International Journal of Coal Geology 147–148 (2015) 46–57

Contents lists available at ScienceDirect

International Journal of Coal Geology

journal homepage: www.elsevier.com/locate/ijcoalgeo

Permeability variation associated with fines production from anthracite coal during water injection

Zhenghuai Guo, Furqan Hussain *, Yildiray Cinar

School of Petroleum Engineering, The University of New South Wales, Sydney, NSW 2052, Australia

ARTICLE INFO

Article history:
Received 20 December 2014
Received in revised form 19 June 2015
Accepted 19 June 2015
Available online 27 June 2015

Keywords:
Coal
Clay
Fines
Permeability
Water flow

ABSTRACT

Produced water during coal seam gas (CSG) production carries fines. A few laboratory studies reported in open media suggest that fines migration can cause variation in coal permeability during water flow. However, a detailed laboratory study has not been reported so far to explain this variation in coal permeability. The characterization of coal and produced fines and water quality may shed light on the root causes of variation in coal permeability.

This paper presents an experimental study on an anthracite coal sample from a CSG field in China to investigate the impact of fines migration on coal permeability. Proximate, petrographic and XRD tests are conducted for a robust characterization of the coal sample. The coal sample is first covered with Araldite epoxy to minimize any confining stress effect during the flow test. Then the coal sample is saturated with filtered distilled water which is also injected to the coal sample. The injection pressure is kept constant during the flow and the production rate is measured continuously to calculate permeability. Once the measured permeability stabilizes, the injection pressure is increased to see the effect of pressure gradient on fines migration and permeability variation. Effluent water is collected frequently and analyzed by a laser particle counter to determine the concentration and size of the produced fines. The fines are then separated from the water samples using membrane filters and analyzed under a scanning electron microscope and electron dispersive X-ray (SEM–EDX) to investigate their composition and morphology.

The proximate test shows 9.6% ash (air-dried-basis) in the coal sample while the low-temperature ashing XRD shows kaolinite (38.5%), illite (26.2%) and chloride (2.8%) clay in the mineral matters. Production of fines and permeability increases and decreases are observed during water injection. The permeability decrease is attributed to the blockage of cleats by fines whereas the permeability increase indicates the mobilization of trapped fines. The characterization of produced fines shows that the majority of fines are clay particles with some coal fines also observed.

1. Introduction

Permeability is a key parameter controlling fluid flow in CSG reservoirs. The key factors that affect coal permeability are:

(1) Stress — increase in effective stress causes coal cleat to close resulting in permeability variation (Pan and Connell, 2012). In addition, stress causes prolonged deformation due to creep effect – resulting in sustained variation in permeability (Zhu et al., 2011);
(2) Gas adsorption/desorption — adsorption/desorption causes coal matrix to shrink/expand resulting in permeability variation (Pan and Connell, 2012; Zhou et al., 2013);
(3) Salt and mineral dissolution and precipitation — the dissolution and precipitation of salts and minerals may alter the flow path to affect the permeability. Decrease in coal seam pressure during CSG production reduces the solubility of carbonate in water and results in the carbonate precipitation (Connell et al., 2008; Moghadasi et al., 2007); and
(4) Fines migration — fines are mobilized during flow and may cause blockage of flow path resulting in permeability decrease (Gash, 1991; Keshavarz et al., 2014).

In this study, we focus on coal permeability variation associated with fines migration. Liu et al. (2011) presented a comparison of produced fines in different phases of CSG production in the South Quinshui Basin, China. They reported that the average size of the produced fines decreases from about 8 mm in the early phase of dewatering to smaller than 1 mm in the later phase of gas production. This indicates that fines migration occurs at all stages of gas production from CSG reservoirs and its impact on coal permeability needs to be understood accurately.

Coal mainly consists of macerals and minerals. The major minerals of coal are clays (Thomas, 2013). Field studies show that the mineral content of fines is 10%–30% higher than that of coal (Chen et al., 2009;

* Corresponding author.
E-mail address: furqan.hussain@unsw.edu.au (F. Hussain).

http://dx.doi.org/10.1016/j.coal.2015.06.008
0166-5162/

Massarotto et al., 2014). Clay particles are believed to be one of the major fines that can be mobilized and retained to cause permeability damage in different sandstones (Civan, 2000; Khilar and Fogler, 1999; Mohan, 1996; Mohan et al., 1993). Clays found in coal or sandstones can be swelling clays (e.g. smectite) or non-swelling clays (e.g. kaolinite and illite). If swelling clays are present, permeability variation may also be affected by clay swelling.

Fines migration in coal has been observed in the field. Some researchers have discussed the mechanisms of coal fines generation/mobilization (Cao et al., 2012; Li et al., 2010; Liu et al., 2011; Marcinew and Hinkel, 1990; Tang et al., 2011). These mechanisms include:

(1) Tectonic effect,
(2) Fracturing, drilling and perforation,
(3) Hydraulic drag and lift due to fluid flow,
(4) Desorption of gas, and
(5) Increase of effective stress.

A few studies have shown a permeability variation associated with fines migration in coal during water flow. Hyman et al. (1990), Gash (1991) and Nick et al. (1995) injected water through coal samples under constant effective stress and observed permeability reduction with time. Gash (1991) also showed a permeability increase by reversing the flow direction. Note that, the increase in permeability by flow reversal is deemed to be a sign for fines migration that causes pore throat opening (Gruesbeck and Collins, 1982; Khilar and Fogler, 1984; Khilar et al., 1982). Zhang et al. (2011) and Bai et al. (2011) injected fines suspension into coal samples. They demonstrated that the permeability is affected by the size of fines injected, cleat size and flow rate.

The studies mentioned above about fines migration in coals show a possibility of coal permeability reduction by blockage of cleats with fines during water flow. Yet, they are not without limitations:

(1) The fines in produced water are not well-characterized (size, concentration and composition etc.) – hence it is not possible to evidently show the presence of and understand the fines migration in coal; and
(2) Coal characterization (coal rank and mineralogy, etc.) is not conducted – so that the coal type and quality cannot be correlated to the produced fines. This correlation may help understand the mechanism of fines generation in a coal sample.

The main purpose of this paper is to study the fines production from a coal sample taken from a CSG field, and correlate it to coal permeability to water with consideration of the limitations mentioned above. A systematic experimental approach is presented which includes coal characterization, single-phase water flow through the coal, permeability and effluent monitoring during the study and characterization of the produced fines. The paper then attempts to examine the results to find out the root causes for permeability variation.

2. Experimental methodology

2.1. Characterization of the coal sample

We used the following coal characterization techniques:

(1) XRD tests — to determine mineral composition;
(2) Proximate test — to determine organic components (fixed carbon and volatile matter) and inorganic component i.e. ash);
(3) Ultimate analysis — to determine the chemical composition of the sample; and
(4) Petrographic analysis — to determine vitrinite reflectance and hence coal rank.

Table 1
Results of the proximate test.

	%
Ash	9.8
Volatile matter	6.7
Fixed carbon	83.5

We categorized our coal sample as an anthracite coal on the basis of the measured average vitrinite reflectance of 3.6 (Seidle, 2011). Results of proximate and ultimate tests are given in Tables 1 and 2.

The low temperature ashing (LTA) XRD and Oriented-aggregated XRD are conducted on the powdered sample of the coal to identify the mineral contents. For LTA XRD, representative coal powder sample is subjected to the low-temperature oxygen-plasma ashing as described by the Australian Standard 1038.22, and the resultant low-temperature ash (LTA) residue is collected. The low-temperature ash is then analyzed by the X-ray powder diffraction using a Phillips PW1830 diffractometer with Cu K—alpha radiation. The JCPDS Powder Diffraction database is used for the minerals' identification. Mass percentage of individual minerals in the sample is determined using the SIROQUANT™ software. This software is based on the Rietveld XRD analysis technique described by Taylor (1991). The results are summarized in Table 2.

For the oriented-aggregated XRD, the low temperature ash is generated the same way as described for the LTA XRD method. Then, the ash particles, less than 2 μm effective diameter, are isolated from the ash powder. The clay fraction of the isolated ash is then investigated further by the X-ray diffraction of oriented aggregates on a Philips PW-1830 diffractometer, using glycol and heat treatment. The relative proportions of the different clay minerals in this fraction for each ash sample are determined by the method of Griffin (Carver, 1971). The results are summarized in Table 3.

As can be seen, these two different XRD methods give different clay proportions. The most likely reasons are: 1) the LTA XRD sample contained a lot of kaolinite particles larger than 2 μm, and in the oriented-aggregated XRD analysis, only particles smaller than 2 μm are analyzed; and 2) different methods are used for the mineral fraction estimates. Because of better sample representation, the LTA XRD represents the whole sample while the oriented-aggregated XRD shows more critical analysis of clay minerals. But, the oriented-aggregated XRD results may not represent the whole sample. Hence, the sample's clay mainly consists of kaolinite, illite and chlorite (Table 3). However, there is a minor percentage of smectite (Table 4). Besides clay mineral, the coal sample also contains amorphous materials (31.4%) and some minor quartz and ankerite (4.5%) (Table 3).

2.2. Preparation of water

We used distilled water in the experiments. Having no fines in the water used was our priority. Therefore, we filtered the used water

Table 2
Results of the ultimate analysis.

	Dry ash-free basis (%)
Carbon	91.8
Hydrogen	3.2
Nitrogen	1.3
Sulphur	0.4
Oxygen	3.3