Vdaf = 9.8%, ash yield Ad = 13.3% and moisture yield Wt = 1.0%. This coal material was used for reconstituted coal cores preparation.

We use coal particles, a heat-shrinkable tube and two guide blocks to make a reconstituted coal sample (Fig. 2a). According to Cao et al. (2013), the particle size of coal fines in Qinshui basion ranges from 0.01 to 2 mm with a peak range of 0.1–0.4 mm [31]. In this study we chose the particle size of 0.2–0.4 mm. The reconstituted coal sample making process is as follows:

(1) Coal sample (Fig. 2c) were crushed and sieved on vibrating screen to the same particle size of 0.2–0.4 mm.
(2) 20 g dry samples were weighed and evenly mixed with 2 mL standard brine.
(3) In order to evenly compact coal particles, the compaction process was divided into three steps. For the first two steps, the pressure was set as 5 MPa forcing for 2 min. In the third step, the pressure was gradually increased to 27–39 MPa in 3 min, and then maintained the constant pressure for 10 min. After that, the reconstituted coal can be taken out of the mold (Fig. 2b), which is about 3.5–4.5 cm in length and 2.45 cm in diameter (Fig. 2a).

Part A of the coal (Fig. 2c) was used to prepare series a and series b reconstituted coal specimens. The permeability of reconstituted coals ranges of 3.77–15.10 mD, 100–1000 times of that of natural coal cores, and the porosity is varies from 3.70 to 19.18% (Table 1). In order to investigate the influence of macrolithotype effect on porosity and permeability of reconstituted coal, three lithotypes, vitrain, clarain and fusain, were hand-picked from the coal. Considering the content of vitrain is low, and it is difficult to separate vitrain from clarain, we put them together. M-1, M-2, M-3, M-4, M-5 and M-6 were prepared with different proportion of clarain, vitrain and durain (Table 2). Preparation pressure is the main factor that controls reconstituted coal sample initial permeability. Fig. 3 shows the relationship between porosity and permeability of reconstituted coal samples and preparation pressure. Considering the permeability of coal seam after fracturing in Fanzhuang block is about 5–9 mD, we set the pressure at 35 MPa to make reconstituted coal cores which initial permeability is about 5 mD. Then we use these reconstituted granular coal samples to conduct the porosity and permeability test under different effective stress.

2.2. Experiment apparatus and scheme

2.2.1. Porosity and permeability test

The porosity and permeability of reconstituted coal cores under net confining stress were tested by using an automatic porosity and permeability instrument (AP – 608). Gas source for confining pressure is supplied by high-pressure N_2 and the high-purity helium serves as the test gas source. The flow chart of the experimental setup is shown in Fig. 4. The confining pressure values were set as 3.5, 5.5, 7.5, 9.5, 11.5, 13.5, 15.5 and 17.5 MPa, and the temperature was 20 °C. The displacement pressure was fixed to eliminate the influence of slippage effect on permeability of reconstituted coal cores. In our experiment, the confining pressure was defined as effective stress approximately.

2.2.2. Low-temperature nitrogen adsorption method

Low-temperature nitrogen adsorption experiments were conducted with "Quantachrome –nova 2000", a Surface Area Analyzer,