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Relationships between permeability, porosity and effective stress for low-permeability sedimentary rock

Jiangtao Zheng [a,b], Liange Zheng [b], Hui-Hai Liu [c], Yang Ju [a,b,d,*]

[a] State Key Laboratory of Coal Resources and Safe Mining, China University of Mining & Technology, Beijing 100083, China
[b] Earth Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
[c] Aramco Research Center, Houston, TX 77084, USA
[d] State Key Laboratory for Geomechanics and Deep Underground Engineering, China University of Mining & Technology, Xuzhou 221006, China

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ABSTRACT

As the effective stress increases, low-permeability rock undergoes fairly small porosity changes, but significant decrease in the permeability. Empirical relationships based on laboratory-measured data, typically exponential or power laws, have been proposed to describe the stress–permeability, stress–porosity, and permeability–porosity relationships. However, these approximations yield poor fitting in low effective stress ranges, or unreasonable prediction for certain effective stresses. In this study, we develop a series of theoretical models for the essential relationships among the porosity, permeability and the effective stresses for low-permeability sedimentary rock, based on the concept of Two-Part Hooke's Model (TPHM). The TPHM conceptualizes an intact rock into a soft part and a hard part, which comply with the natural-strain-based and engineering-strain-based Hooke's law, respectively. The derived relationships are validated by the experimental data from the literature. The comparisons show that the theoretical predictions agree well with the experimental results. The soft-part, comprising of only a small portion of the rock body, is responsible for the significant permeability reduction in low stress levels. The high stress-sensitivity of permeability is mainly attributed to the micro-crack (soft-part) closure in the intact rock.

1. Introduction

The stress-dependence of porosity and permeability for low-permeability sedimentary rock is important for various engineering applications, such as fossil fuel exploitation,[1–8] CO_2 geological sequestration.[9,10] coal mining safety,[11–13] modeling fluid percolation and pore pressure evolution in the crust,[14–17] and nuclear waste disposal.[18,19] In oil and gas exploitation industry, the unconventional reservoirs, such as tight oil/gas formations, typically refer to those have in-situ permeability less than 0.1 mD ($1\ mD = 10^{-15}\ m^2$).[20,21] In this paper low-permeability sedimentary rock refers to those with permeability less than 0.1 mD under reservoir conditions. Nowadays, hydraulic fracturing is widely used to recover oil and natural gas from tight sandstones and shale gas reservoirs, which usually show highly stress-sensitive mechanical and/or hydraulic properties. Knowledge of the dependence of such properties on stress is critical for production estimation and recovery method design.[3,6] Geologic carbon sequestration (GCS) has been considered as one of the effective method for mitigating the global climate change. The permeability evolution with effective stress of the caprock, usually low-permeability formations, is vital for predicting its retarding effects of the upward CO_2 migration and thus the safety of the GCS site.[10,22] Similarly, low-permeability formations such as clay rocks have long been considered as one of the promising host rock for the disposal of radioactive nuclear waste. The stress-dependence of porosity and permeability in these formations, especially in an excavation damaged zone (EDZ), is of great importance for the performance assessment of the disposal site.[19]

The permeability and porosity changes with effective stress are complex for low-permeability rock. Particularly, a significant drop of permeability is usually observed for low-permeability rock in a low-effective stress range and accompanied with a small porosity decrease. In contrast, the permeability and porosity decrease with increasing effective stress are usually in a predictive manner for high-permeability rock.[14,16,23] It is hard to provide a physically robust explanation for the hydraulic behavior of low-permeability rock using the current models.

With an increase in effective stress, low-permeability rock undergoes fairly small porosity changes, typically less than 10% of the porosity value under zero stress conditions.[6,24–27] Some

* Corresponding author at: State Key Laboratory of Coal Resources and Safe Mining, China University of Mining & Technology, Beijing 100083, China
E-mail addresses: juy@cumtb.edu.cn, yju@lbl.gov (Y. Ju).

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empirical relationships, usually exponential laws, have been proposed between porosity and effective stress based on laboratory-measured data.[28–32]

In contrast, significant permeability decreases have been observed with relatively small increases in effective stress. For example, with the effective stress increases from zero to around 15 MPa, the permeability of this type of rock usually decreases more than one order of magnitude.[1,6,14–16,24,33,34] Such a phenomenon is referred to stress-sensitive rock permeability at low effective stress levels. It should be noted that the artificial cracks or dilation cracks during the sample preparation may play an non-negligible role in the permeability drop with the effective stress increase.[4] However, the stress-sensitivity also exists in the unloading cycle of stress-dependent permeability tests.[14,35] in which most of the artificial cracks have been closed by the previous loading. Furthermore, as pointed out by Mclatchie et al.[1] and Vairogs et al.[2] for tight sandstones, the lower the reference permeability (routinely tested permeability), the greater the permeability reduction (in terms of percentage) under increasing effective stress. Some empirical relationships between permeability and effective stresses were proposed based on laboratory-measured data. Representative relationships include exponential laws[16,36–38] and power laws.[14,15,30,39] However, the exponential laws yield poor fitting in low effective stress ranges and the power laws give unreasonable prediction for certain effective stress values.

To describe the relationship between the significant permeability drop and insignificant porosity reduction under effective stress has been a great challenge for scientists over a long time. Up to now, empirical relationships, usually in the form of a power law, were used to relate permeability and porosity under effective stress based on laboratory-measured data. For example, Dong et al.[14] systematically measured the porosity and permeability change with increasing effective stress. The relationship between permeability and porosity was represented by a power law, i.e. $k/k_0 = (\phi/\phi_0)^m$, where ϕ and ϕ_0 are the porosity under the current stress state and ambient conditions, respectively; k and k_0 are the permeability under the current stress state and ambient conditions, respectively; m is a material constant named the porosity sensitivity exponent of permeability. The underlying assumption in relating permeability change to the total porosity change is that the reduction of the total volume of pore space is the only driver for the permeability decrease—an assumption that leads to some problems with these relationships, one of which is the abnormally high value of m. As known, if the flow path is largely controlled by slot-like micro-crack networks (as has been postulated by many researchers[6,11,14,16,25,26,38–42]), the permeability change with the crack aperture reduction (reflected by porosity reduction) should approximately obey the "cubic law"[42,43] which implies that value of m should be around 3. However, the calculated values of m based on the experimental data for low-permeability samples were much higher than 3, with m value up to 70.17.[14,16] The extremely high exponent in the current power law for the relationship between permeability and porosity suggests that relating permeability changes to the total porosity changes is not a valid assumption. In this paper, we therefore attempt to establish relationships that are more physically reasonable for low-permeability rock.

This study is based on the concept of the Two-part Hooke's model (TPHM), which is a macroscopic model that deals with mechanisms of micro-mechanics in a phenomenological manner.[44,45] Natural rock, which contains different mineral compositions, pores and micro-cracks, are inherently heterogeneous and will experience non-uniform deformation under uniform stress. This has been demonstrated by both experimental observations and theoretical analyses. For instance, Zimmerman[46] analyzed the compressibility of sandstones from a micro-mechanical point of view and pointed out that the pore structure is the main reason that the compressibility of sandstone changes with stress. Similarly, Jaeger et al.[47]stated the crack-like voids in a porous rock samples are responsible for the observed nonlinear deformation in low stress range. Distinguishing the influences of different types of pore structure (stiff and compliant porosity), was also employed by Shapiro et al.[48] for better interpretation of the rock physical behavior. More recently, Liu et al.[44,45] conceptually divided the rock body into "soft" part and "hard" part and pointed out that the natural strain (volume change divided by rock volume at the current stress state), rather than the engineering strain (volume change divided by the unstressed rock volume), should be employed in Hooke's law for accurately modeling the elastic deformation, unless the two strains are essentially identical (as they might be for small mechanical deformations in the "hard" part). Based on this concept, a series of constitutive relations between stress and a variety of hydro-mechanical rock properties were derived, e.g., stress-dependent rock bulk compressibility, pore compressibility, rock porosity and fracture aperture.[44,45,49] The relationships derived using TPHM are consistent with those revealed from micromechanical point of views, albeit with different physical origins.[44] These relationships based on TPHM represent the experimental data in literature very well. However, the TPHM-based stress-dependent permeability relationship for a rock is not investigated yet in the literature. In this paper, we intend to formulate the stress-dependence of permeability based on the concept of TPHM. The derived relationships explain well the permeability stress-sensitive phenomena in the low effective stress range for low-permeability sendimentary rock. The cornerstone of our development is the recognition of the fact that porosities from the soft and hard parts have different contributions to the permeability change with stresses. As demonstrated in the late part of this article, the soft part, while only a small portion of the low-permeability rock, plays a critical role in the stress-dependent permeability relationship.

2. Existing relationships for stress-dependent rock properties

The stress-dependent rock mechanical and/or hydraulic properties have been extensively studied, due to their importance in engineering applications.[8,50–54] In this section, we discuss the existing empirical relationships for describing the stress-dependence of rock porosity and permeability. Also presented are relationships between rock permeability and porosity under different effective stresses. Note that the effective stress refers to the confining pressure minus the pore pressure in this paper.

2.1. Relationship between porosity and effective stress

The influence of effective stress on porosity for low-permeability sedimentary rock is relatively small.[25,26] The relationship between porosity and effective stress, albeit with a slightly different form, can be described by exponential function as shown in the following equations.

After studying the porosity of shale samples from various depths, Athy[28] presented the compaction induced porosity–depth relationship using an exponential equation:

$$\phi = \phi_0 \exp(-bx) \tag{1}$$

where ϕ is porosity at depth x, ϕ_0 is the porosity of surface sample, and b is a material constant. This relationship could also be applied to sandstones.[29] Because the equivalent effective stress can be deduced from burial depth, Shi and Wang[30] reformat Eq. (1)