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Time-dependent deformation of porous sandstones during pore pressure fluctuations and its effect on porous sandstone properties: Implications for subsurface hydrogen storage.

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In underground hydrogen storage operations, reservoir rocks often experience periodic pore pressure fluctuations due to annual or more frequent gas extraction and injection cycles. These fluctuations subject the reservoir rocks to cyclic effective stress changes, causing their mechanical and transport behaviours to differ from those under static conditions. However, understanding how porous rocks react to pore pressure oscillations in situ conditions is still limited. To address this, we selected three types of sandstones with different physical properties (Castlegate, St Bees, and Zigong sandstone, respectively), and conducted pore pressure oscillation experiments over several weeks at different rates and amplitudes to simulate underground hydrogen injection and extraction processes. Permeability was periodically measured during the initial loading phase and stress cycle intervals. 3D images of the samples before and after pore pressure cycling were obtained by performing X-ray micro-computed tomography scans, and digital core models were established to characterise the geometric topological features of the three sandstones quantitatively. Experimental results indicate that all three types of sandstone exhibit more significant increases in axial strain and decreases in permeability than the control groups under constant pore pressure conditions. The strain changes induced by these stress cycles were the primary control on permeability decline in the sandstones. Notably, in the case of the high-porosity Castlegate and St Bees sandstones with porosities of 19.8% and 18.6%, respectively, we observed that both the accumulation of inelastic strain and the decrease in permeability were positively correlated with an increase in the rate, amplitude, and cycles of pore pressure oscillations. In contrast, for the Zigong sandstone, which has lower porosity, there was no obvious correlation among these factors. Microstructural evidence based on CT analysis revealed that the inelastic deformation mechanisms in the three types of sandstones were dominated by grain rotations and rearrangements. However, compared to Zigong sandstone, characterised by its closely packed grains and lower porosity, only 7.9%, Castlegate and St Bees sandstones demonstrated more pronounced changes in pore structure and a more significant loss in porosity. This implies that sandstones with higher porosity, having more space to accommodate grain movements and rearrangements, are more sensitive to rapid pressure changes during cyclic loadings, leading to a more significant response of their physical properties to pore pressure cycling.

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