Impact of Cyclic Gas Injection on Well Integrity in Underground Compressed Air Energy Storage: an Experimental Study

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Introduction

Underground compressed air energy storage (CAES), which stores high-pressure air in subsurface formations using excess energy for later release during peak demand, offers an effective approach to grid stabilization. Recently, coal seams have attracted interest as potential CAES storage formations due to their inherent fracture networks and existing infrastructure.

The repeated gas injection and production create cyclic pressure loading around the wellbore, potentially weakens the injection well, inducing cumulative damage along the rock-cement-casing interfaces (Fig.1). These materials deform differently to cyclic loading, leading to possible leakage pathways and time-dependent wellbore instability, which has been little examined to date. To address this gap, this study conducts a series of experiments using a coal-cement-casing composite sample to evaluate damage evolution under cyclic gas injection. The outcomes enhance understanding of the near-wellbore deterioration mechanisms under cyclic loading and provide experimental evidence to assess time-dependent well integrity and different gases injectivity for long-term CAES operations.

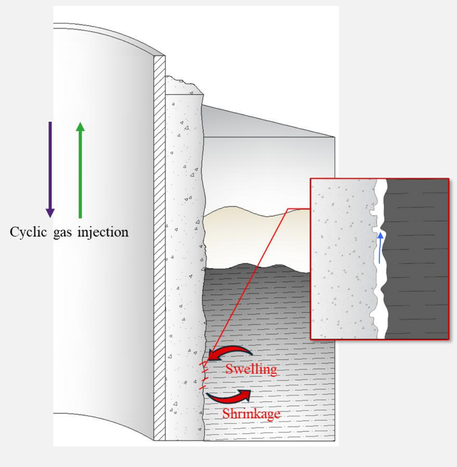

Fig. 1. interfacial degradation and potential leakage pathway induced by gas cyclic injection in CAES.

Methodology

A series of experiments was conducted to evaluate wellbore integrity under cyclic gas injection. Fig.2(a) presents the experimental setup used to perform cyclic gas injection under controllable confining pressure conditions, with permeability measured using the transient method.

A coal–cement–casing composite specimen was fabricated to replicate the geometry of an actual wellbore structure (Fig. 2(b)). Both the confining pressure and axial pressure were maintained at 4 MPa. One pressure cycle was defined as increasing the gas injection pressure from 0.5 MPa to 3.0 MPa and then reducing it back to 0.5 MPa.

Nitrogen was injected over 70 pressure cycles, during which permeability, gas adsorption capacity, and adsorption–desorption-induced strains were continuously monitored.

Results

Evolution of Permeability

- To investigate the evolution of permeability, measurements were conducted after every 5 or 10 pressure cycles. The permeability results are presented in Fig.3(a). At higher effective stress levels (1.5–2.5 MPa), permeability remains relatively stable, whereas a partial recovery is observed at an effective stress of 1 MPa.
- To better illustrate this trend, permeability data at 1 MPa effective stress are plotted separately in Fig.3(b). The results show a rapid decrease in permeability during the early cycles, followed by a gradual increase after approximately 20 cycles. This behaviour is likely associated with initial compaction and closure of pre-existing micro-fractures and cleats, followed by the progressive development of new micro-fractures.

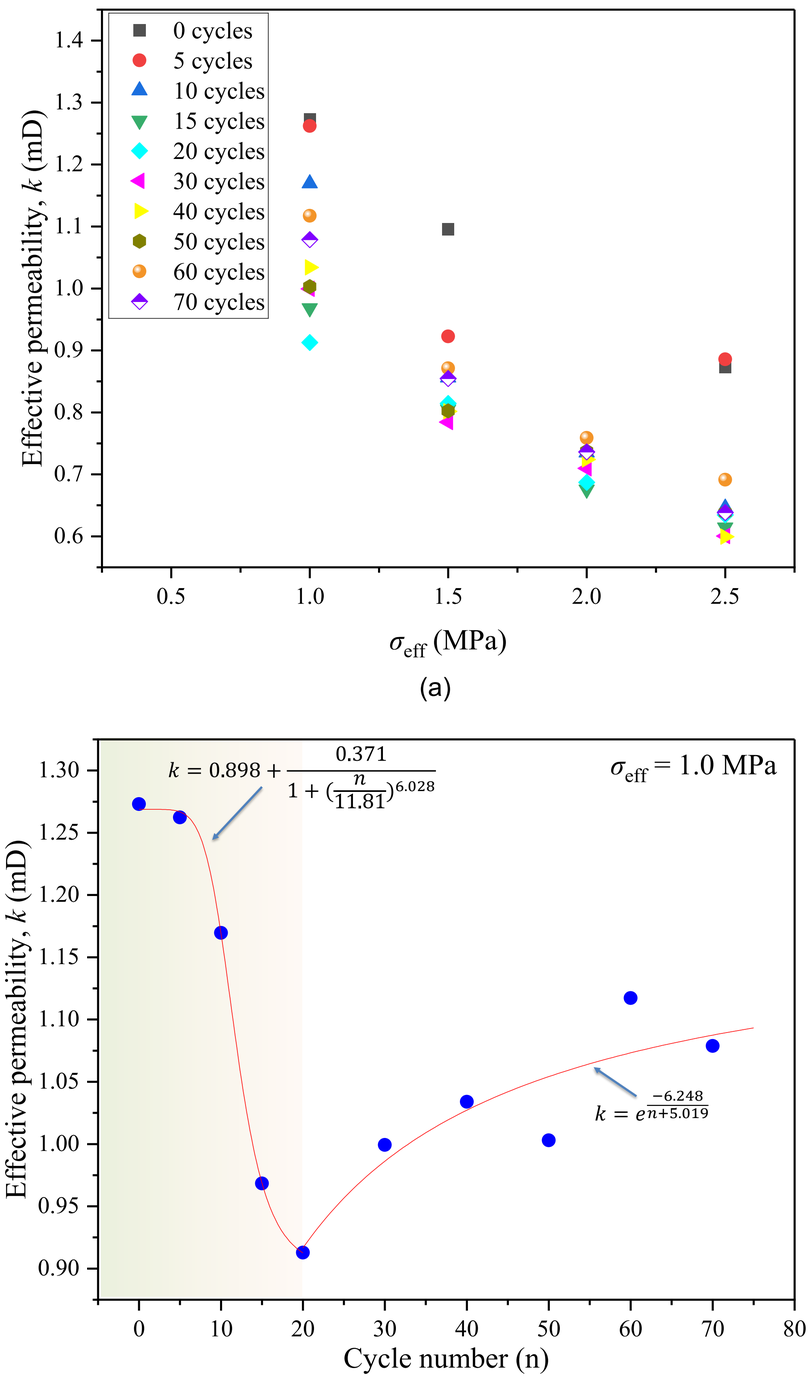

Fig. 3. (a) Permeability evolution under different effective stress levels, and (b) Permeability evolution at an effective stress of 1 MPa.

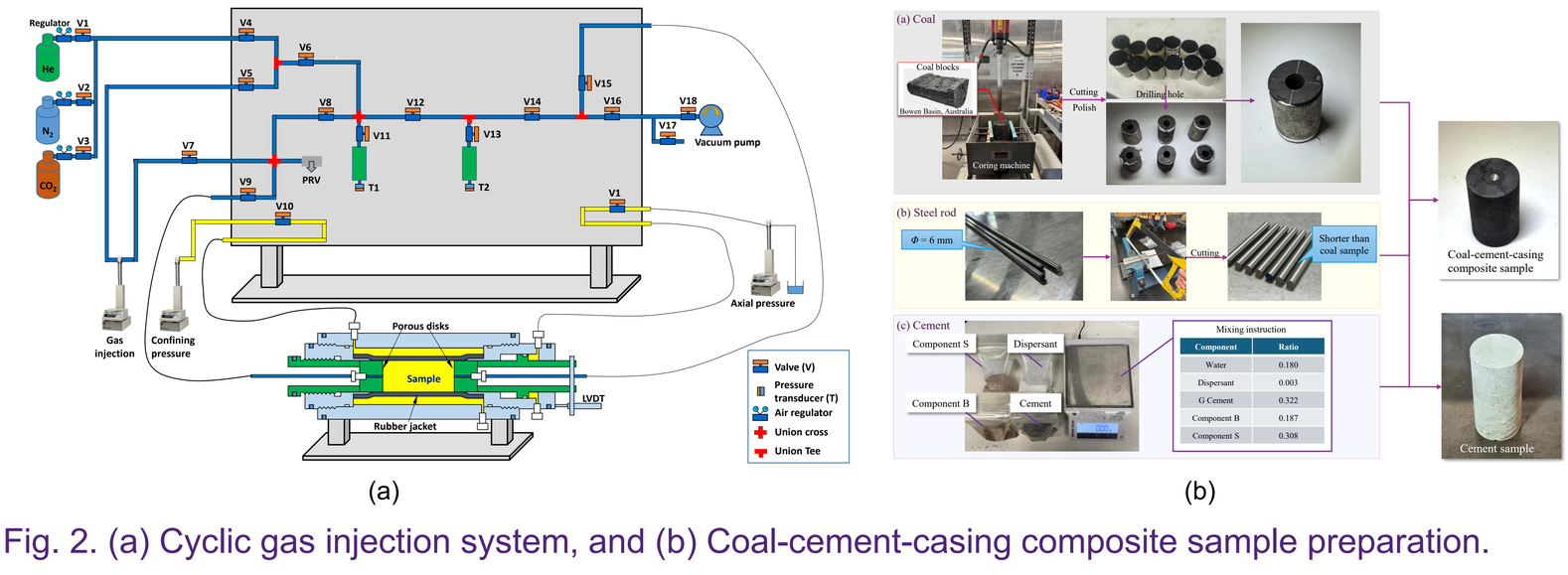

Fig. 2. (a) Cyclic gas injection system, and (b) Coal-cement-casing composite sample preparation.

Permeability Parameters Analysis

By fitting permeability data using equation (1), k_0 and C_f can be obtained.

$$k = k_0 exp(-3C_f * \Delta\sigma_e) \quad (1)$$

- k_0 is the permeability at the initial effective stress of σ_{e0}
- C_f is the cleat compressibility
- $\Delta\sigma_e$ is the effective stress change

The results suggesting that the fracture system is gradually weakening (Fig.4).

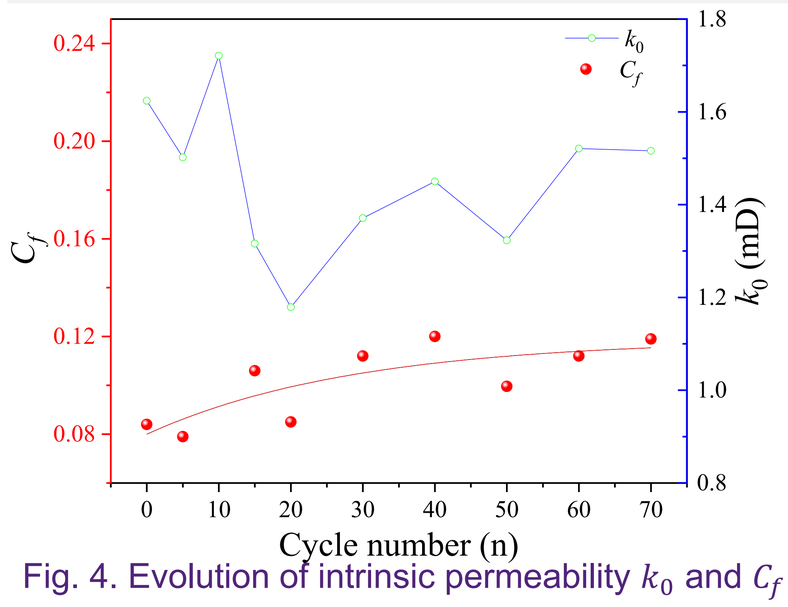

Fig. 4. Evolution of intrinsic permeability k_0 and C_f during cyclic injection.

Evolution of Pore Volume

Fig. 5(a) shows the adsorption volume (atm) per cycle, including both adsorbed gas and free gas within the sample pore space.

By converting the adsorption amount to the equivalent gas volume at 3 MPa, Fig.5(b) shows the porosity change per cycle.

The increasing pore volume suggests the development of new micro-fractures and increased accessible surface area.

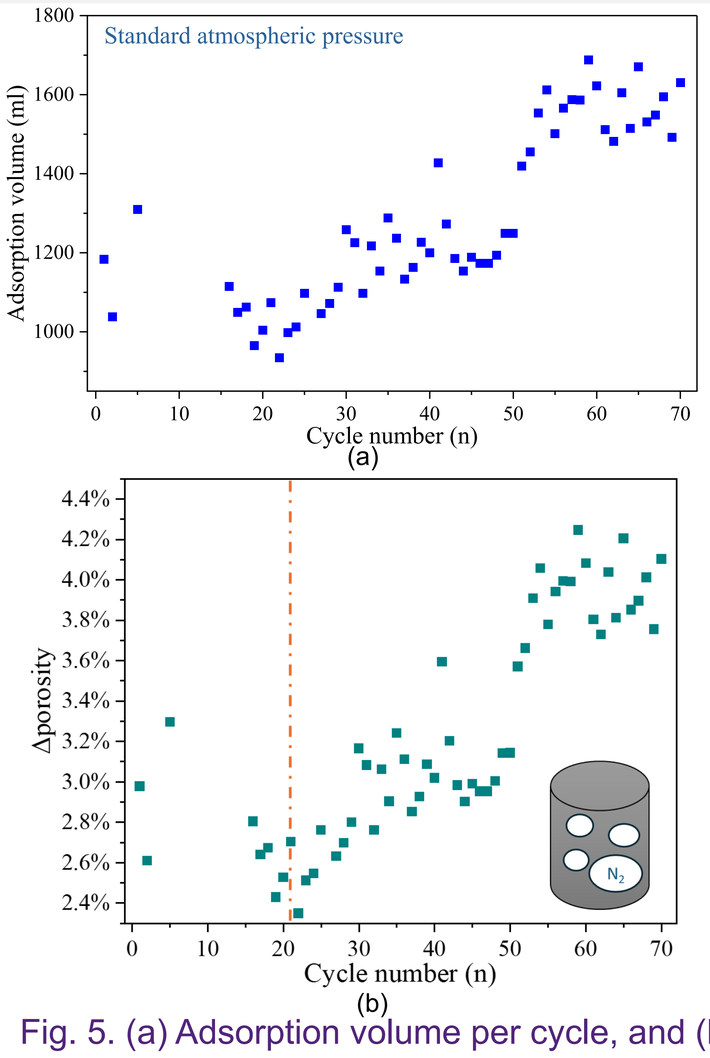

Fig. 5. (a) Adsorption volume per cycle, and (b) Porosity evolution per cycle.

Conclusions

- Permeability evolution shows a two-stage response, transitioning from initial compaction to progressive damage with cycling.
- Fitted permeability parameters indicate increasing cleat compressibility, consistent with mechanical weakening.
- Adsorption-induced pore volume increases support the development of new micro-fractures.