UQ Centre for Natural Gas

Experimental Study of Coal Directional Sorption-induced Strain Under Different Temperatures

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Introduction

Australian coal is highly cleated and has shown evident anisotropic flow behaviours, so, requires reliable inputs of directional coal mechanical and petrophysical properties to forecast or understand reservoir behaviour for CBM or ECBM recovery processes.

Unfortunately, such data is very scarce in the literature. In cases where the volumetric strain is not available, it's often sourced from literature, which may not always be for the same targeted coal seam. This presents a significant challenge to the confidence and reliability of the generated results.

Aims

- Quantify Australian coal sorption capacity and induced directional strain under various temperatures and
- Investigate the feasibility of estimating sorption-induced strain directly from the isotherm curves.

Research Questions

- What is the response of coal directional deformation to the gas injection and depletion?
- Is coal anisotropy affected by the type of absorbing gasses?
- How does the temperature affect coal adsorption capacity and directional deformation?
- Can we estimate coal strain values from the adsorbed gas amount, regardless of the type of adsorbing gas and reservoir temperature?

Background

Langmuir Isotherms

Langmuir equation is used to model the coal adsorption performance. The Langmuir volume constant V_L indicates the maximum capacity of a coal sample to adsorb gas and Langmuir strain constant ε_L indicates the maximum sorption-induced strain of a coal sample under an infinite pressure.

$$V = V_L \frac{P}{P + P_L}$$

$$\varepsilon = \varepsilon_L \frac{P}{P + P_L}$$

where V is the gas adsorption volume, ε is sorption-induced strain; P is the gas pressure; V_L, ε_L and P_L are the Langmuir volume, strain and pressure constants, respectively.

Method

Two rectangular coal samples (20 mm× 22 mm ×35 mm), taken from Goonyella middle seam named S1 and German Creek seam named S2, respectively, were prepared for this study. Anisotropic deformation of the sample was determined by attaching three strain gauges in the directions perpendicular to face cleats, butt cleats and the bedding plane (Figure 1 (a)). The experiments were conducted with the three gases (He, N_2 and CO_2) and three temperatures (35, 40 and 45 °C). The gas injection procedures are as follows:

1. Set up the T= 35°C
2. Helium injection from vacuum to 9 MPa
3. Start gas depletion to 1 MPa then vacuum
4. Repeat the whole process for T= 40°C, and 45°C
5. Once Helium gas measurement is done, then replace it with Nitrogen and CO_2, and repeat the above steps

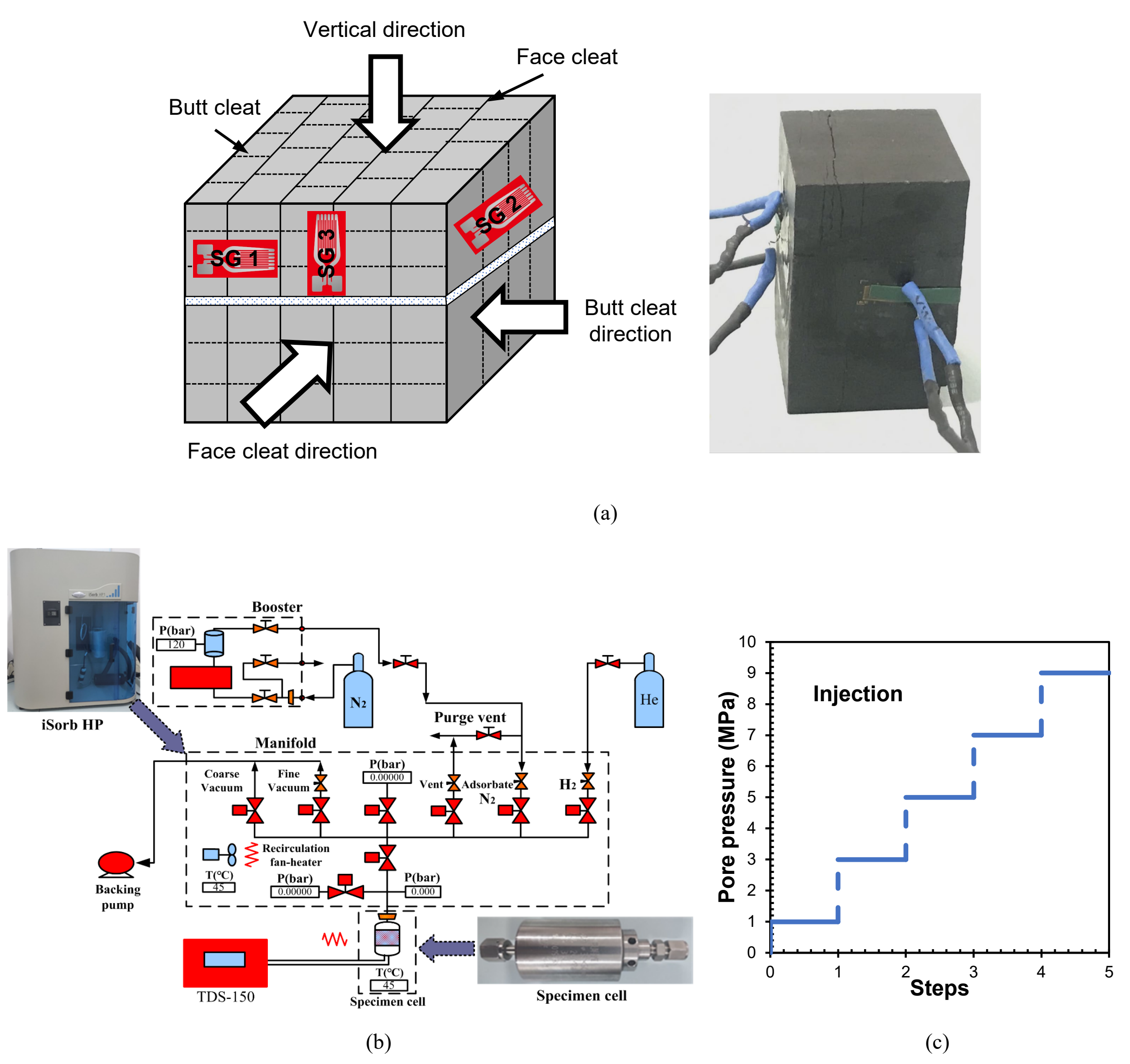

Figure 1: (a) Illustrations of coal sample and strain gauge orientations where SG 1, SG 2, SG 3 represent face cleat direction, butt cleat direction and vertical direction, respectively. (b) Experimental system and setup. (c) Pressure sequence for He , N_2 and CO_2

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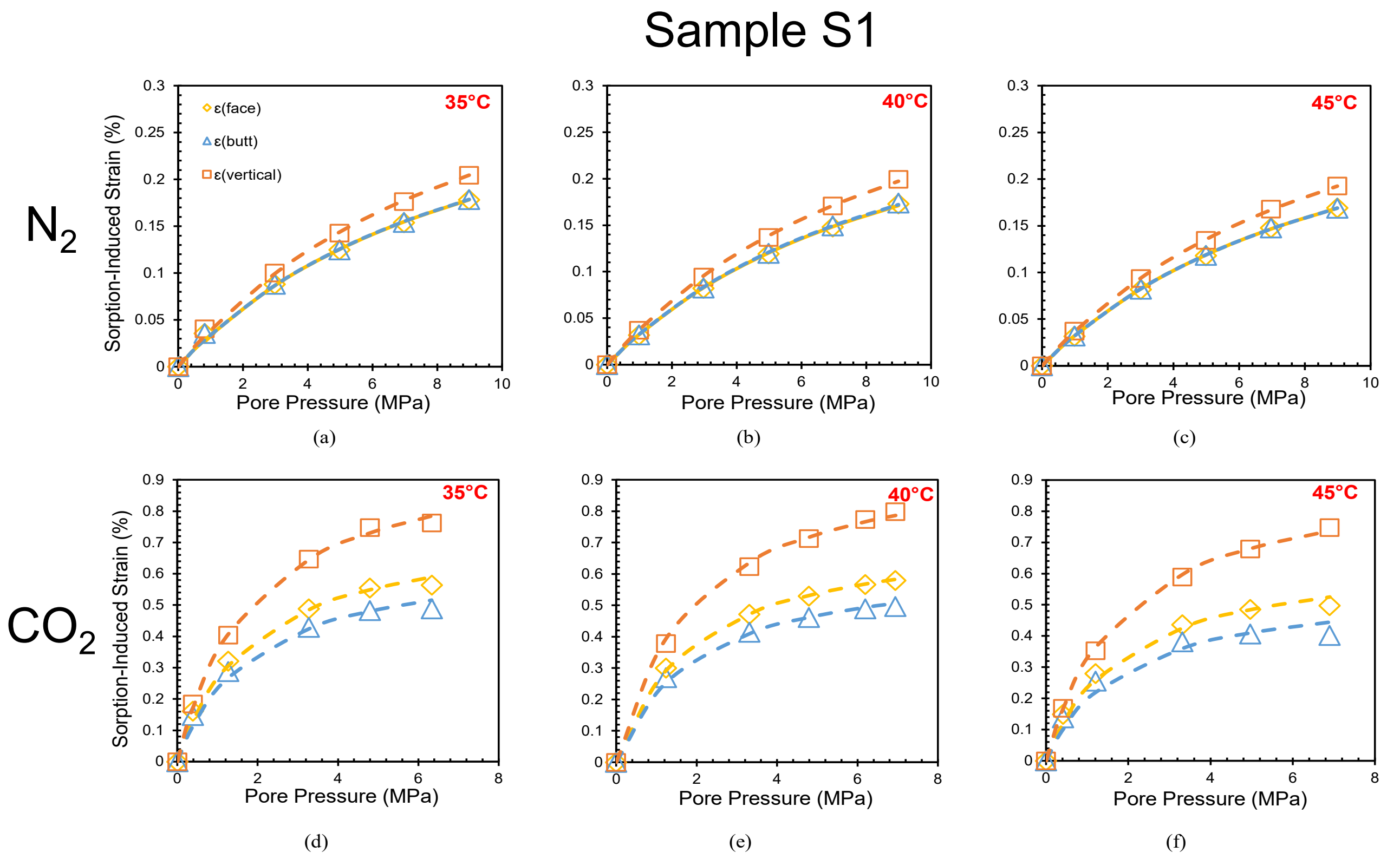


Figure. 4. Relationship between pore pressure and strain of sample S1 during N_2 injection at (a) 35°C; (b) 40°C; and (c) 45°C. Relationship between pore pressure and strain of sample S1 during CO_2 injection at (d) 35°C; (e) 40°C; and (f) 45°C

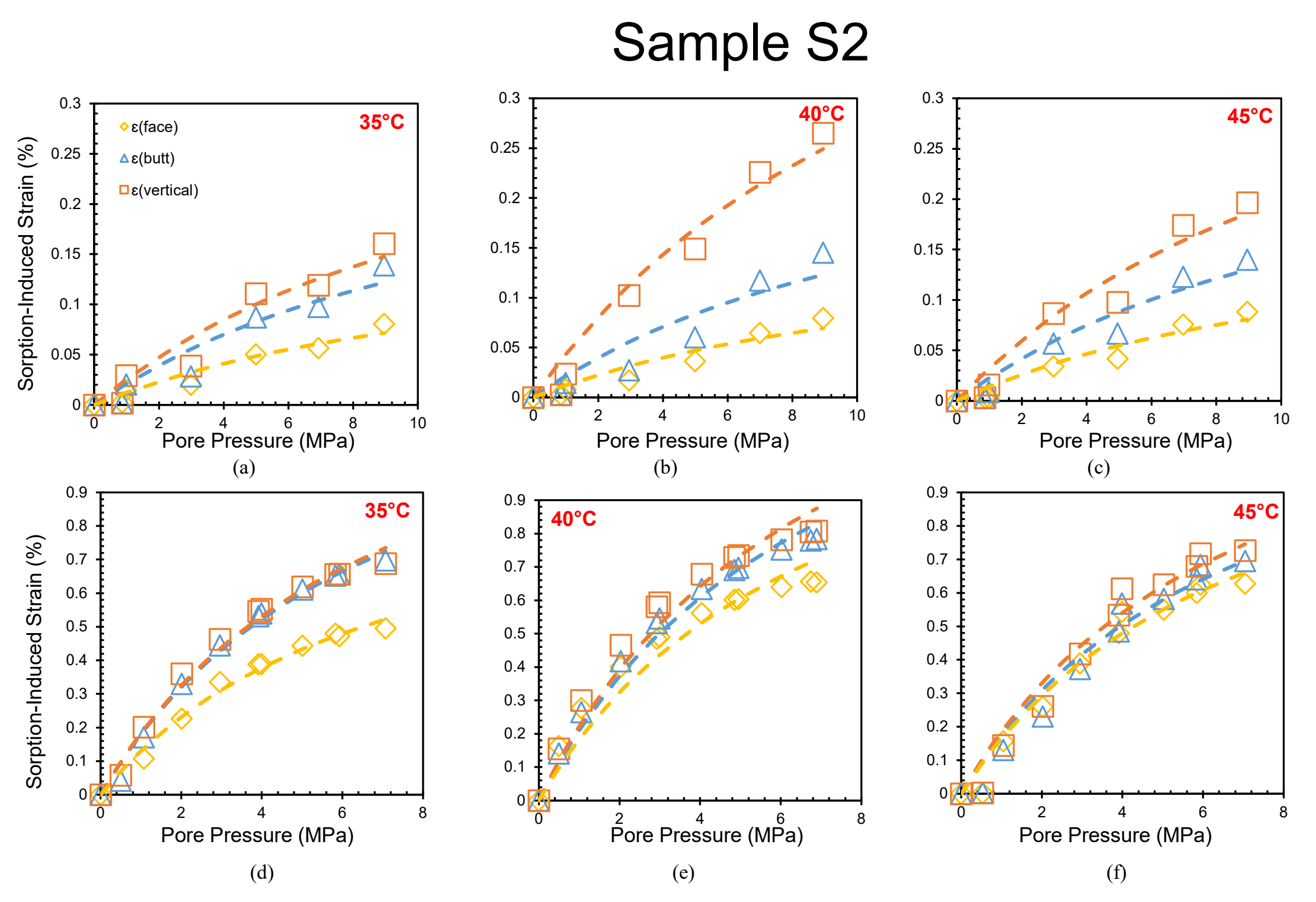


Figure 5. Relationship between pore pressure and strain of sample S2 during N_2 injection at (a) 35°C; (b) 40°C; and (c) 45°C. Relationship between pore pressure and strain of sample S2 during CO_2 injection at (d) 35°C; (e) 40°C; and (f) 45°C

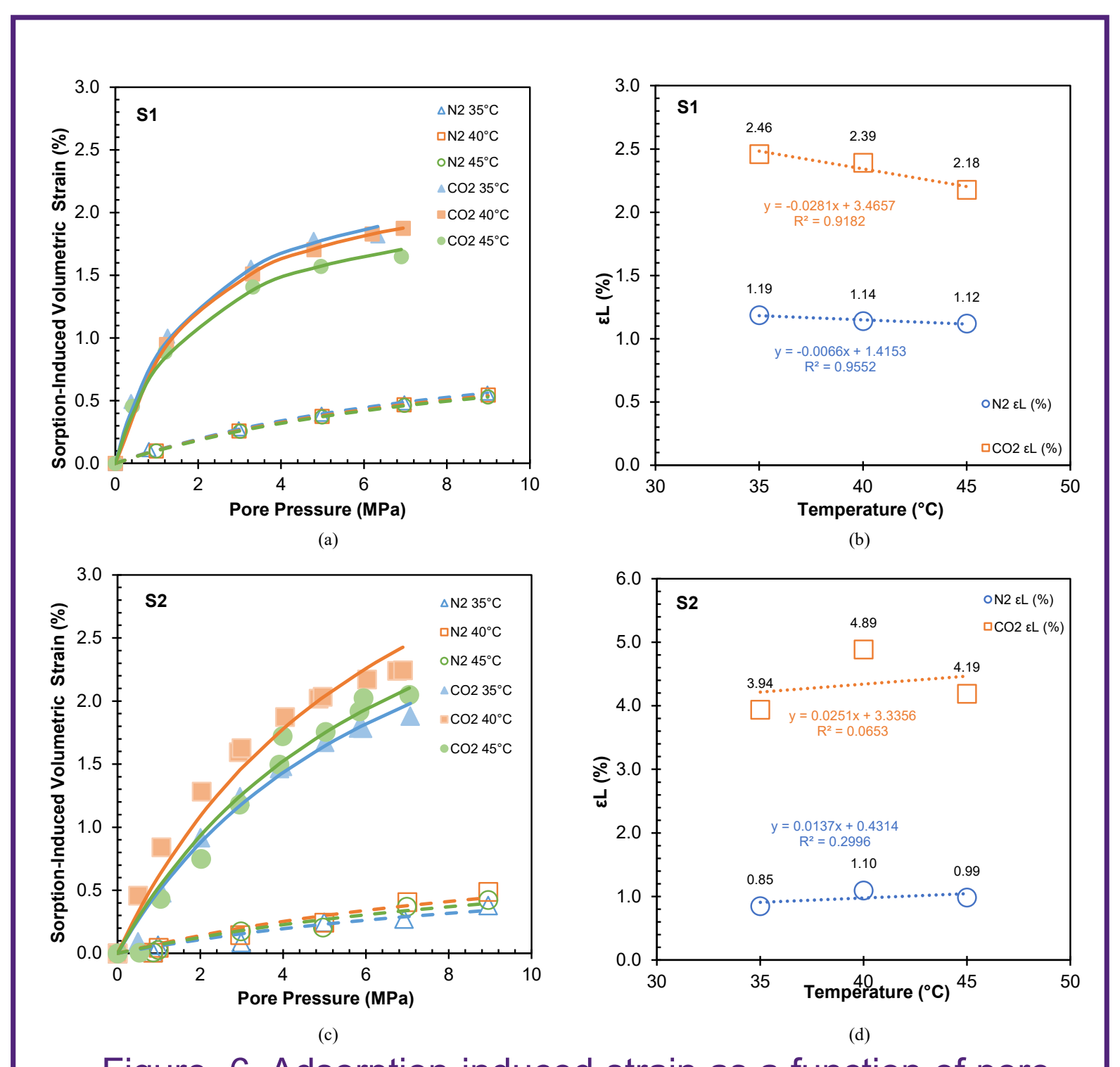


Figure. 6. Adsorption-induced strain as a function of pore pressure for (a) Sample S1 and (c) Sample S2; Langmuir strain constant for (b) Sample S1 and (d) Sample S2

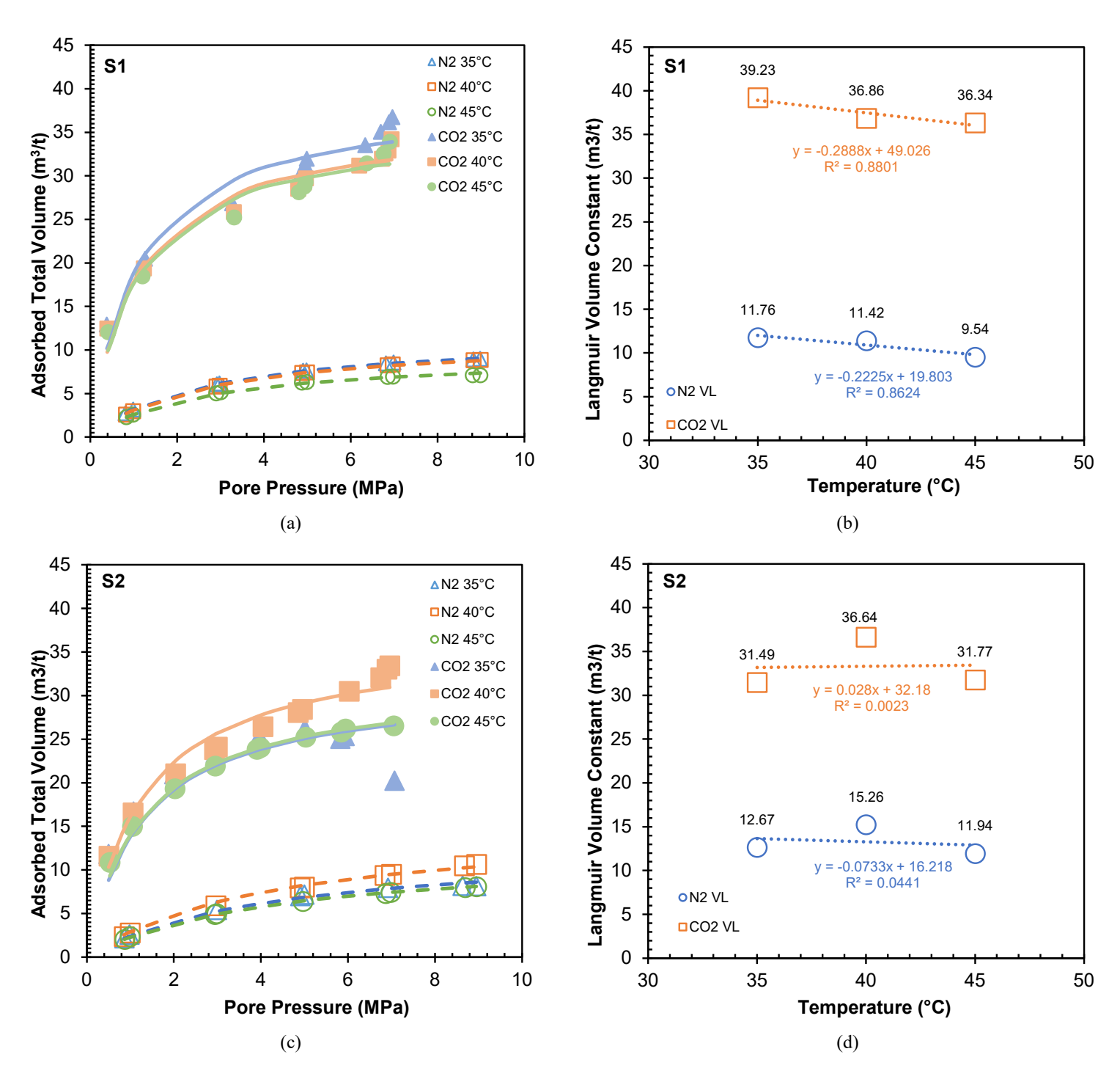


Figure. 7. Langmuir adsorption isotherm for (a) sample S1 and (c) sample S2. Langmuir volume constant V_L for (b) sample S1 and (d) sample S2

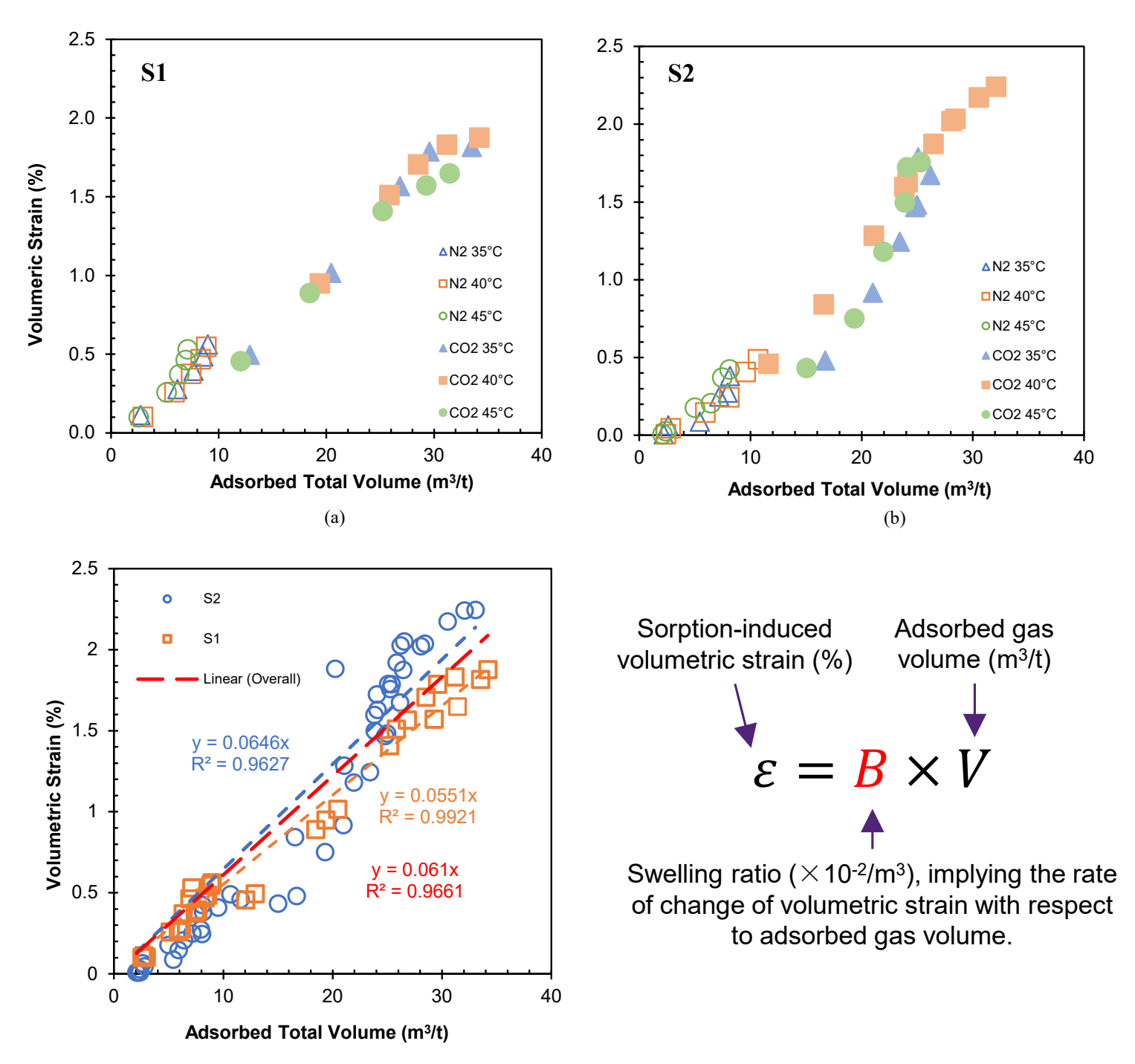


Figure 8. Sorption-induced strain as a function of Adsorbed volume for (a) sample S1, (b) sample S2 and (c) both sample S1 and S2 with linear fitting.

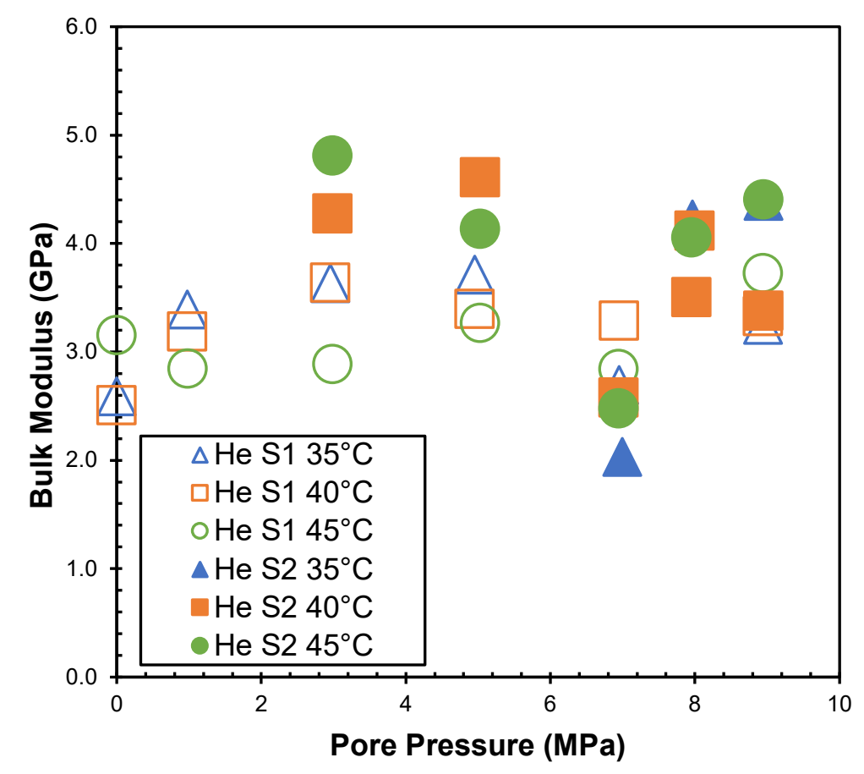
Results

Mechanical Properties

we use Helium to test the mechanical properties of the samples.

Bulk modulus: Figure 2 indicates that temperature and pore pressure do not significantly affect bulk moduli for both samples. Overall, sample S2 has a higher Bulk modulus value of 3.81 than S1 of 3.19, which implies a higher compression resistance subjected to the He injection.

Young's modulus: Young's modulus (Figure 3) increased as the temperature rises in all directions for both samples. The averaged Young's modulus ratio of E_{face}: E_{butt}: $E_{vertical}$ for S1 is 1.15:1.23:1.00 and for S2 is 1.06: 1.00: 1.00. Thus, the minimum Young's modulus occurs along the vertical (bedding) direction. The average Young's modulus from three directions are 3.77, 3.90 and 3.96 GPa for sample S1 and 2.66, 3.71 and 4.04 GPa for sample S2 at the temperatures of 35°C, 40°C, and 45°C, respectively.



$$K = \frac{\sigma}{\varepsilon_v}$$

← Pressure

← Volumetric strain

Figure 2. Bulk modulus determined by He for sample S1 and S2

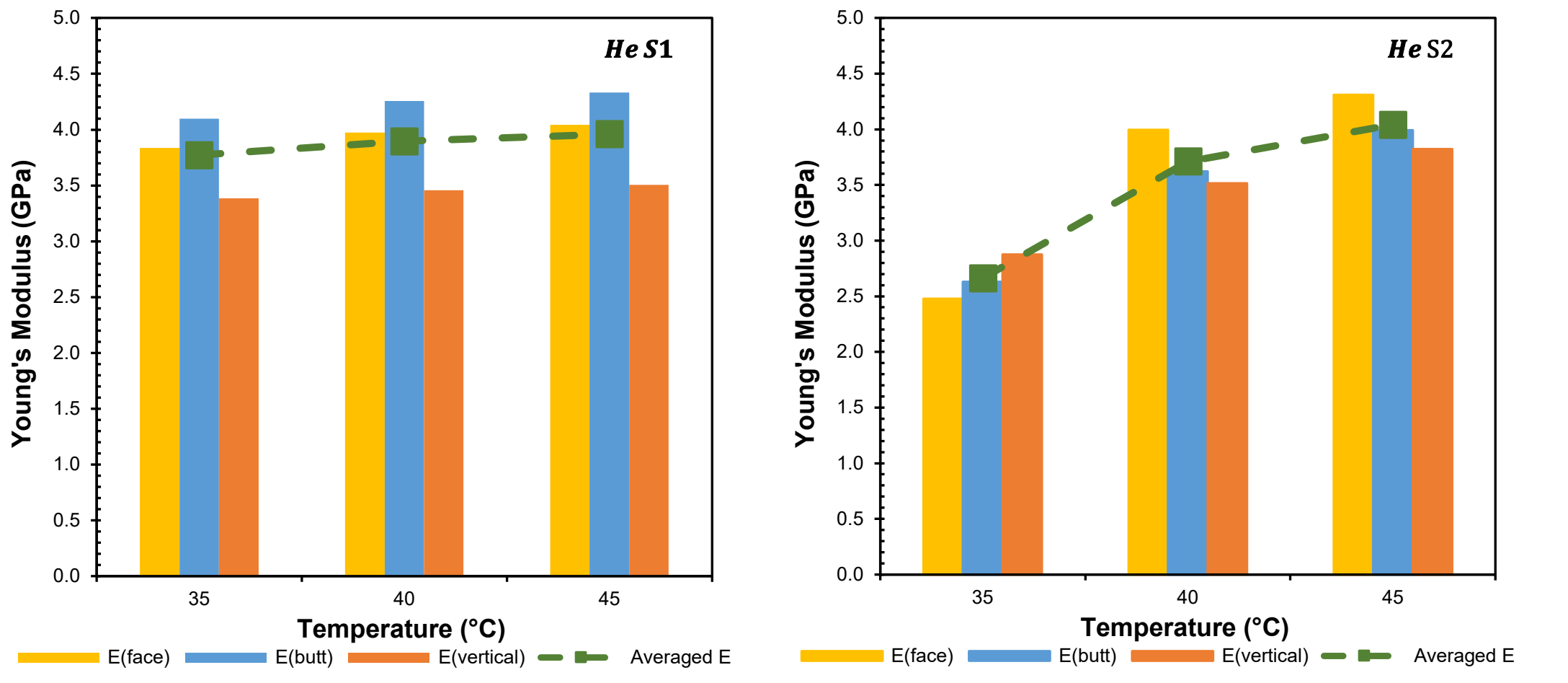


Figure 3. Young's modulus for different directions with various temperatures for (a) sample S1 and (b) S2

Swelling Anisotropy

When an adsorbing-gas (e.g., N_2 or CO_2) is injected, the measured strain is the sum of the strain induced by pore pressure and the sorption-induced strain. Thus, the sorption-induced strain is computed using the equation below

$$\varepsilon_{N_2\ swelling} = \varepsilon_{N_2} - \varepsilon_{He}$$

$$\varepsilon_{CO_2\ swelling} = \varepsilon_{CO_2} - \varepsilon_{He}$$

We computed the directional sorption-induced strain for both samples with different temperature and gases using the above equations and present them in Figure 4 and 5. The anisotropic feature of tested coal samples is clearly demonstrated from different responses of strains in three directions. The Langmuir model is then employed to fit the relationship between pore pressure and sorption-induced strain.

Directional strain ratio: The averaged strain ratios of ε_{face}: ε_{butt}: $\varepsilon_{vertical}$ for sample S1 using N_2 are 0.87:0.87:1.00, and for sample S1 using CO_2 are 0.71:0.60:1.00. In contrast, the averaged strain ratios of ε_{face}: ε_{butt}: $\varepsilon_{vertical}$ for sample S2 using N_2 are 0.42:0.71:1.00, and for sample S2 using CO_2 are 0.80:0.98:1.00.

Temperature effect on Langmuir strain constrain: For S1, A higher temperature results in a lower Langmuir strain constant due to gas storage capacity reduction with increasing temperature.. For S2, no noticeable correlation between the Langmuir strain constant and the temperature has been identified

Adsorption Capacity

Volumetric strain Vs. pore pressures (Figure 6):

Temperature effect: For sample S1, the Langmuir strain constant and temperature are inversely correlated (shown in Figure 6 (b)). The reduction in the Langmuir strain constant could be explained by the decline of adsorption capacity when temperature rises. However, the Langmuir strain constants for sample S2 do not show a direct relationship with temperature (shown in Figure 6 (d))

Difference between gases: maximum swelling under the CO_2 injection is approximately double that under N_2 for sample S1, and four times than that under N_2 for sample S2

Adsorption volume Vs. pore pressures (Figure 7):

Temperature effect: For S1, a higher temperature corresponds to a low adsorption volume for the same pressure point. However, S2 does not show a direct relationship between adsorption capacity and temperature

Difference between gases: The ratio of V_L between using CO_2 and N_2 is 3.44 for sample S1 and 2.51 for sample S2.

Volumetric strain Vs. Adsorption volume (Figure 8):

Three linear correlations were computed for data points of sample S1, sample S2 and both, respectively and are shown in Figure 8. The obtained swelling ratios for sample S1, S2 and both are 0.0551, 0.0646 and 0.061, respectively. This observation infers that it may be acceptable to estimate swelling strain if the adsorption amount is known, regardless of the type of gas and temperature. The overall linear fitting leads to a swelling ratio of 0.061, indicating that every cubic meter of gas sorption would generate 0.061% volumetric swelling strain. With a known Langmuir isotherm curve for a coal, this universal correlation can be applied to estimate the swelling strain at a given gas pressure.

Conclusions

- The anisotropic behaviour of the tested coal sample has been identified, and the direction perpendicular to the bedding plane shows the largest strain
- N_2 and CO_2 adsorption results show a difference in the directional sorption-induced strains.
- Compared with N_2, the sorption capacity of CO_2 is two to three times larger. This shows that CO_2 has a higher adsorption affinity than N_2, which makes it ideal to be sequestrated in the coal seams and displaces CBM.
- Total volumetric strain and adsorption volume are well linearly correlated regardless of the adsorbing gas type and temperature. The mean volumetric swelling per cubic meter of sorption gas for the tested coal samples is 0.061%. The sorption-induced strain can be directly estimated from the Langmuir isothermal curve

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