Evolution of Permeability Anisotropy in Coal: An Experimental Study

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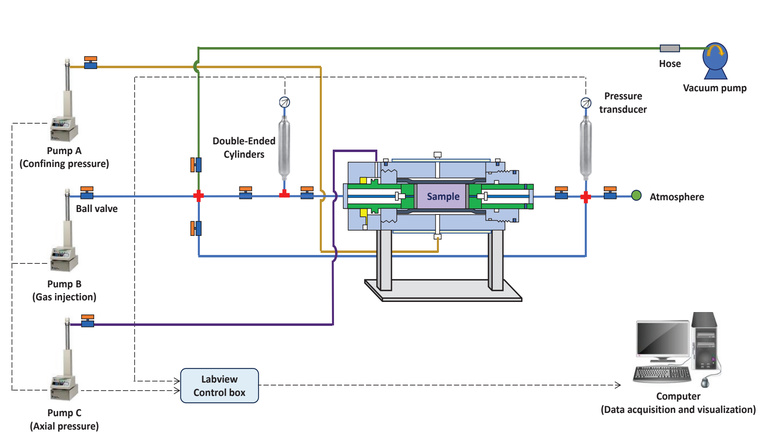
Introduction

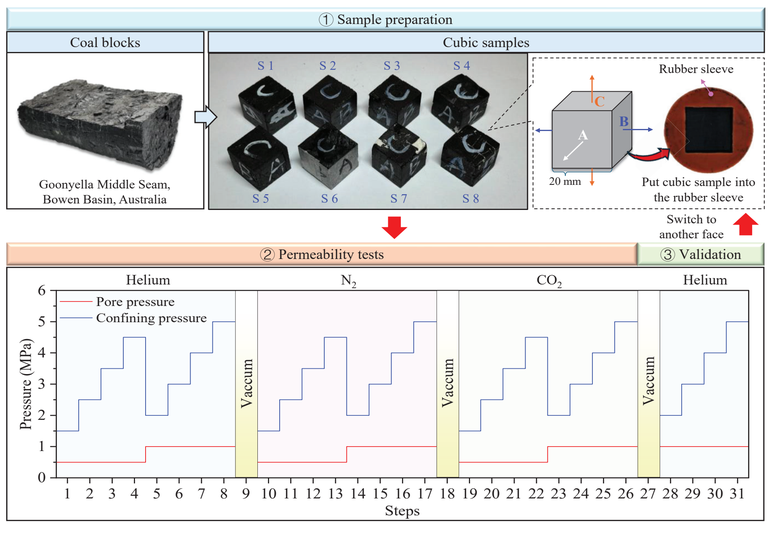
Coal seams serve not only as reservoirs for coal seam gas (CSG), but also as promising candidates for CO_2 geological sequestration and underground compressed air energy storage (CAES). Gas flow in coal is primarily governed by its cleat system, leading to strong permeability anisotropy that directly affects borehole placement, injection efficiency, and long-term reservoir performance. While the anisotropic nature of coal permeability is well recognized, most predictive models assume isotropy or a constant anisotropy ratio, overlooking how anisotropy evolves under changes in effective stress or with gases of different adsorption affinities. To address this gap, this study systematically investigates the effective stress- and gas-dependent evolution of coal permeability anisotropy through extensive laboratory measurements on cubic coal samples. The outcomes provide insights that are directly applicable to optimizing borehole design and improving the reliability of CSG production, CO_2 storage, and CAES applications.

Methodology

The permeability experimental system (Fig.1. (a)) was designed for transient method measurements. Permeability was first measured with helium under stepwise confining pressure increases, at a constant axial pressure of 1.0 MPa and pore pressures of 0.5 and 1.0 MPa. Subsequent N_2 and CO_2 tests followed the same schedule, with adsorption equilibrium established prior to measurement. Tests were conducted in three orthogonal directions (A, B, C), with 24 h vacuuming between gases and directions to remove residuals. Finally, helium tests were repeated to assess measurement repeatability. (Fig. 1. (b))



(a)



(b)

Fig. 1: (a) Permeability experimental system. (b) Experimental procedure.

Results

Evolution of Anisotropy Ratio

To quantify the anisotropy of the coal samples, the anisotropy ratio (R) is defined as:

$$R = \frac{k_{max}}{k_{min}} \qquad (1)$$

where k_{max} is the maximum permeability and k_{min} is the minimum permeability among the three directions under the same stress conditions.

To establish a quantitative relationship between effective stress and R, we fitted R as a linear function of effective stress changes using Equations (2).

$$R = a \times (\sigma_e - \sigma_{e0}) + b \qquad (2)$$

By fitting the relationships between *a* and *b* with k_0 (Fig. 3.), the relationships between anisotropy ratio (R), effective stress change ($\Delta\sigma_e$), and initial permeability (k_0) can be expressed as shown in Table 1.
Table 2 . lists the critical values of k_0 under different gas conditions , at which the trend of anisotropy ratio with effective stress changes.. Fig.4. shows the effect of b on R at Zero $\Delta\sigma_e$.

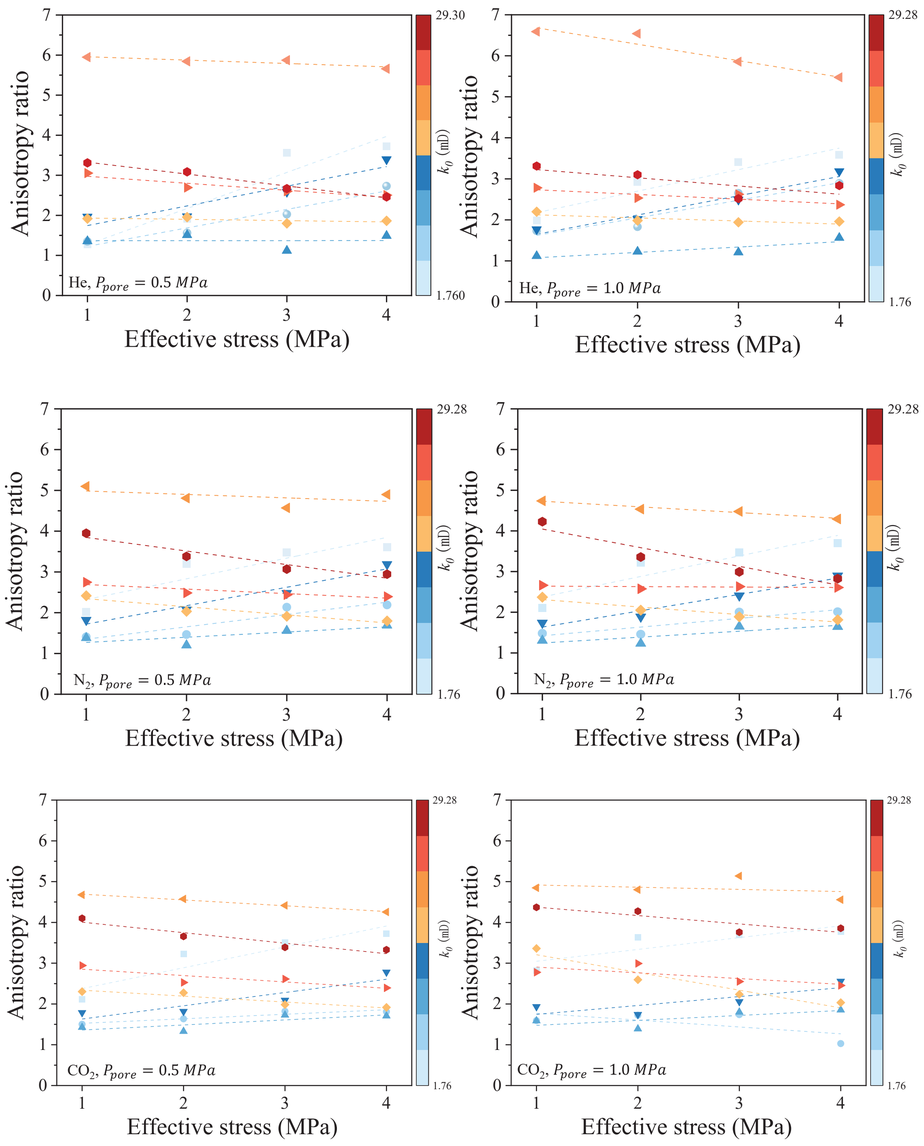


Fig. 2. Anisotropy ratio (R) of coal under varying effective stresses for different gases.

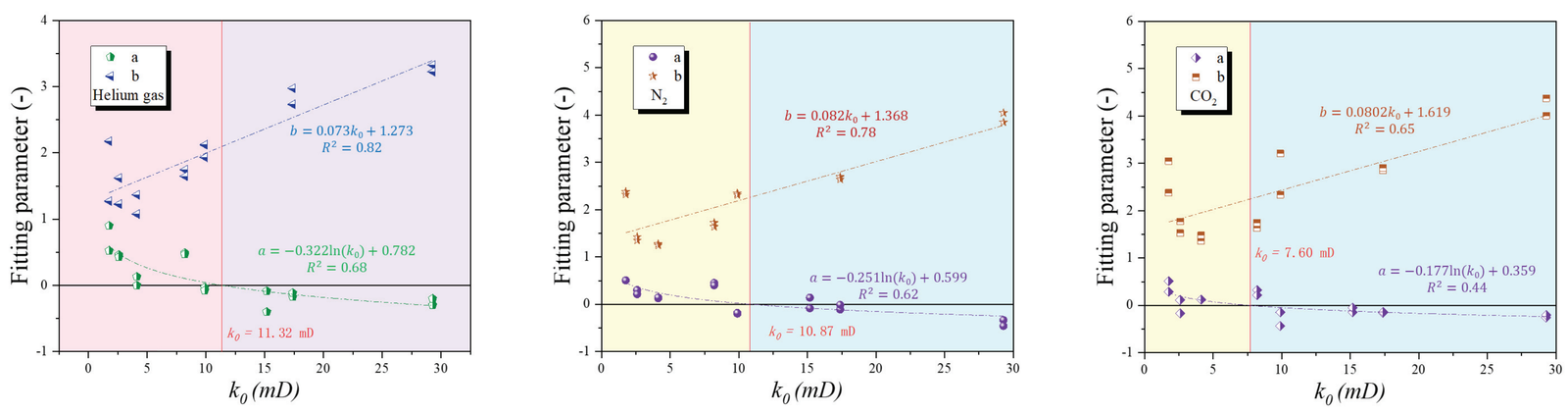


Fig. 3. Anisotropy ratio (R) of coal under different initial permeability (k_0)

Table 1. Fitted Expressions for R–$\Delta\sigma_e$–k_0 Relationships

Gas	Fitted Equations
He	$R = (-0.322 \times lnk_0 + 0.782) \times \Delta\sigma_e + 0.073 \times k_0 + 1.273$
N_2	$R = (-0.251 \times lnk_0 + 0.599) \times \Delta\sigma_e + 0.082 \times k_0 + 1.368$
CO_2	$R = (-0.177 \times lnk_0 + 0.359) \times \Delta\sigma_e + 0.082 \times k_0 + 1.629$

Table 2. Critical values of k_0

Gas	Critical value of k_0 (mD)
He	11.32
N_2	10.87
CO_2	7.60

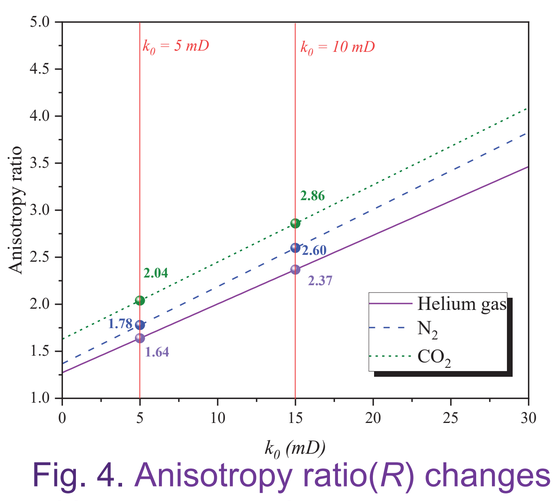


Fig. 4. Anisotropy ratio(R) changes with gas type and k_0

Conclusions

- Effect of effective stress on anisotropy ratio: Increasing effective stress reduces permeability in all directions.
- R depends on initial permeability k_0 :
  - Below critical k_0: ratio increases with stress.
  - Above critical k_0 : ratio decreases with stress.
- Effect of gas adsorption: Gas adsorption (N_2, CO_2) lowers the critical permeability. Adsorption leads to an increase in anisotropy ratio.

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