Experimental determination of carbon sequestration response to reservoir quantities.

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Experimental Determination Of Carbon Sequestration Response To Reservoir Quantities

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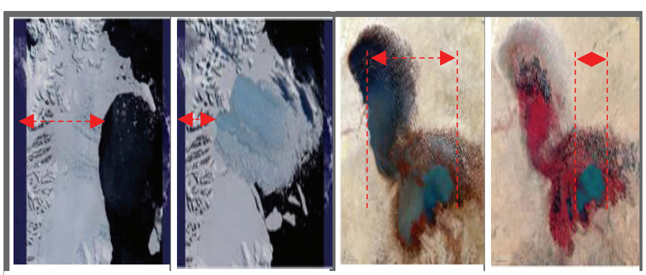
ABSTRACT

Rigorous data mining and experimental methods have been applied to characterise and determine the carbon storage (CS) response to 20 reservoir petrophysical quantities. Such extensive characterisation is lacking in extant literature. Five analogous core samples with varying structural quantities were used in the experimental phase. The series of graphs generated in the course of the investigation quantitatively show that the correlation between CS and petrophysical quantities ranges from linear to higher-order polynomial. Heterogeneity was found to be beneficial when knowledge of CS response is well understood and applied. Based on the outcome of this study, CS engineers can apply knowledge to practice by screening reservoirs and selecting storage sites or layers with relatively high pore density, specific surface area, pore number, and displacement pressure. Conversely, selecting sites with significantly lower pore surface, pore size, and compression factor also improves CS and sealing. Such screening decisions will save implementation costs and reduce technical complications, especially in heterogeneous reservoirs.

Keywords—Carbon Capture, CCUS, Permeability, Porosity, pore size, geology.

1 INTRODUCTION

The carbon Capture, Utilisation, and Storage (CCUS) scheme has been widely adopted as one of the feasible options for reducing CO_2 greenhouse gas contributions to climate change. The motivations for this option include environmental, technological, political, economic, and public health. CCUS attempt to reverse or reduce global warming temperature and its adverse impact on the environment [1], see Figure 1.



a. 31/01/2022	b. 07/03/2022	c. 1973	d. 2017

Figure 1 shows NASA imagery of the environmental impact of climate change of (a) and (b) melting and collapse of Larsen B Ice shelf and (c) and (d) the historical shrinking of Lake Chad. [2], [3]

The CCUS schemes are expected to inspire technological innovations and is planned to generate over 50,000 jobs and \$200 billion in the UK economy [4], [5]. The general impact on public health and wellbeing includes reducing heatwaves that make workspaces unbearable [6]. It has been used to garner political support among the electorate [7]. Key players use it to demonstrate global leadership and diplomacy.

About 35 billion metric tonnes of CO_2 are produced annually [8]. Annual global oil and gas production is currently at 4.8 billion and 3.8 billion tonnes, respectively [8]. If we capture and store CO_2 in the reservoir pores vacated by the produced oil and gas, this will remove about 24% of current CO_2 emissions from the atmosphere. However, this process of storage in reservoir pores is not as straightforward.

Reservoir entities can be classified into geological, geometrical, and fluidic categories. To complicate matters, reservoirs are usually set in geological layers that possess some heterogeneity, such that each layer interacts differently with injected and resident fluids,. Consequently, CO_2 injection has to effectively couple with these reservoir entities individually and collectively to achieve CO_2 Enhanced Oil Recovery (EOR) and sequestration optimisations. Other investigators have not properly explored the CO_2 sequestration optimisation subject area in light of its response to reservoir entities and heterogeneity. This study aims to expand on this subject area.

A comprehensive technical screening and evaluation are required to identify reservoirs with characteristics that can support the CCS scheme. This study used ceramic membranes as reservoir rock analogues to investigate Carbon Sequestration (CS) response to characteristic reservoir parameters. Twenty of such parameters were elicited after an extensive review of relevant literature. CO_2 permeation was adopted as a criterion for evaluating CS since a reliable CS site is one that prevents CO_2 from permeating further, thereby acting as a seal and storage site. Figure 2 depicts a reservoir system with multiple sections of varying properties with the potential to be CS sites. Site A has the largest grain but the smallest pores. When CO_2 molecules permeate those tiny pores, they may become trapped or sealed due to displacement and capillary pressure effects. However, the volume of trapped CO_2 may be small compared to what Site B (large grain but largest pore size) can accommodate. CS engineers are faced with the challenge of screening and selecting from sites like these to ensure maximum CS volume and seal integrity. A rigorous experimental method has been applied to investigate this engineering dilemma.

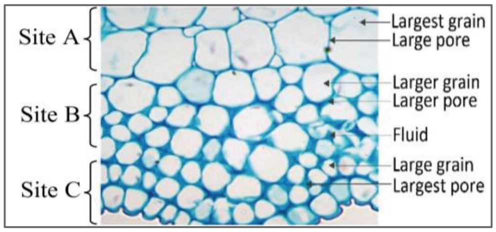


Figure 2 shows the reservoir porous structure for CO2 permeation and CS potential site options

2 EXPERIMENTAL METHODS

The experimental materials and equipment pictorial diagram are presented in Figure 3 and Figure 4. The experimental procedure involves injecting CO_2 into an analogous core sample at set pressures and temperatures [9]. Permeates are measured when steady-state is achieved. The experiment was conducted using pressure and temperature ranges of 1-3atm and 293-673K. Five analogue cores were sampled. A total of 1830 experimental runs and 7400 data points were generated.

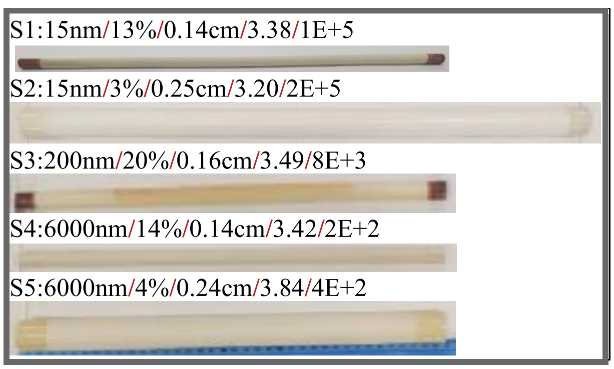


Figure 3 shows some parameters of the analogous core samples (S1-5): pore size / porosity / radial thickness / tortuosity / aspect ratio.

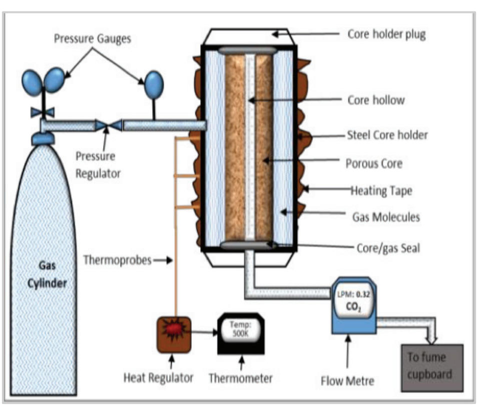


Figure 4 shows the CS experimental pictorial diagram.

2.1 Evaluation Techniques

For a site to be suitable for CS, it has to act as a seal to securely prevent the further permeation or flow of CO_2 beyond the boundary. Therefore, the technique used to evaluate the structural mix of a potential seal is to observe the change (increase or decrease) in each of the 20 quantities that enable a decrease in CO_2 permeation for a series of pore systems.

2.2 Supporting Theories and Equations

The equations used to describe structural quantities were derived from well-established theories and laws:

Pressure = P; Temperature = T; Volume = V
Gas Constant = R; Compressibility Factor = z
Number of Moles = n; Molecular Weight = MW
Density = ρ; Contact angle = θ; Parachor = Pch
Subscripts: $_o$ = oil; $_g$ = gas; $_{Std;}$ = Standard condition
Core outer radius = r_{outer} Core inner radius = r_{inner}
Effective Pore Size = r_p (Supplied by manufacturer)

1. Porosity, $\phi = 1 - \left(\frac{Specific\ Particle\ Density}{Specific\ Bulk\ Density}\right)$
2. Tortuosity, $\tau = (1 - 0.41 ln\phi)$
3. Pay Zone or Core Height, h
4. Gas Entering Surface Area, $A = 2\pi r_{outer}\, h$
5. Radial Thickness, $r_{thickness} = r_{outer} - r_{inner}$
6. Aspect Ratio, AR $= \frac{r_p}{r_{thickness}}$
7. Gradient, $\lambda = \left(\frac{entity\ value_{CS\ site} - entity\ value_{Inj\ site}}{\text{Sum of component lengths}}\right)$
8. The Ideal Gas Law, PV $= nRT$
9. Reservoir (rev) and Standard (std) States Analogy, $\left(\frac{PV}{zT}\right)_{res} = \left(\frac{PV}{T}\right)_{std} = Constant$
10. Darcy Radial Gas Flow, $Q_{std} = \frac{K}{\mu}\frac{\pi h}{T}\frac{T_{std}}{P_{std}}\frac{(P_1{}^2 - P_2{}^2)}{\ln\frac{r_{outer}}{r_{inner}}}$
11. Interstitial Flow Throughput, $IFT = \frac{Q_{std}}{\phi} = \frac{1}{\phi}\frac{\pi h}{T}\frac{T_{std}}{P_{std}}\frac{(P_1{}^2 - P_2{}^2)}{\ln(\frac{r_{outer}}{r_{inner}})}$
12. Number of Pores, $N_p = \frac{\phi\pi h(r_{outer}{}^2 - r_{inner}{}^2)}{\pi(r_{pore})^2(r_{outer} - r_{inner})} = \phi h\frac{(r_{outer} + r_{inner})}{(r_{pore})^2}$
13. Interstitial Pore Holding Capacity, $IPHC = \frac{Darcy\ Flowrate}{Number\ of\ Pores} = \frac{Q_{std}}{N_p} = \frac{Q_{std}\,(r_{pore})^2}{\phi h(r_{outer} + r_{inner})}$
14. Reservoir Quality Index, RQI $= 0.0314\sqrt{\frac{K}{\phi}}$
15. Capillary Pressure, $P_c = \frac{2\sigma cos\theta}{r_p}$
16. Displacement Pressure, $P_d = \frac{2\sigma cos\theta}{r_p}$
17. Buoyancy Pressure, $P_b = (\rho_o - \rho_g)gh$
18. Surface Tension $\sigma = \left(Pch_o\left[\frac{\rho_o}{MW_o}\right] - Pch_g\left[\frac{\rho_g}{MW_g}\right]\right)^4$
19. Effective Reservoir Pore Radius, $r_{35} = 0.732 + 0.588\log K - 0.8641\log\emptyset$

3 RESULTS

The study aims to reveal CCS response to 20 identified reservoirs' petrophysical quantities. The CS response results are represented in 20 graphs (Figure 5, Figure 6, and Figure 7), showing various regressions between CS and reservoir petrophysical quantities. Quantities having linear and power relationships with CS provide more straightforward solutions than those with higher-order relationships.

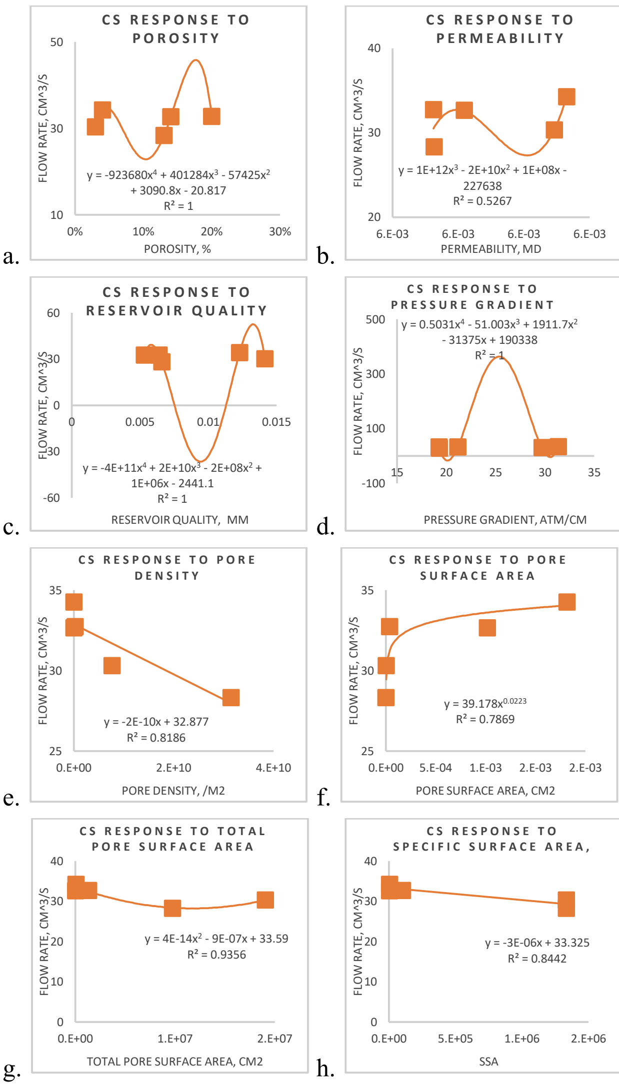


Figure 5 shows geological quantities: CS improves with increasing pore density (e) and specific surface area (h) and decreasing pore surface area (f).

Thus, analysis of the graphs shows that injecting the CO_2 in the direction of increasing pore density, specific surface area (Figure 5e and h), pore number (Figure 6b), displacement pressure, and CO_2 density (Figure 7a and d), causes an eventual linear decrease in the permeation of CO_2. In contrast, injecting the CO_2 in the direction of decreasing pore surface area (Figure 5f), pore size (Figure 6a) and compression factor (Figure 7f) significantly decreases further CO_2 permeation.

The strongest linear regression correlation for the investigated structural quantity is between CS and pore density ($R^2 = 81\%$). This indicates that 81% of the changes in CS can be explained by the variation in pore density across the reservoir. Furthermore, CS is most sensitive to variation in Specific Surface Area, as demonstrated by the relatively high slope of (-3E-06 cm/s).

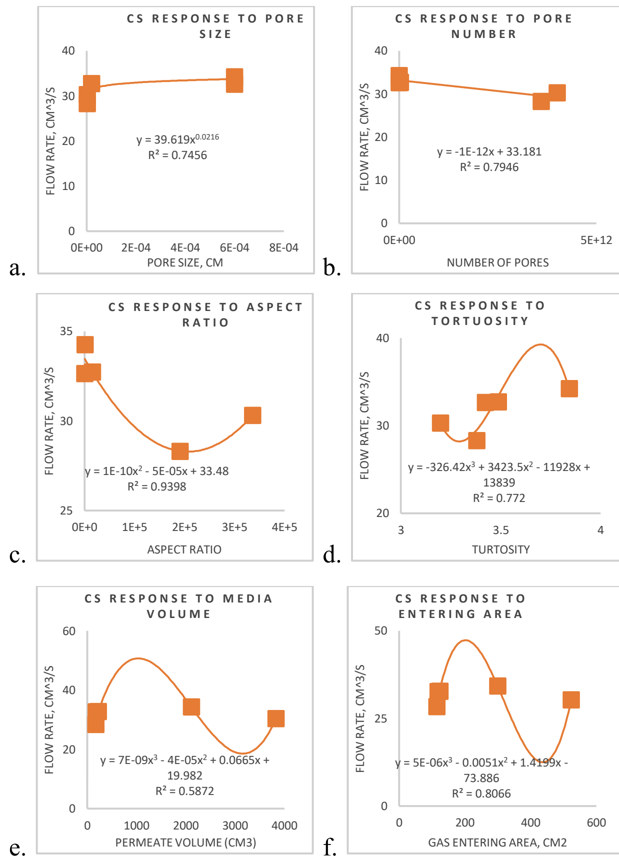
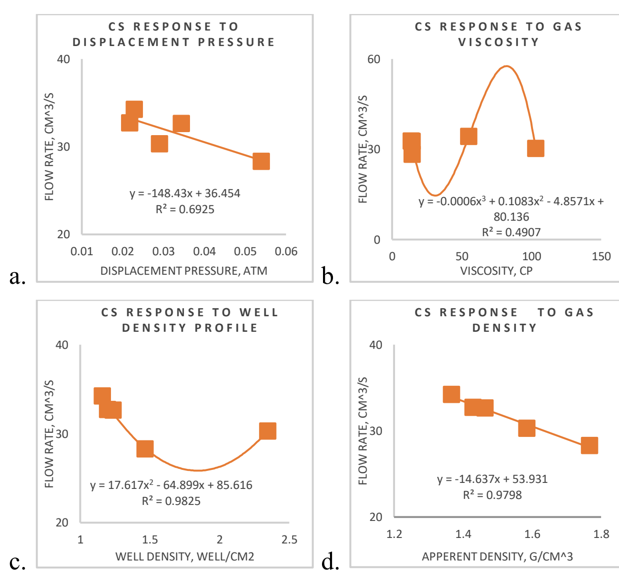
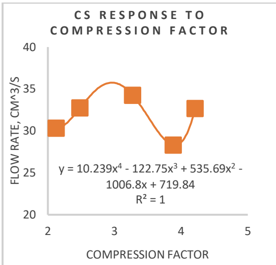


Figure 6 shows geometrical quantities: CS improves with a decreasing pore size (a) and increasing pore numbers (b).



e. 

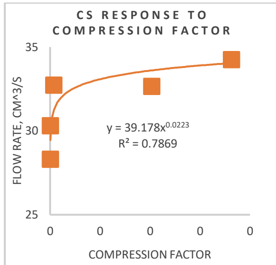
f. 

Figure 7 shows fluid quantities: CS improves with increasing displacement pressure (a) and gas density (d), decreasing compression factor.

Figure 8 shows the degree of heterogeneity for the respective quantities. A closer look at the results in Figure 5, Figure 6, and Figure 7 shows that quantities with relatively high heterogeneity (>100%) in Figure 8 are the ones most likely to have a linear correlation with CS (save for displacement pressure). Thus, suggesting that some structural heterogeneity could be used to improve CS effectiveness in reservoirs.

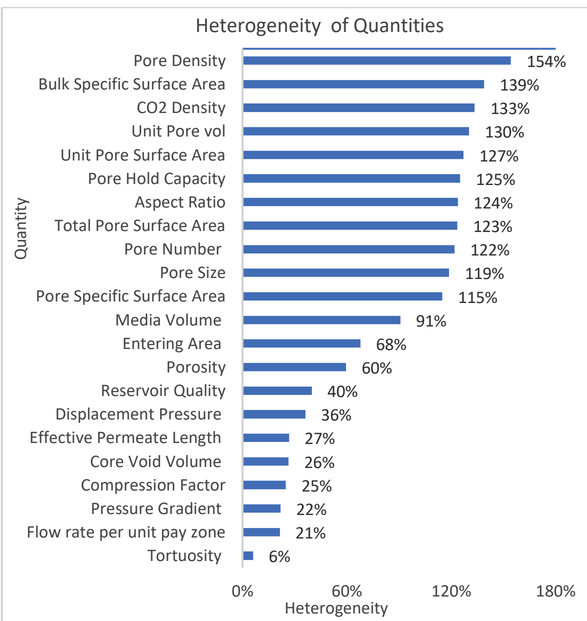


Figure 8 shows the heterogeneity in the samples used

4 CONCLUSION

An experimental method has been applied to investigate one of the solutions to climate change, CCUS. The results reveal that CS is responsive to 20 geological, geometrical, and fluid quantities. Simple linear equations can describe the relationship of CS to 6 of the quantities. CS responds to two of the quantities with a natural log and one with a power equation. The vast majority (11) of the quantities are related to CS by higher-order polynomials. Structural heterogeneity was found to be instrumental in CS response. Based on the outcome of this study, CS engineers can apply knowledge to practice by screening reservoirs and selecting storage sites or layers with relatively high pore density, specific surface area, pore number, and displacement pressure.

Conversely, selecting sites with significantly lower pore surface, pore size, and compression factor also improves CS and sealing. Such screening decisions will save implementation costs and reduce technical complications, especially in heterogeneous reservoirs. It is recommended that these experiments be conducted with reservoir cores or analogous organic cores to investigate CS response to the organic components in porous materials.

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