Journal of Natural Gas Science and Engineering 64 (2019) 72–80

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

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

Kaolinite flakes and coal fines production in lignite core under ambient conditions: A case study of Neyveli Lignite Field at Cauvery Basin, Southern India

Venkat Pranesh[a,*], S. Balasubramanian[b], R.S. Kumar[c], R. Sakthivel[d], P. Rajkumar[d], S. Ravikumar[e]

[a] *Engineering and Solid Fuels Division, Dawn Calorific Exports, Chennai, Tamil Nadu, India*
[b] *Department of Inorganic Chemistry, University of Madras, Chennai, Tamil Nadu, India*
[c] *Department of Earth Science, Annamalai University, Chidambaram, Tamil Nadu, India*
[d] *Department of Geology, Bharathidasan University, Khajamalai Campus, Tamil Nadu, India*
[e] *Department of Mechanical Engineering, Jeppiaar Maamallan Engineering College, Sriperumbudur, Tamil Nadu, India*

ARTICLE INFO

Keywords:
Neyveli Lignite
Coal fines
Kaolinite clay
Waterflood
Gas recovery
Permeability

ABSTRACT

Coal fines production and structural collapse during waterflooding process was widely observed and reported in several coalbed methane (CBM) fields. Besides, fines migration also plays a major role in the destruction of coal cleats and consequently, declining the gas recovery. This paper presents the coal fines production in lignite core as a function of kaolinite. Actually, it is a clay fine particle that rests on coal surface under the dominances of the four forces, namely, lift, drag, gravity, and electrostatics. Under hydrodynamic and thermodynamic forces these fines detach from the rock surface and migrate in the porous interspace, and at a certain point it is captured, and thereby deteriorating the well productivity and structural collapse as well. Many researchers have investigated these fines migration mechanisms in anthracite and bituminous coals, but to best of our knowledge till date this research was not carried out in lignite coals. In order to successfully demonstrate this mechanism in lignite, three sets of coreflood experiments have been conducted under ambient conditions for analyzing the coal and kaolinite fines transport and their impact on gas recovery. Lignite samples are procured from Neyveli Mines at Cauvery Basin in Southern India and then the simulated version is used for the analysis. The coreflood results revealed that the gas recovery increases for increasing PVI and that there is an observation of pressure drop across the core for increasing PVI and this phenomenon is attributed to enhancing concentration of fines. Additionally, the water flow velocity elevates the velocity of coal fines and the microstructural analysis indicated the presence of kaolinite flakes among coal fines. The entire experimental model was tested against the statistical model in SPSS and showed good agreement. Overall, it is understood that even lignite reservoirs are prone to fines migration and permeability decline.

1. Introduction

The frequent causes of formation damage and gas well productivity decline in coalbed methane fields are clay fines migration and coal fines production mainly due to hydrodynamic forces (Zeinijahromi et al., 2012; Huang et al., 2018). Natural reservoir fines attached to rock grains are composed of clays typically kaolinite, illite, quartz, etc. Due to colloidal forces and the imbalance in mechanical equilibrium causes fines to detach from the rock grain to mobilize along with the displacing fluid, thereby plugging the pore space and restricting the permeability which ultimately leads to well impairment and production decline. Generally, fines have a size of the order of 1 μm and a net surface charge (Raha et al., 2007). Coal fines are usually produced during overflushing of water in the coal matrix that leads to structural collapse. This causes a decline in permeability and gas recovery, and huge amount of gas will be adsorbed in the coal fines or even dissolved in water (Han et al., 2015). Guo et al. (2015a), analyzed the variation in the permeability of anthracite coals during water injection. Firstly, the authors have obtained coal samples from the CBM field in China and they were subjected to petrographic and XRD analysis. Then, a series of core flooding experiments have been performed. The waterflooding test was conducted at a constant injection pressure and variation in coal permeability was observed. Moreover, their experiments revealed production of clay and coal fines that changed the anthracite permeability. An

---

[*] Corresponding author.
E-mail address: vpr2092@hotmail.com (V. Pranesh).

https://doi.org/10.1016/j.jngse.2019.01.023
Received 15 September 2018; Received in revised form 23 January 2019; Accepted 31 January 2019

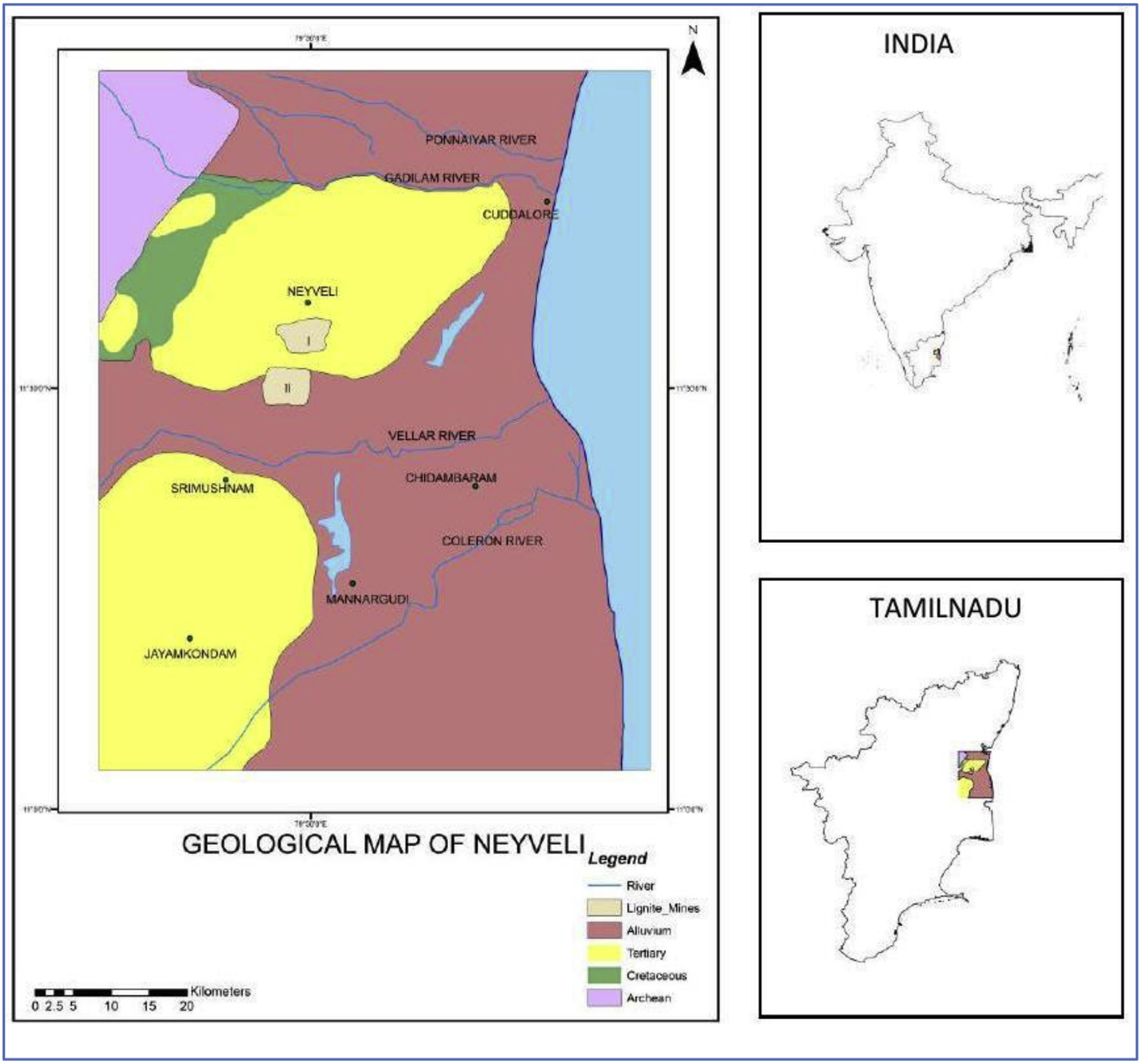

Fig. 1. Geological map of Neyveli Lignite Field.

increase and decrease in permeability were observed during water injection. Ultimately, the authors have emphasized that the permeability decline is attributed to the cleats obstruction by clay and coal fines. Additionally, the transport of fines contributed in the coal permeability rise.

Zhao et al. (2016) studied the coal fines characteristics and generation mechanism in CBM wells in the Chinese Southern Basin of Qinshui. The authors have made analytical investigations on coal samples from this field and also conducted coal fines experiments. Importantly, the results indicated that during gas production the coal formation is hindered by tectonic stress, which is generated between fault zone and partings. Coal and its associated minerals are brittle materials, which are formed by coalbed fragmentation in the rock floor during folding. In their case, coal fines are relatively large in size, which indicates that they have not undergone strong shearing after their formation. It also reveals that huge amount of coal fines is produced during water production stage. The authors have mainly emphasized that coal fines play a significant role in the determination of coal structure and gas production management. Their ultimate claim is that the tectonic stress in the coal formation causes the production coal fines. Guo et al. (2016b) made analytical and physical modeling of fines migration induced permeability damage in bituminous coal caused during the production of water. Initially, the authors have carried out XRD, SEM-EDX analysis on bituminous coal samples. Even in this investigation, it was found that the bituminous coals are prone to permeability decline due to fines migration. The experimental results mainly indicated that approximately 35% decrease in bituminous coal permeability was noted for 33 days of water injection. Also, the analytical model supports their experimental outcomes and furthermore, indicated that the most of the fines are displaced during the beginning of water flow test.

Kaolinite clay and its associated rocks are common in several oil, gas, geothermal, and coal seam formations. Mostly, kaolinite fines have a drastic effect on the permeability of porous rock formations. Russell et al. (2017), studied the kaolinite effects in rock on fines mobilization. They have performed laboratory investigations on the permeability changes in the rock containing kaolinite during low salinity water injection. The major observations from their experiments are rise and decline in permeability as well as salinity alteration during flow in porous media and specifically, water chemistry has a severe effect on fines migration and permeability blockage. Overall, their results emphasized that kaolinite clay content rocks are often susceptible to formation damage and well productivity decline. Ding et al. (2009) have reported that there is a rich kaolinite reserves in the Permo-Carboniferous starta of North China and indicated that there are three types of kaolinite rocks in that area: the first one is called tonsteins, which occurs in the floors, roofs, and partings of the coalbed. The second type is wider and thinner and it is not adjacent to coal-bed, but the lower part of Upper Permian coal measures. The third type is a 0.5–5 m thickness soft kaolin clay that is associated with surface weathered coals. The analytical and microstructural results indicate that kaolinite mineral content is generally higher than 70% and suggest the presence of Mo, W, Zr, Hf, Th, Ag, Sb in kaolinite rocks. The first type is from the in situ changes of volcanic ashes air fall. The second type is due to adjacent landmass and the third type is associated with coal weathering.

Zhao et al. (2018) made investigations on the formation of a kaolinite—NH_4—illite-pyrophyllite-chlorite assemblage in a marine influenced anthracite and related strata from the Jincheng Coalfield, Qinshui Basin, Northern China. It was noted from their research that the formation of kaolinite occurred during early diagenetic and epigenetic processes has been highly changed to other phyllosilicates by processes related to the different stages of advances in coal rank. The NH_4-illite origin in the Jincheng coals is the illitization consequence of an early diagenetic kaolinite precursor by kaolinite interaction with N derived from organic matter. Plausible mechanisms for the origin of the NH_4-illite in the Jincheng non-coal rocks at least include isomorphous substitution of NH_4 for K in the K-illite structure. The well-crystallized K-illite in the non-coal rocks possibly formed from detrital K-illite, and was recrystallized with the advances of coal rank. Pyrophyllite absence in non-coal samples may be due to epigision and palaeo environmental assessment of the Cretaceous System exposed in thenetic kaolinite insufficiency in the horizons of non-coal. The occurrence of pyrophyllitization was studied during a late stage of metamorphism.

The earlier reports indicate the importance of kaolinite content on coal seams and recently, vermicular kaolinite content was found in the fly ash that was processed from the pulverized coals from the Indian (Bokaro and Jharia, Jharkhand) coal fields (Valentim et al., 2016). Hence the objective of this paper is to investigate the kaolinite clay and coal fines migration in simulated lignite core. The lignite coal samples were obtained from the Neyveli Lignite Mine at Cauvery Basin, Southern India. Fig. 1 presents a typical Indian map of Cauvery Basin.

1.1. Geological setting and study area

The Neyveli lignite mine is located exactly between $11^{\circ}13' - 11^{\circ}38'$ N Latitude and $79^{\circ}24' - 79^{\circ}33'$ E Longitude. The coal field covers a distance of 44 km in N-S direction and 12 km in E-W direction. The lignite deposit is a part of the Cuddalore Formation of Late Miocene age and is associated with ferruginous and argillaceous sandstone and clay beds (Rao et al., 2009). The Cauvery Basin is a North East - South West rift basin, which was formed during the Late Jurassic to Early Cretaceous splitting of the Archean Indian basement and Australia-Antarctica plates (Veevers et al., 1991). Cauvery basin covers an area of approximately 25,000 km^2, which comprises of well preserved Albian to Maastrichtian age shallow marine sedimentary sequences that were deposited on the eastern coast of the southern Indian State of Tamil Nadu (Sundaram et al., 2001). Additionally, there are huge deposits of carbonate sediments in many parts of the Cauvery Basin (Chakraborty and Sarkar, 2018). Fig. 2 shows the geological and hydrological cross section of Neyveli lignite formation.

The hydrology of this formation can be classified into three sections as: unconfined, semi-confined, and confined aquifer (NLC, 2018). The first section is attributed to the ground level up to a maximum depth of 50 m consisting of lateritic sand stones/alluvium, and water level fluctuates between ground level and 15 m. The second section occurs top of the lignite seam in the Southern Parts of Mine. Its thickness varies between 5 and 10 m and exerts 3 to 5 kgf/cm^2 minimal pressure. The occurrence of confined aquifer is predominant and its thickness is around 400 m in the core lignite region and pinches in the west. There is a continuous thick clay barrier within the lignite bearing strata at a depth close to 40–50 m that divides the aquifer into two parts such as Upper and Lower confined aquifer. This is mainly recharged due to rainfall in the 420 sq km of demarcated recharge, which is lying in the west of the lignite field. Overall, it exerts a 5 to 10 kgf/cm^2 upward pressure at the lignite seam base. Fig. 3 shows a sample lignite rock, which was taken from the Neyveli lignite mine.

2. Materials and methods

This section presents the material and methods that were employed in this research work, which mainly describes the novel method for coal core preparation. This is entirely different from conventional core drilling and sampling methods. Lignite samples, like the one in Fig. 3 were obtained from Neyveli mine. The lignite core was prepared and this research was executed through the following steps:

- **Step 1:** Sample acquisition from mines
- **Step 2:** Pulverization
- **Step 3:** Mixing of pulverized lignite and kaolinite clay
- **Step 4:** Molding and drying
- **Step 5:** Lignite core and ultrasonic treatment
- **Step 6:** Coreflood Experiment
- **Step 7:** Microstructural evaluation
- **Step 8:** Statistical evaluation

After obtaining samples from the mines, the lignite was pulverized to a fine powder in 250 mesh range. Then, pulverized lignite and kaolinite clay powders were mixed in the proportion 80% and 20% in the Hamilton Beach mixer at 300 rpm. Subsequently, the mixture was sent to the molding process for acquiring the cylindrical core. This process was performed and monitored in a careful manner since the nature of the product should not be altered. A cylindrical pattern of length 20 cm and diameter 10 cm was used for molding. The mixture is fed into the pattern and it is heated at 40 °C in an industrial oven. Extreme temperature and time will make the mixture rigid and this will be against the true nature of lignite and coal. Therefore, 40 °C is maintained for about 15 min in order to obtain a brittle lignite core saturated with kaolinite clay. On the whole, a lignite core of 10 cm diameter and 20 cm length was obtained and later these three cores were dried for 24 h. Next, the core is sent to ultrasonic treatment for generating cleats (fractures) for fluid and particle flow. The three lignite cores have undergone an ultrasonic treatment at 5 MHz for about 20 s and fractures appeared in several sections of the core and we assume that kaolinite particles were trapped in between the cleats. Overall, three cores were obtained at ambient temperature coreflood test such as 35 °C, 40 °C, and 45 °C.

Actually, it was observed that the hardness (in Rockwell Scale) of the acquired lignite mine sample is measured to be 13 HRC at 40 °C for the indentation time of 10 s. But, 15 HRC (Hardness Rockwell Scale) was measured for a simulated lignite core with kaolinite clay saturation under those conditions. An increase in 2 HRC (Rockwell hardness) was observed. It is inevitable, because errors/uncertainties will occur during material sampling. But, we felt that this will not have serious effect and proceeded to further work. Fig. 4 present a layout of experimental setup. It can be seen from the figure that the prepared lignite core (rolled with thin rubber sleeves) is placed in a stainless steel core

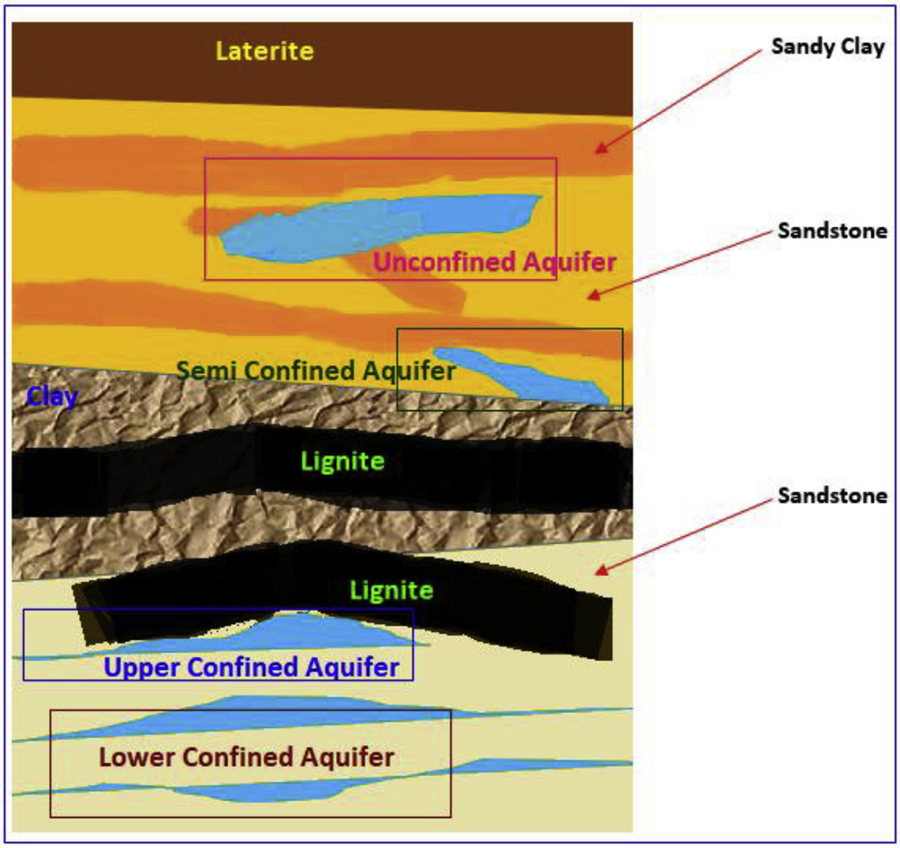

Fig. 2. Schematic diagram of geological and hydrological cross section of Neyveli Lignite Formation (Not to Scale).

Fig. 3. Image of Neyveli lignite rock.

holder. In turn the core holder is placed inside the oven. The oven is attached with a thermocouple and three pressure gauges (to measure the pressure difference across the core). One pressure gauge is connected to the core center and another two are connected to the inlet and outlet flow lines of the core. One side of the core holder has provisions for LPG and water flow, while the other side has the flow line for effluent collection. The water tank is fitted with a high pressure pump. The flow lines are provided with ball valves and the entire core-oven thermal system is connected to the data acquisition system and subsequently, connected to the computer.

Three sets of experiments were carried out at 35 °C, 40 °C, and 45 °C. Initially, the oven was set to these ambient temperatures. Then the LPG gas valve is opened and allowed to flow into the oven in order to saturate with the core holder. A mass of 25 kg/s was delivered to the core for each set of experiment and after that gas cylinder valve is closed. For the first experimental set, the oven temperature is maintained at 35 °C and the time for gas saturation is 5 min. Then cold water is pumped into the core continuously for fluid and particle mobilization. After exiting the oven it is disposed in the effluent collector and passed for microstructural examination (FESEM) for coal fines and kaolinite flake identification. This experiment was repeated for another two ambient temperatures at 40 °C, and 45 °C. Finally, the experimental results were tested against the statistical model for correlation and validation with 95% confidence level. The experimental results will be explored in the following sections and the analytical test data of this lignite sample are presented in Table 1.

3. Results and discussions

3.1. Impact of various physical parameters on coal fines and kaolinite production

3.1.1. Gas recovery rate

The gas recovery rate measures how effectively the gas is recovered from the coal reservoir to the wellbore drainage area. Fig. 5 shows the gas recovery rate with respect to increasing pore volume injection (PVI). It can be seen from this figure that gas rising linearly for all ambient temperature conditions. At 1 PVI the gas recovery rate was found to be 7.2%, 6.5, and 5% at 35 °C, 40 °C, and 45 °C, but at 2 PVI a gas recovery rate of 16.1%, 14.8%, and 9.6% was recorded, which is a dramatic increase in the recovery rate. Overall, the gas recovery percentage increases to 33.2%, 31.7%, and 29.4% for 5 PVI at these temperature conditions. It should be noted that the water injection pressure and velocity are kept constant and can be observed that at the

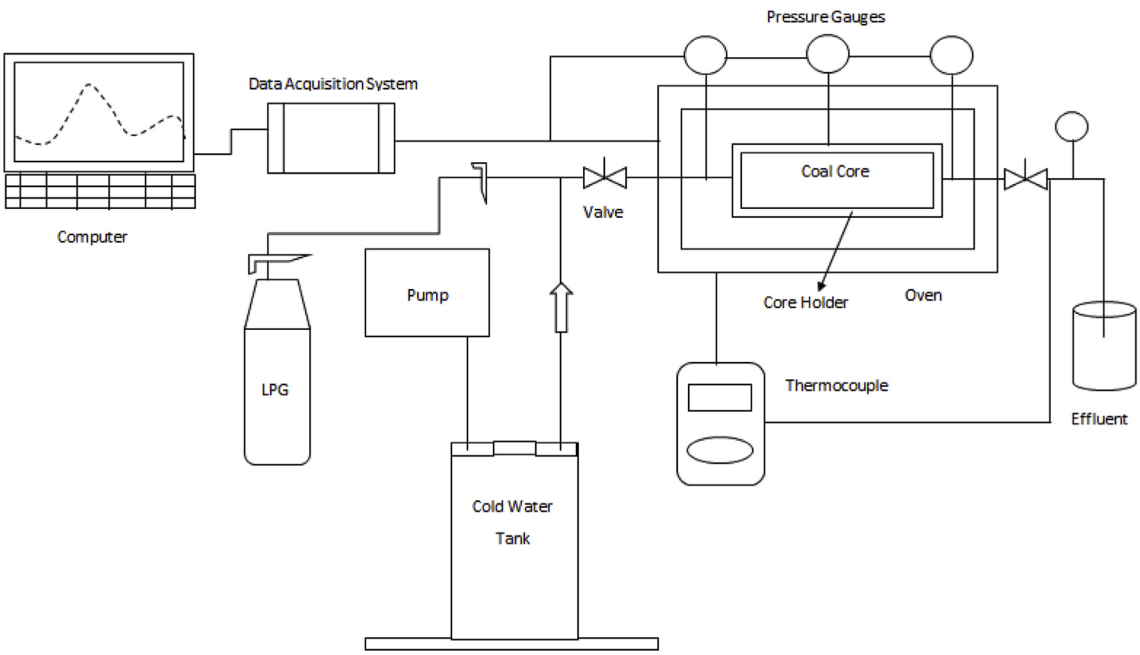

Fig. 4. Experimental setup.

Table 1
Analytical test data of Neyveli lignite rock.

1. PROXIMATE ANALYSIS	Typical analyses	Range in values	Range in TS-I Lab.
Moisture	52.20%	50–56	49.83–51.78
Ash	2.60%	2–5	4.97–8.00
Volatile Matter	24.80%	24–28	23.18–23.8
Fixed Carbon	20.40%	20–24	18.97–19.49
Gross calorific value Kg.cal/kg	2865	2600–2900	2711–2791
Net Calorific value Kg.cal/kg		2200–2400	2308–2384
Specific Heat of lignite 0.64 to 0.65 at 50% Moisture level and 3% Ash			
2. ULTIMATE ANALYSIS			
Moisture	10.40%	10.0–14.0	11.35–19.52
Ash	4.60%	3.0–8.0	1.93–5.66
Carbon	53.05%	49.0–55.0	47.24–57.45
Hydrogen	4.15%	3.5–4.4	3.66–4.31
Nitrogen	0.75%	0.5–0.7	0.04–0.71
Sulphur	0.80%	0.9–1.3	0.94–1.35
Oxygen	26.25%	18.0–24.0	20.04–25.74
Hard groove grindability Index on air dried basis at 12%–13% Moisture level 110-140			
3. CHEMICAL ANALYSIS OF LIGNITE ASH			
Silica as SiO_2	16.20%	10.0–20.0	21.09–41.99
Iron as Fe_2 O_3	4.15%	2.0–5.0	8.67–17.50
Aluminium as Al_2 O_3	20.60%	15.0–22.0	7.46–18.51
Titanium as TiO_2		0.5–1.0	
Calcium as CaO	26.70%	23.0–33.0	10.99–19.49
Magnesium as MgO	6.75%	4.0–7.0	3.00–8.16
Sulphuric anhydrides SO_3	25.60%	25.0–35.0	9.87–23.92
Sodium Na_2O		0.8–1.2	0.93–1.49
Potassium as K_2O			0.05–0.46
4. FUSION CHARACTERISTICS OF LIGNITE ASH			
Initial deformation point (°C)		1080–1150	
Boiling Point (°C)		1250–1320	
Flow point (°C)		1320–1350	
Bulk density (g/cc)		1.1 to 1.2	

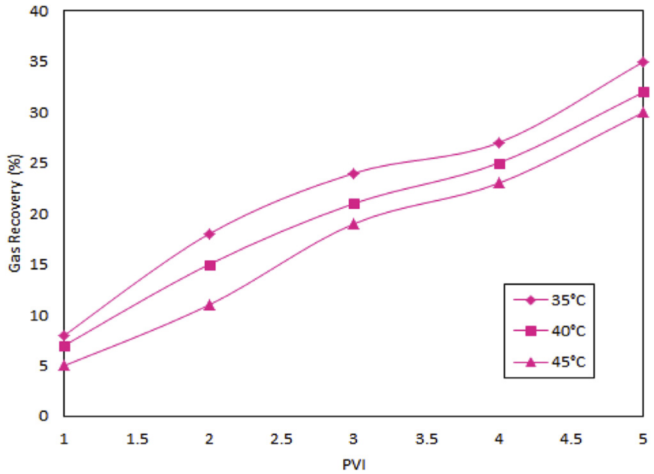

Fig. 5. Variation of gas recovery with respect to increasing pore volume injection.

ambient temperature condition of 35 °C produces a higher gas recovery rate. In this scenario, the lignite core is stable and there is no production of coal particles and fines migration. At the same time, there is a high feasibility of nanoscale particle generation and subsequently, these particles will be suspended in the gas phase in cleats and will be carried away by the gas flow. After achieving this gas recovery rate, the pressure and velocity of waterflood are increased gradually.

3.1.2. Permeability decline

It can be seen from Fig. 6 that the lignite core permeability declines for increasing injection time. Here the water flood velocity and pressure were increased for generating coal fines and kaolinite clay fines as well. It can be viewed from Fig. 7 that increasing waterflood velocity rapidly enhances the production velocity of coal fines. Generally, production velocity is a term associated with manufacturing industries-usually called “Manufacturing Velocity”. It is a measure of how fast the materials under process are moving towards the despatchable state. Likewise, in the present context, it refers to the ability of soaring waterflood velocity to leverage the velocity of coal fines, which can be finally

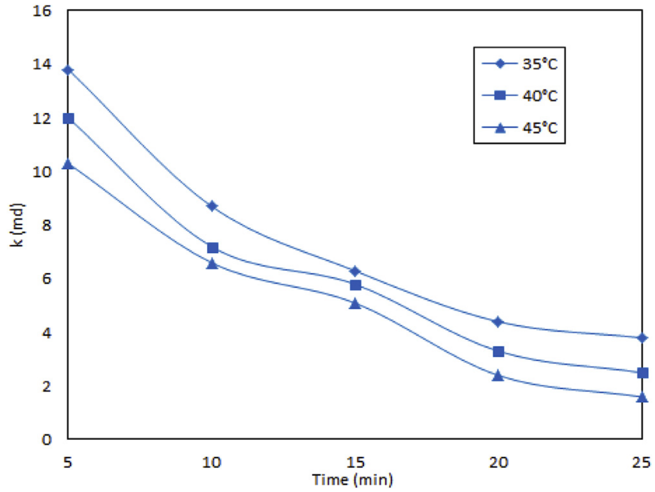

Fig. 6. Variation of permeability with respect to increasing time.

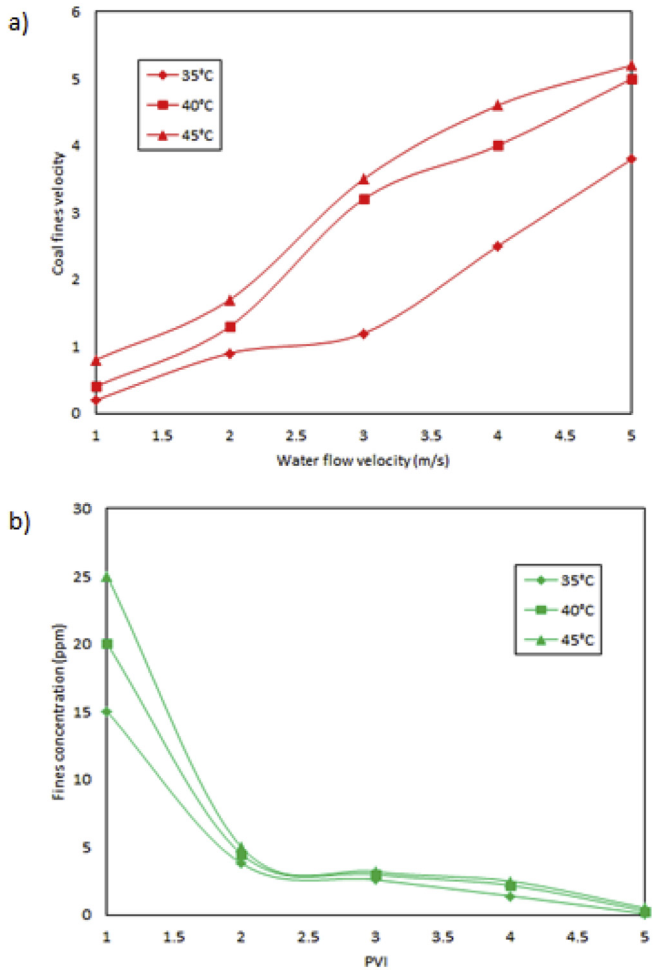

Fig. 7. a) Variation of coal fines velocity with respect to increasing water flow velocity, b) Variation of fines concentration with respect to increasing pore volume injection.

collected in an effluent container. At 5 min the permeability of lignite core was found to be 13.9 md, 12 md 10.2 md at 35 °C, 40 °C, and 45 °C respectively. But, at 10 min, the permeability was measured to be 8.7 md, 7.3 md, 6.8 md respectively, and finally dropping to 3.8 md, 2.5 md, and 1.9 md respectively at 25 min. It is observed that at 45 °C ambient temperature regime indicated less permeability decline, when compared to the other two conditions. So that it can be implied that coal permeability declines at increasing formation temperatures. Sometimes, the pore pressure creates or evolves, new permeable spaces in the coal matrix, but it is mostly feasible during high coal seam temperature (Bai et al., 2017). As mentioned previously, elevating the reservoir formation temperature decreases the porous formation that contains fines. Actually, fines are attached to the rock surface due to strong electrostatic force. During higher reservoir temperature, the surface holding power of electrostatic force gets reduced and as a result, the fine particle detach easily and migrates in the pore passage and after some point it gets trapped in the pore throat and thereby, declining the permeability of the porous medium, overall restricting fluid flow to the well.

3.1.3. Coal fines velocity and concentration

It can be seen from Fig. 7 a that at 1 m/s of water flow velocity produces 0.4 m/s, 0.5 m/s, and 0.8 m/s coal fines velocity at descending ambient conditions. The coal fines velocity gradually increases with increase in flow velocity and an increasing injection pressure of the water. The nature of water is fresh with no content of salinity and hence, we are not considering the chemical reactions with the lignite. Even there are reports that low salinity waterflooding may induce the fines migration in several porous formations (Borazjani et al., 2017). It can be noticed from Fig. 7 that at 45 °C and 40 °C generated more coal fines velocity than at 35 °C. It can also be implied that the water flow velocity is quite sluggish at 35 °C. But, the mass of coal fines production in the effluent did not vary, but took some time to generate this mass. Therefore, it can be stated that at 45 °C and 35 °C there is an occurrence of rapid structural collapse and this is the reason for the production of high velocity of coal fines. Based on Figs. 6 and 7 a), it can be specified that there is no recovery of gas, because of the formation damage. Furthermore, it is noticed that some amount of gas is adsorbed on the lignite. Table 2 presents the data of structural collapse time and the amount of coal fines produced.

After huge production of coal fines, the injected water is not retained and only the least quantity of water was detected in the effluent collector. Since the permeability decline and increase in coal fines velocity leads to restriction in the water flow and some amount of water may be adsorbed by lignite and also, suggests that some amount of gas may be dissolved in water. Fig. 7 b indicates the decreasing concentration of fines for increasing pore volume injection for all ambient temperatures. Initially, there are major differences in the fines concentration for each temperature, but their differences are minimized for rising PVI. Whatsoever, the fines concentration plummets for increasing PVI and in this case, 35 °C ambient temperature reported low decline in the fines concentration and 45 °C condition is quite high when compared to this temperature, and 40 °C showed moderate behavior as usual.

3.1.4. Pressure drop

Fig. 8 shows the pressure drop across the lignite core for increasing pore volume injection and this should not be confused with waterflood injection pressure. Actually, it is pressure difference, which was measured by pressure gauges across the core. After the decline of gas recovery and waterflood velocity, the pressure across the core drops gradually. In some cases, the anisotropy of coal makes difficult for fluid

Table 2
Lignite core structural collapse and coal fines data.

S.No	Temperature (°C)	Structural Collapse Time (s)	Amount of Coal Fines (g)
1	35	340	293.42
2	40	690	329.17
3	45	800	456.08

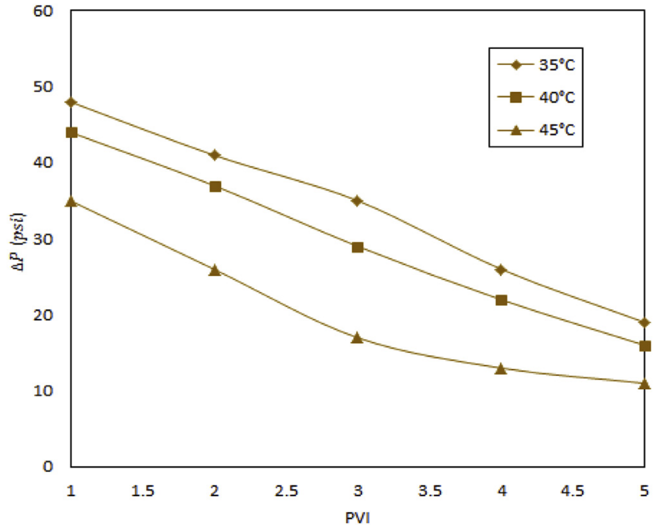

Fig. 8. Variation of pressure drop with respect to increasing pore volume injection.

and particle to transport in the coal cleats (Yao et al., 2016). Consequently, the reservoir pressure drops heavily and the structural geological formation of coal seam should be explored deeply for effective gas production and minimization of formation damage. It can be observed from Fig. 9 that at 35 °C, 40 °C, and 45 °C the pressure was found to be 48.1 psi, 46 psi, and 35 psi respectively. Then the pressure changes (ΔP) that falls to 42.9 psi, 37.3 psi, and 25.6 psi respectively at 2 PVI at ascending ambient conditions. Finally, reaching to 19.4 psi, 18.6 psi, and 12.7 psi respectively at 5 PVI. It should be observed that high drop in lignite core pressure was noted at 45 °C and minimum and moderate pressure drop was observed at 35 °C and 40 °C. But at 45 °C ambient temperature a major drop in the pressure was observed. This is wholly due to the factors of high permeability decline and large volume of coal fines production (Zhang et al., 2018a; Guo et al., 2015a).

3.2. Microstructural analysis

At the end of each experiment, the effluent that was filled with coal fines was sent for microstructural (FESEM) examination. The FESEM (field emission scanning electron microscope) image was obtained for all the three effluent collectors under 1 μm magnification. The microstructural results are presented in Fig. 9. It can be seen from all the three figures that there is a conspicuous appearance of kaolinite flakes and large amount of coal fines. It is a general claim that the shape and geometry of fines can be determined by SEM/FESEM and it was emphasized that the geometric parameters of fines play a significant and critical role in the determination of permeability decline of a porous rock medium. Generally, the dimensions of mobilizing fines vary from 0.1 μm to 10 μm (Khilar and Fogler, 1998). Fines are clearly seen in the FESEM images and it is clear that fines repel from the lignite surface due to weak London-van der Waals attraction and high electric double layer repulsion. The latter force is accelerated due to the decrease of the ionic strength of the permeating fluid that is water (Sen and Khilar, 2006; Paria and Khilar, 2004). Additionally, permeating fluid pH and velocity will repel the fine particle from adhering to the rock surface (Aji, 2014).

Even water content was identified in the images, which is indicated by black spots. During waterflood velocity many portions of the lignite core collapsed and carried away to the effluent. It is inferred that large quantity of water was adsorbed by lignite core. Zhang et al. (2018b) reported that changes in nanoscale mechanical property of coal may influence the water adsorption with coal. Importantly, Feng et al., 2018 studied the lignite water occurrence and its interaction with lignite. Their work revealed that the presence of water in the lignite changes the energy state in the rock and as well the physical and chemical structures. Furthermore, change in coal pore structure, water holding capacity and oxygen containing functional groups were observed. Moreover, the O-containing functional groups can alter the surface

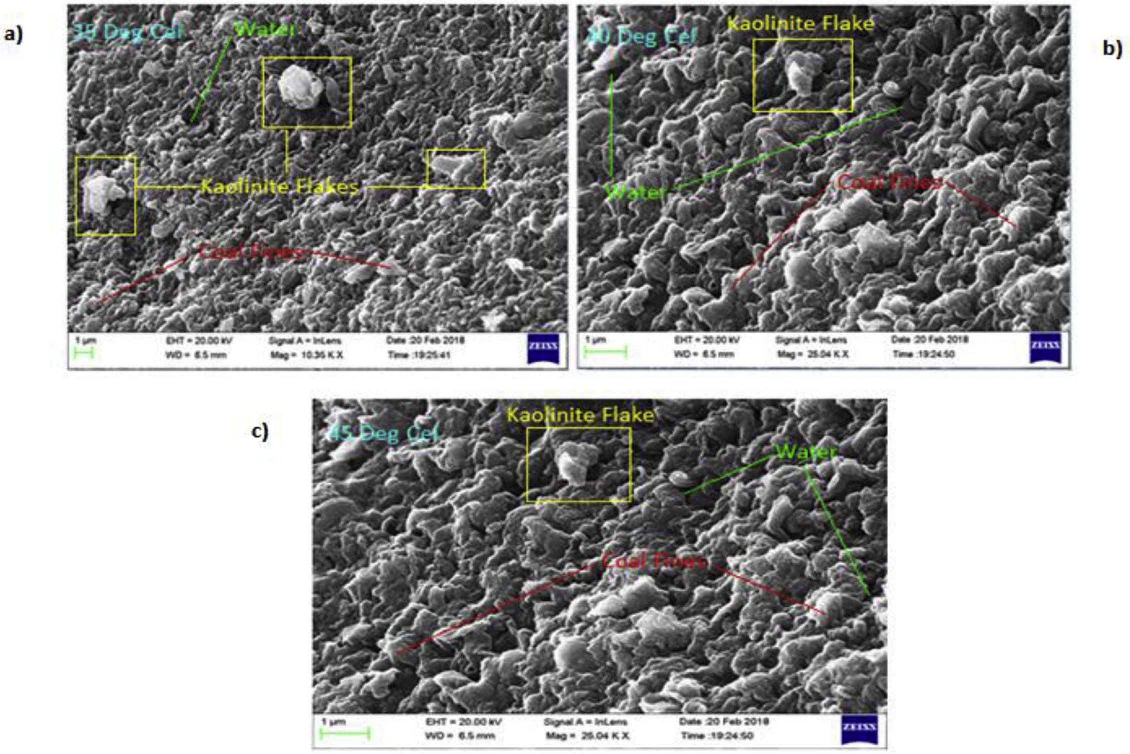

Fig. 9. FESEM images showing kaolinite flakes, coal fines and water under 1 μm magnification: a) 35 °C, b) 40 °C, and c) 45 °C.

morphology of lignite and rapidly adsorb the water, as it was observed and reported in Shengli lignite in China (Wang et al., 2014). Also, it can be explicitly stated that the gas was adsorbed in the lignite and some amount of it might have dissolved in water. Because, there is no sign of gas content in FESEM images and it is assumed that the gas should have been adsorbed by coal fines. Cao and Yugui (2018), pointed out that gas adsorption on coal particles is mostly due to sorption kinetics and diffusion behavior of coal. Sometimes, macromolecular structural characteristics of coal may play a crucial role on gas-coal adsorption (Liu et al., 2018). Additionally, there are also evidences to support this gas-coal surface behavior. For example, Zhou et al. (2018), studied the effects of coal nanopore structure on methane adsorption. Specifically, it was found from their research that gas will be adsorbed completely in the mesopores and nanopores of the coal. It can be only detected at large magnifications such in 200 nm-500 nm. But, our FESEM images are just in the 1 μm range. Actually, the goal of this paper is to only detect the presence of kaolinite flake content between the coal fines effluent. Therefore, 1 μm range of FESEM image is sufficient for clay fines detection and gas adsorption detection is feasible upon testing these samples between meso to nano scales.

3.3. Statistical evaluation

The statistical evaluation for this experiment is performed to find the accuracy in the model. SPSS (Statistical Package for Social Science), a multiple linear regression equipped statistical simulation tool was employed to acquire the regression plot as this can be used to determine the model accuracy and reliability. Major factors such as gas mass flow rate (kg/s), water flow velocity (m/s) and fluid recovery (%) were taken as inputs for this modeling. Tables 3–5 show the regression model summary, analysis of variance (ANOVA), and regression coefficient for lignite core under the ambient temperature regime.

It can be seen from Table 3 that the regression model predicts the value of R as 0.950, it is a proportion variance of dependent variables such as fluid mass flow rate, velocity, and recovery rate, which the model predicts from the input that is the independent variable. Actually, it is the square of the correlation measure and shows the proportion of variance in the output variable or dependent variable (Pranesh, 2016). It is also called as the regression coefficient or the coefficient of determination, its values lie in the range between 0 and 1. Generally, R^2 having 0.9 indicates a good fit (Pranesh et al., 2018) and in this case, it's a good fit. Adjusted R square is beneficial in the measure of the model success which accounted for 95% and 92% variance in the output (dependent) variables. The Adjusted R square was found to be 0.902 in this model. The ANOVA table gives the significance of this model < 0.005 as shown in Table 4 and the coefficient for dependent variables is presented in Table 5.

Fig. 10 shows the regression plot between statistical and experimental models. It can be seen from this figure that there is a close correlation between these models. The correlation was obtained from a plot of ambient temperature (degree Celsius) vs structural collapse time (seconds). Overall, the model revealed good agreement and there were no major differences in the model accuracy. Therefore, it can be implied that this model is reliable for laboratory based investigations of coal core flood test under ambient temperature conditions. Thus, this paper has successfully demonstrated the kaolinite clay and coal fines penetration in a (Neyveli geographical area) lignite core under ambient condition.

Table 3
Regression model summary for lignite core under ambient temperature regime.

Model Summary				
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.950[a]	0.902	0.895	37.1004

Table 4
ANOVA for lignite core under ambient temperature regime.

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	32564.152	3	110451.298	80.425	.000[b]
	Residual	35913.218	27	1387.957		
	Total	385466.340	29			

Table 5
Coefficients Summary for lignite core under ambient temperature regime.

Coefficients[a]					
Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std.Error	Beta		
1 (Constant)	20.344	23.052		0.889	0.385
Mass flow rate (kg/s)	0.032	0.018	0.485	1.785	0.132
Velocity (m/s)	0.021	0.084	0.037	.295	0.769
Fluid Recovery (%)	29.865	23.045	0.468	1.182	0.221

[a] Dependent Variable.

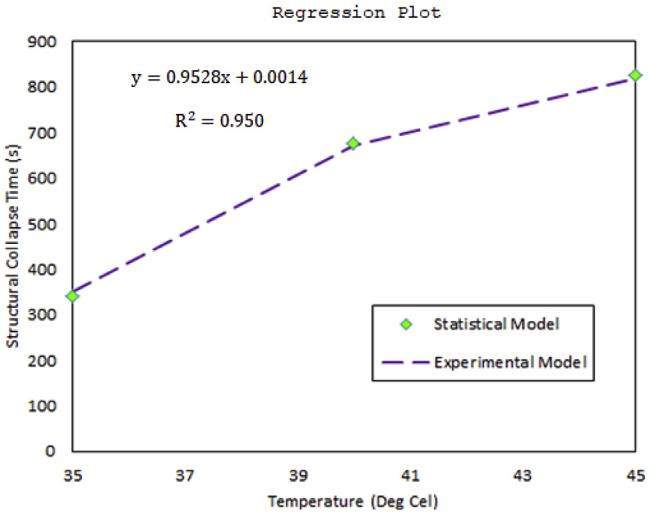

Fig. 10. Regression plot and model validation.

4. Conclusions

The lignite rocks from Neyveli Lignite Samples were acquired and successfully simulated. Also, the geology of Neyveli and Cauvery basin were critically analyzed. Following conclusions can be drawn based on the experimental outcomes:

1) The initial waterflood test indicated good recovery of gas in the lignite core. After that the recovery was stopped completely due to large fractures and structural collapse. Additionally, coal and kaolinite fines that were present in cleats contributed to the permeability decline and pore passage crumple.
2) Furthermore, it was proved that higher waterflood velocity produces large amount of coal fines, since high waterflood velocity generates more fractures across the core and its impact leads to the rapid collapse of the lignite core. Also, it was noticed that increasing PVI decreases the fines concentration.
3) After permeability damage, a plummet in pressure across the lignite

core was observed at all three ambient conditions. Moreover, kaolinite flakes, coal fines, and water content were observed in the FESEM images under 1 μm magnification for all three samples. In addition, statistical results were obtained for experimental and regression models. Finally, it is clear and well understood that lignite seam reservoirs are also prone to fines migration and coal fines production under normal fluid flow conditions. Hence, this may be the first paper to elucidate the importance of kaolinite clay and coal fines production in lignite deposits.

Acknowledgement

The lead author would like to thank Dr. B. Kanimozhi, Professor of Thermal Engineering at Sathyabama University for FESEM acquisition and fruitful discussions on hydrodynamic behavior of lignite. VP and RSK thank Mr. Aran Castro, Research Scholar at Earth Science Department of Annamalai University for the Neyveli lignite map acquisition. Also, especial thanks to Mr. N. Sankaranarayanan, Assistant General Manager at Neyveli Lignite Corporation for supplying the lignite samples and analytical test data. Additionally, we thank the anonymous reviewers for their invaluable comments for the improving the quality of this paper.

References

Aji, K., 2014. Experimental investigation on the impact of coal fines generation and migration on coal permeability. Asia Pac. J. Chem. Eng. 9, 535–542.

Bai, T., Chen, Z., Aminossadati, S.,M., Rufford, T.,E., Li, L., 2017. Experimental investigation on the impact of coal fines generation and migration on coal permeability. J. Petrol. Sci. Eng. 159, 257–266.

Borazjani, S., Behr, A., Genolet, L., Van Der Net, A., Bedrikovetsky, P., 2017. Effects of fines migration on low-salinity waterflooding: analytical modelling. Transport Porous Media 116, 213–249.

Cao, L., Yugui, Z., 2018. Interpretation of Gibbs surface excess model for gas adsorption on heterogeneous coal particle. Fuel 214, 20–25.

Chakraborty, N., Sarkar, S., 2018. Syn-sedimentary tectonics and facies analysis in a rift setting: cretaceous Dalmiapuram formation, Cauvery basin, SE India. J. Palaeogeogr. 7, 146–167.

Feng, L., Yuan, C., Mao, L., Yan, C., Jiang, X., Liu, J., Liu, X., 2018. Water occurrence in lignite and its interaction with coal structure. Fuel 219, 288–295.

Guo, Z., Hussain, F., Cinar, Y., 2015. Permeability variation associated with fines production from anthracite coal during water injection. Int. J. Coal Geol. 147–148, 46–57.

Han, G., Ling, K., Wu, H., Gao, F., Zhu, F., Zhang, M., 2015. An experimental study of coal-fines migration in Coalbed-methane production wells. J. Nat. Gas Sci. Eng. 26, 1542–1548.

Huang, F., Kang, Y., You, L., Li, X., You, Z., 2018. Massive fines detachment induced by moving gas-water interfaces during early stage two-phase flow in coalbed methane reservoirs. Fuel 222, 193–206.

Khilar, K., Fogler, H., 1998. Migrations of Fines in Porous Media. Kluwer Academic Publishers, Dordrecht.

Liu, X., Song, D., He, X., Nie, B., Wang, Q., Sun, R., Sun, D., 2018. Coal macromolecular structural characteristics and its influence on coalbed methane adsorption. Fuel 222, 687–694.

NLC, M., 2018. Neyveli Lignite Corporation Ltd.

Paria, S., Khilar, C.,K., 2004. A review on experimental studies of surfactant adsorption at the hydrophilic solid-water interface. Adv. Colloid Interface Sci. 110, 75–95.

Pranesh, V., 2016. Statistical Modelling of American Unconventional Petroleum Reservoirs: Bakken and Eagle Ford Shale Fields, first ed. LAP LAMBERT Academic Publishing, Germany, pp. 85–95.

Pranesh, V., Thamizhmani, V., Ravikumar, S., Padakandla, S., 2018. Multiple linear regression theory based performance optimization of Bakken and Eagle Ford shale oil reservoirs. Int. J. Eng. Res. Appl. 8, 2248–9622.

Raha, S., Khilar, C.,K., Kapur, P.,C., Pradip, P., 2007. Regularities in pressure filtration of fine and colloidal suspension. Int. J. Miner. Process., vol. 84, 348–360.

Rao, D.,S., Nagendra, R., Mohideen, E.,R., Nayak, B.,R., 2009. Characterization of sulphides patches from the Neyveli lignite deposit. J. Miner. Mater. Char. Eng. 8, 223–228.

Russell, T., Pham, D., Neishaboor, M.,T., Badalyan, A., Behr, A., Genolet, L., Kowollik, P., Zeinijahromi, A., Bedrikovetsky, P., 2017. Effects of kaolinite in rocks on fines migration. J. Nat. Gas Sci. Eng. 45, 243–255.

Sen, T.,K., Khilar, C.,K., 2006. Review on subsurface colloids and colloid-associated contaminant transport in saturated porous media. Adv. Colloid Interface Sci. 119, 71–96.

Ding, S.,L., Liu, Q.,F., Wang, M.,Z., 2009. Study of kaolinite rock in coal bearing stratum, North China. Procedia Earth Planet. Sci., vol. 1, 1024–1028.

Sundaram, R., Henderson, R.,A., Ayyasami, K., Stilwell, J.,D., 2001. A lithostratigraphic revision and palaeo environmental assessment of the Cretaceous System exposed in the onshore Cauvery Basin, Southern India. Cretac. Res. 22, 743–762.

Valentim, B., Flores, D., Guedes, A., Shreya, N., Paul, B., Ward, C.,R., 2016. Vermicular kaolinite relics in fly ash derived from Bakaro and Jharia coals (Jharkhand, India). Int. J. Coal Geol., vol. 162, 151–157.

Veevers, J.J., Powell, C.McA., Roots, D., 1991. Review of seafloor spreading around Australia, I: synthesis of the pattern of spreading. Aust. J. Earth Sci. 38, 415–433.

Wang, Y., Zhou, J., Bai, L., Chen, Y., Zhang, S., Lin, X., 2014. Impacts of Inherent O-containing functional groups on the surface properties of Shengli Lignite. Energy Fuels 28, 862–867.

Yao, Z., Cao, D., Wei, Y., Li, X., Wang, X., Zhang, X., 2016. Experimental analysis on the effect of tectonically deformed coal types on fines generation characteristics. J. Petrol. Sci. Eng. 146, 350–359.

Zeinijahromi, A., Vaz, A., Bedrikovetsky, P., 2012. Well impairment by fines migration by gas fields. J. Petrol. Sci. Eng. 88–89, 125–135.

Zhang, Y., Lebedev, A., Al-Yaseri, A., Yu, H., Xu, X., Sarmadivaleh, M., Barifcani, A., Iglauer, S., 2018a. Nanoscale rock mechanical property changes in coal after water adsorption. Fuel 218, 23–32.

Zhang, S., Liu, J., Wei, M., Elsworth, D., Sarmadivaleh, M., Barifcani, A., Iglauer, S., 2018b. Coal permeability maps under the influence of multiple coupled processes. Int. J. Coal Geol. 187, 71–82.

Zhao, X., Liu, S.A., Sang, S., Pan, Z., Zhao, W., Hu, Q., Yang, Y., 2016. Characteristics and generation mechanism of coal fines in coalbed methane wells in the Southern Qinshui Basin, China. J. Nat. Gas Sci. Eng. 34, 849–863.

Zhao, L., Ward, C.,R., French, D., Graham, I.,T., Dai, S., Yang, C., Xie, P., Zhang, S., 2018. Origin of a kaolinite-NH_4 –illite-pyrophyllite-chlorite assemblage in a marine –influenced anthracite and associated strata from the Jincheng Coalfield, Qinshui Basin, Northern China. Int. J. Coal Geol. 185, 61–78.

Zhou, S., Liu, D., Cai, Y., Karpyn, Z., Yao, Y., 2018. Comparative analysis of nanopore structure and its effect on methane adsorption capacity of Southern Junggaar Coalfield coals by gas adsorption and FIB-SEM topography. Microporous Mesoporous Mater. 272, 117–127.