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Characterisation of creep in coal and its impact on permeability: An experimental study

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ABSTRACT

Creep is a time-dependent deformation that affects coal permeability and should be considered in the prediction of Coalbed Methane (CBM) production. This study experimentally characterises and quantifies the impact of creep on coal permeability. The experiments were conducted on a bituminous coal sample, excavated from Bowen Basin, Australia, using a triaxial gas rig equipped with strain and displacement transducers. Two different types of gases (helium and methane) were injected into the sample under various stress and pore pressure conditions. It was found that for the experiments with helium, creep caused permanent partial closure of cleats and pathways under constant effective stress, and hence a reduction in permeability. Under hydrostatic stress only, a Residual Deformation Ratio (*RDR*) of 14.1% and a Permeability Loss Ratio (*PLR*) of 71% were found following the removal of the axial load. This can be due to the damage to coal microstructure along with closure of cleats. For the experiments with methane, coal experienced an instantaneous elastic deformation, at the onset of pore pressure depletion, followed by consolidation and matrix shrinkage. Then, creep occurred when gas desorption ceased. A total permeability loss of 26% was achieved due to an increase of 1.91 MPa in effective stress caused by gas desorption. In addition, the model previously developed by authors was validated against the experimental permeability data. A good agreement was found between the model-predicted permeability data and the experimental permeability data, particularly for higher pore pressure ranges.

1. Introduction

Coal permeability is a critical parameter for the prediction and evaluation of Coalbed Methane (CBM) production. Coal is a dual-porosity medium composed of cleats and matrices, which are the main conduit for gas migration and storage site, respectively. The change of coal permeability results from variation of effective stress and shrinkage and swelling of coal matrix owing to desorption and sorption of the gases in the reservoir. Matrix shrinkage and cleat compression mechanisms have inverse effects on permeability during CBM production. Whereas matrix shrinkage leads to dilation of coal cleat and an increase in permeability, cleat compression results in a decrease in permeability. The effects of the two mechanisms on coal permeability have been extensively studied (Levine, 1996; Palmer and Mansoori, 1996, 1998; Seidle and Huitt, 1995; Shi and Durucan, 2004).

Alteration in porosity due to deformation of cleat-matrix assemblage leads to change of permeability. Deformation in coal can occur much faster due to being much softer than adjacent rocks (roof and floor rocks) (Brantut et al., 2013; Kaiser and Morgenstein, 1981). The relative softness of coal is due to large macromolecular organic networks in coal that do not possess strong bonds (Espinoza et al., 2016). Coal deformation process occurs at very slow rates during coalification and formation of overlying sedimentary rocks over geologic time scales. However, the deformation process (elastic and/or inelastic) may accelerate due to increasing effective stress during extraction of fluids in the reservoir (Schatz and Carroll, 1981). The impact of elastic deformation on coal permeability has been considered by some researchers (Liu and Rutqvist, 2010; Pan and Connell, 2011; Shi and Durucan, 2004). Nevertheless, investigations on the effect of inelastic deformation on coal permeability have not been carried out rigorously. Inelastic deformation of coal may occur during CBM production and well shut-in at static pore pressure. Compaction of coal reservoir occurs due to pressure depletion under uniaxial strain condition (the reservoir is confined laterally), which causes reduction in permeability and hence production rate (Wang et al., 2012). The mechanically induced compaction of coal due to increased effective stress is generally called primary consolidation, which is an inelastic deformation. When effective stress is constant,

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Nomenclature

A,B,C	experimental coefficients, dimensionless
c_f	fracture compressibility, Pa^{-1}
E_e	Young's modulus of elasticity, Pa
$E_{e,i}$	Young's modulus of elasticity in i direction $(i=x,y,z)$, Pa
$E_{e,j}$	Young's modulus of elasticity in j direction $(j=x,y,z)$, Pa
E_{ve}	Young's modulus of visco-elasticity, Pa
$E_{ve,i}$	Young's modulus of visco-elasticity in
i	direction $(i=x,y,z)$, Pa
k	permeability, Darcy
k_0	initial permeability, Darcy
p	pore pressure, Pa
p_0	initial pore pressure, Pa
P_d	downstream pressure, Pa
P_L	Langmuir pressure constant, Pa
P_u	upstream pressure, Pa
PLR	porosity loss ratio, dimensionless
Q	flow rate, m^3/s
RDR	residual deformation ratio, dimensionless
t	time, hr
t_f	failure time, hr
t_y	yield time, hr
V_L	Langmuir volume constant, m^3/kg

Greek letters

α_i	thermal coefficient in i direction $(i=x,y,z)$, $°C^{-1}$
$\Delta\varepsilon_T$	thermal strain increment, dimensionless
$\Delta\varepsilon_{T,i}$	directional thermal strain increment $(i=x,y,z)$, dimensionless
$\Delta\varepsilon^{s,axi}$	axial shrinkage strain increment, dimensionless
$\Delta\varepsilon^{s,axi}_{\max}$	maximum axial shrinkage strain increment, dimensionless
$\Delta\varepsilon_i$	directional total strain $(i=x,y,z)$, dimensionless
$\Delta\varepsilon^s_i$	shrinkage strain increment in i direction $(i=x,y,z)$, dimensionless
$\Delta\varepsilon^{con,s}_{axi}$	axial consolidation and shrinkage strains
$\Delta\varepsilon_{axi}$	total axial strain increment, dimensionless
$\Delta\varepsilon_e,axi$	axial elastic strain increment, dimensionless
$\Delta\varepsilon_{ve},axi$	axial visco-elastic strain increment, dimensionless
$\Delta\varepsilon_{vp}-$	
lt,axi	visco-plastic deformation in axial direction, if long-term strength exceeded
$\Delta\varepsilon_{vp}-$	
st,axi	visco-plastic deformation in axial direction, if short-term strength exceeded
$\Delta\sigma_{eff},i$	effective stress increment in i direction $(i=x,y,z)$, Pa
$\Delta\sigma_i$	stress increment in i direction $(i=x,y,z)$, Pa
$\Delta\sigma_j$	stress increment in j direction $(j=x,y,z)$, Pa
ΔT	temperature increment, °C
ε	total strain, dimensionless
ε_e	elastic strain, dimensionless
ε_L	parameter of Langmuir curve, dimensionless
$\varepsilon_{\max,axi}$	maximum axial deformation, dimensionless
ε_p	plastic or residual deformation, dimensionless
ε_{ve}	visco-elastic strain, dimensionless
ε_{vp}	visco-plastic strain, dimensionless
η_i	viscosity coefficient in i direction $(i=x,y,z)$, $Pa\cdot s$
η_j	viscosity coefficient in j direction $(j=x,y,z)$, $Pa\cdot s$
η_{ve}	viscosity coefficient of visco-elastic media, $Pa\cdot s$
η_{ve},i	viscosity coefficient of visco-elastic media in i direction $(i=x,y,z)$, $Pa\cdot s$
η_{vp}	viscosity coefficient of visco-plastic media, $Pa\cdot s$
μ	gas viscosity, $Pa\cdot s$
υ	Poisson's ratio, dimensionless
υ_{ji}	component of the Poisson's ratio tensor $(i,j=x,y,z;i\neq j)$, dimensionless
σ	stress, Pa
σ_a	axial stress, Pa
σ^e_h	horizontal effective stress, Pa
σ^e_h0	initial horizontal effective stress, Pa
σ_{ls}	long-term strength, Pa
σ_r	radial stress, Pa
σ_{ss}	short-term strength, Pa

the compaction is known as secondary consolidation or creep, which is also an inelastic deformation (Barden, 1968; Bjørlykke et al., 2010). However, it is sometimes difficult to differentiate between genuine creep and consolidation effects (Fjær et al., 2008).

Creep is a mechanical and/or chemical process that is initiated by microstructure deterioration or restructuring of rocks. It is affected by parameters such as temperature, stress, and time. Creep can occur through four mechanisms namely: (1) Cataclasis: a delayed deterioration of microstructure that its dependency on time is relatively negligible and also generates a finite stress-dependent deformation (Fabre and Pellet, 2006; Frayne et al., 1990); (2) Pressure solution: solubility of the solids immersed in liquids change with stress (Yost and Aronson, 1987), or in other words, stress induces dissolution-precipitation. This type of creep may be dominant when water-gas two phase flow exists in coal reservoir; (3) Granular creep or particulate sliding: the imposition of grains rearrangement by frictional sliding as well as pressure solution in order to accommodate grain shape alteration throughout compaction process (Frayne et al., 1990); and (4) Adsorption-diffusion: a temporary compaction deformation induced by adsorption or diffusion which is different from that of permanent deformation of solid phase (Hol et al., 2013; Sone and Zoback, 2010). The dominant creep mechanism is determined by material properties such as moisture content, grain size, and strength as well as in situ conditions such as stress and strain rates (Frayne et al., 1990). Considering single-phase flow in coal, the dominant creep mechanisms are cataclasis and particulate sliding. In cataclastic flow regime, permeability and porosity are affected by the development of microstructure during compressive cataclastic failure (Zhu and Wong, 1997). Development of compaction is influenced by initial stress state and the stress path in the reservoir during drainage (Settari, 2002).

The impact of mechanical properties and rank on coal deformation and permeability has been extensively studied. Uniaxial compressive strength and Young's modulus increase with coal rank. This is due to less microporous structure of higher rank coal (Pan et al., 2013). Also, studies show higher permeability with pore pressure depletion for the coal with higher lateral Young's modulus (parallel to bedding) (Danesh et al., 2016; Pan and Connell, 2011). Higher rank coals such as anthracite do not creep and generally break explosively in uniaxial compression tests (Pomeroy, 1956). This is because coal matrix and cleat systems are generally stiffer (or denser) in higher rank coals, during the loading process under equal conditions, so that the matrix and cleat systems accommodate less creep deformation compared to lower rank coals. Hence, permeability change for higher rank coals is expected to be less.

Triaxial compression tests have been conducted for simulation of in-situ conditions for coal in order to measure coal geomechanical properties. In such tests, axial and hydrostatic stresses are applied to the coal core that is saturated with a specific gas (e.g. CH_4, CO_2, N_2). Some studies have been carried out on coal characteristics under triaxial compression (Hobbs, 1964; Lin, 2010; Pan et al., 2010) as well as when high pressure gas is involved (Alexeev et al., 2012; Ujihira et al., 1985). In addition,