[PS]Experimental Investigation into Fracture Closure in Caprocks in CO_2 Storage Reservoirs*

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Abstract

The risk of CO_2 leakage through fractures is one of the primary risks for the secure containment of CO_2 in geological storage formations. The potential for fracture closure with pore pressure reduction and sub-surface stress changes, and fracture geometry will control CO_2 leakage rates in storage reservoirs where the seal has been compromised by induced fractures or reactivated pre-existing fractures. Modelling of fracturing formation and reactivation with injection induced stress changes will be important in preventing leakage from occurring, however if leakage does occur, understanding fracture closure and whether fracture closure can be increased or accelerated will be important for remediation efforts. In this study, we investigate a speculative acid induced fracture closure remediation technique using a series of laboratory acid injection experiments in shale caprocks. In the tests, viscous acid is injected through a range of fractured shale caprock samples under confining stress. The permeability of the fractured samples is measured before and after acid treatments using brine flow rates and pressure differentials, to determine how the acid treatment affects fracture apertures and brine flow. Fracture aperture widths are characterised from CT sections taken across the core during flooding cycles. The fracture samples include naturally fractured samples and artificially induced fractures including samples with artificial regularly arranged asperities. Fracture roughness is also measured using photogrammetry before and after acid treatments. The caprocks currently collected for the study are a range of onshore UK shales including Kimmeridge Clay, Whitby Mudstone, and Accrington Mudstone from the Pennine Coal Measures. The range of lithologies allows correlation between observed fracture behaviour and mineralogical variation, for example clay content and cement type. The study focuses on the extent to which fracture closure can be enhanced, and the effectiveness of the technique in varying rock types. Future work will involve introducing CO_2 rich brines and alternative acid formulations into the experimental programme, and a comparative assessment of the natural and artificially induced fractures (by correlating fracture roughness and permeability) to determine the effectiveness of acid treatment with variable confining stress in treated vs. non-treated samples.

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Experimental Investigation Into Fracture Closure in Caprocks in CO_2 Storage Reservoirs

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1. Overview

The risk of CO_2 leakage from fractures is an important consideration for the secure containment of CO_2 in geological storage formations. Leakage may occur along natural or induced pathways such as faults and fractures in the sealing caprock of a formation. Leakage rates will be controlled by fracture geometry, pore-pressure and sub-surface stress changes. Understanding fracture behaviour, such as post-leakage fracture closure, will aid remediation efforts, such as fracture sealing (Tongwa et al. 2013) or enhanced fracture closure. One potential remediation technique is using acid to modify fracture properties (aperture, asperities and deformability). Previous studies (Andreani et al . 2008) have however shown an increase in fracture permeability in fractured samples exposed to acidic conditions.

In this study a preliminary investigation into acid induced fracture closure in a carbonate rich Kimmeridge Clay shale caprock is presented. A fractured sample is exposed to acid under confining stress and brine permeability is measured for the sample (assuming fracture dominance), and for the fracture using a cubic law assumption (Deng et al. 2013) during repeated acid treatments.

$$\alpha_h = \left(12\frac{Q\mu L}{w_f \Delta P}\right)^{\frac{1}{3}} \qquad k_f = \frac{\alpha_h^{\,2}}{12}$$

Equation 1. & 2. Permeability of a fracture using a cubic law assumption, where α_h is the equivalent hydraulic aperture, Q is flow rate, μ is fluid viscosity, L is the fracture/sample length, w_f is the fracture width, ΔP is the pressure gradient across the fracture and k_f is the 'fracture' permeability

2. Sample Preparation

Several samples were collected for the study, including Whitby Mudstone, Accrington Mudstone and Kimmeridge Clay. To date only the Kimmeridge Clay has been analysed in detail and prepared as fractured samples. The Kimmeridge Clay is a dark grey laminated carbonate rich shale that has experienced burial up to 3km depth and has porosity of around 25% (Nygaard et al. 2004) and the mineralogy from XRD is given in Table 1.

Composition	%
Quartz	14.5
Albite	1.7
Calcite	10.8
Dolomite	35.5
Mica	5.0
Illite-Smectite	23.9
Kaolinite	3.7
Pyrite	3.7

Table 1 - XRD analysis for Kimmeridge Clay

To prepare the fractured samples 38 mm diameter core samples were loaded in a modified brazil disk testing rig until tensile failure induced an axial fracture. Due to the nature of the fracture induction, no movement occurred on the fracture resulting in tight fractures. Half diameter plastic spacers were inserted at diagonally opposite ends of the core sample, to produce an offset in the fracture asperities and produce an open fracture.

The cores were sealed in heat shrink and saturated in equilibrated brine prior to testing.

Figure 1 - (clockwise) a-b Induced fracture surface in sample, c-d axial fracture induced in the core, e core samples in heat shrink with loading plattens attached, plastic offset spacers at ends of cores are shown.

3. Experimental Setup

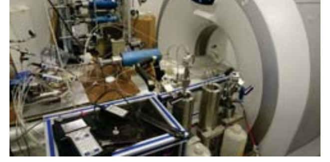

Figure 2 - Laboratory setup showing core holder (blue, centre) in CT scanner.

The experimental setup is shown in Figure 2, and a schematic of the setup is shown in Figure 3. The saturated core samples were placed inside an in-house Hassler style core holder and confining stress applied perpendicular to the fracture axis. Permeability was measured across the fracture using brine flow and differential pressure transducers, and a PH meter was attached to the brine outflow to measure PH fluctuations.

A viscous acid (pH 1) was injected into the sample through a switchable port using an ISCO syringe pump to drive the fluid. In between acid treatments the permeability was measured using brine. The whole setup is computer controlled and constructed within a CT scanner to monitor fracture behaviour during the testing.

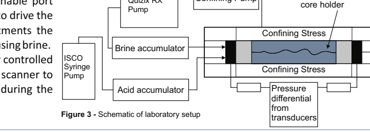

Figure 3 - Schematic of laboratory setup

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4. Test Procedure

Two core samples have been tested to date in the programme. In the initial stage of each test the cores were confined at 1500 psi and the permeability to equilibrated brine was measured. The brine permeability measurements required up to 1 week to stabilise due to creep effects in the cores. Acid injection treatments were then performed on the cores at varying confining stresses and with varying volumes. Each treatment consisted of the injection of a fixed volume of acid, followed by brine flushing and permeability measurements until the permeability readings stabilised.

Sample 1 - In the first sample two acid injection treatments were carried out at 1500 psi. Further acid treatments were then carried out at 3000 and 4000 psi with an initial brine permeability reading prior to each acid treatment.

Sample 2 - In the second sample a series of 5 acid treatments were carried out all at 1500 psi, in order to determine the potential of acid treatment to reduce fracture permeability without the effect of confining stress affecting the results.

5. Permeability Measurements - Confining Stress

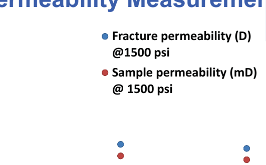

Figure 4 - Initial permeability measurements for sample 1 at 1500 psi with two acid treatments.

For sample 1 the initial permeability measurement and two acid treatments carried out at 1500 psi produced a reduction in the permeability of between 70 and 85%.

The second acid treatment only produced a small permeability reduction.

After the initial acid treatments the confining stress was increased in stages and further acid treatments applied.

The permeability continued to reduce both with confining stress and acid treatment.

At 3000 psi the reduction in permeability due to stress was 75% and from the acid injection was a further 39%.

At 4000 psi the reduction in permeability due to stress was 58% and the reduction due to acid treatment was 72%.

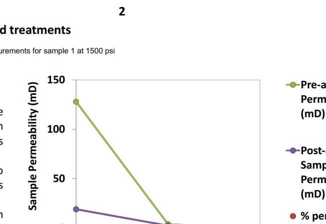

Figure 5 - Permeability change for acid treatments at increasing confining stresses showing permeability change due to stress change and acid treatment.

6. Permeability Measurements - Acid Cycling

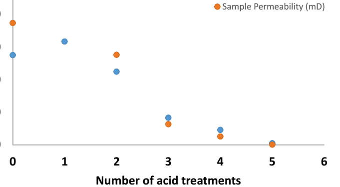

Figure 6 - Permeability measurements for sample 2 for an increasing number of acid treatments.

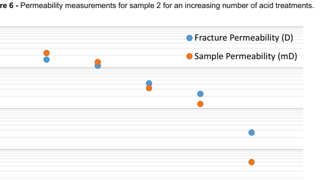

Figure 7 - Permeability measurements for sample 2 for an increasing number of acid treatments.

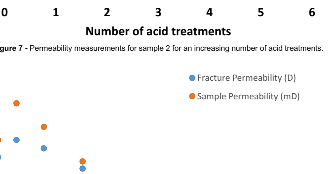

Figure 8 - Permeability change for sample 2 from the end of acid injection 2 to the end of acid injection 3.

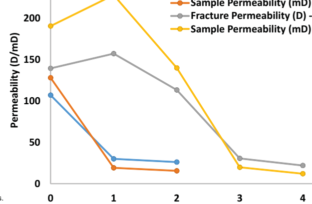

Figure 9 - Comparison of permeabilities for the 1500 psi stages for sample 1 and sample 2

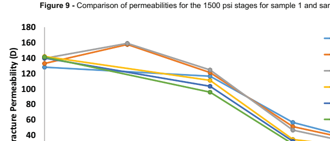

Figure 10 - Comparison of permeabilities measured using different flow rates for sample 2 for different acid treatments.

Figures 6 and 7 show the permeability decrease for sample two for five acid treatments and 1500 psi confining stress. The figures show that the permeability decreases to less than3 D for the fracture permeability and less than 1mD for the sample permeability after 5 acid treatments. The figures also show that for this sample the permeability initially increases due to the first acid treatment.

Figure 8 shows the permeability change between two acid injections (treatments 2 and 3), the zero hour point is at the end of acid injection 2 when the permeability measurement has stabilised. The trend shows an initial increase in fracture permeability some time after the acid injection, and a significant time period before stabilising.

Figure 9 compares the acid treatments in sample 1 and sample 2 and shows the far fewer acid treatments were required in sample 1 to lower the permeability to that of sample 2.

Figure 10 illustrates the variability in permeability reading obtained when using different flow rates with lower flow rates producing lower permeabilities, and is likely to reflect the impact of turbulence on the reading.

7. Fracture Behaviour - CT Scanning

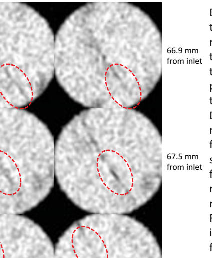

Figure 11 - Variation in CT images along fracture pre- and post-acid.

During the permeability testing and acid treatments each sample was CT scanned at regular intervals, generally prior to acid treatment, immediately or soon after acid treatment, and at appropriate stages as the permeability stabilised, with a final scan at the stable permeability.

Due to the resolution of the scanner it is not possible to directly measure the fracture aperture with accuracy. Figure 11 shows the CT images, the apparent fracture zone in the centre is actually a region of low density and does not represent the aperture.

Figure 12 and 13 show thresholded CT images of the altered region along the fracture with lower density. The images demonstrate the growth of this region with acid treatment.

Figure 12 shows the sample after 2 acid treatments and Figure 13 after 5 treatments.

3D

3D

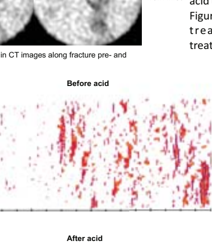

Figure 12 - Thresholded CT image of altered region in sample 1 showing increase due to acid penetration.

Figure 13 - Surface model of thresholded image from CT scan of sample 2. Showing significant increase in altered region within fracture zone.

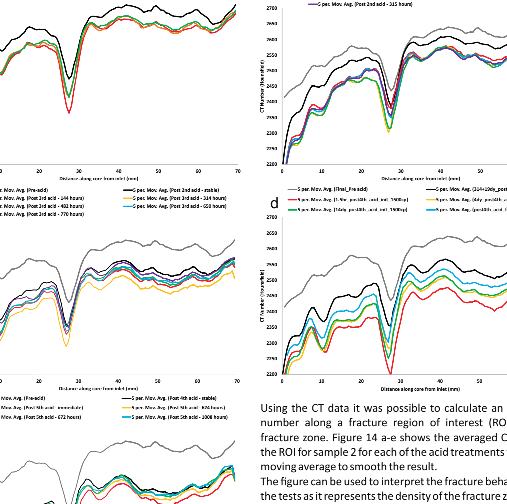

Figure 14 a-e - Averaged CT number profile along the fracture zone for sample 2 for each acid treatment. Profile smoothed using moving average and measured for a fixed region of interest covering the fracture axis. Each chart shows the initial profile prior to any acid treatment followed by the CT number profile for the stable permeability measurement at the end of the preceeding acid treatment stage.

Using the CT data it was possible to calculate an averaged CT number along a fracture region of interest (ROI) along the fracture zone. Figure 14 a-e shows the averaged CT number in the ROI for sample 2 for each of the acid treatments tests, using a moving average to smooth the result.

The figure can be used to interpret the fracture behaviour during the tests as it represents the density of the fracture zone.

The figure shows that the region is densest at the start of the tests before any acid is injected and after the initial creep stage has finished. The general trend observed for each acid treatment is then a reduction of density immediately after the acid injection followed by a gradual increase in the density over time. This is interpreted as representing dissolution of carbonate material, followed by a closure of the fracture zone due to deformation/damage to asperities holding open the fracture. This closure occurs during the reduction in permeability seen in the tests during which the permeability deacreases to stabilise at a lower level. Figure 14 d for the 4[th] acid injection shows the strongest indication of this trend.

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8. Discussion and Further Work

The permeability test data shows a significant reduction in the brine permeability of fractures in low permeability carbonate rich shales exposed to viscous acid injection. The tests show variability in the effectiveness of the treatments, with 1 sample needing fewer treatments to achieve the same permeability reduction. Using CT imaging of the fractures the mechanism for permeability decrease has been interpreted to be due to deformation of an altered region that forms along the fractures zone, and damage to fracture asperities from acid erosion. Figure 15 shows the altered zone in a sample prepared for SEM analysis, the altered region can be seen surrounding the fracture zone, and at contact points with the platten inlet. The altered region is soft and can be damaged by hand. Correlation of the fracture geometry with SEM images in Figure 16 shows reduction in carbonate material at both ends of the sample, although the reduction is more significant in the inlet end. The structure of the altered region has not been investigated, and it is possible there is a permeability increase in this zone with acid damage, this may offset some of the fracture closure that is interpreted in the sample.

Figure 17- Digital models of fractures surfaces from photogrammetry.

Figure 15 - Fractured sample end prepared for SEM analysis showing soft altered region easily damaged during sample preparation.

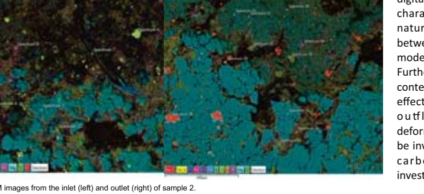

Figure 16 - SEM images from the inlet (left) and outlet (right) of sample 2.

Comparison of the results between the two samples, and the planned comparison of the acid treatment with varying confining pressures against permeability in untreated samples is complicated by the variable nature of each sample, and the fracture surface that is produced in the sample. Figure 17 shows digital fracture surface models that have been extracted from some of the samples using photogrammetry techniques. The upper sample is an artificial fracture surface that has been created in order to attempt to produce a standardised fracture surface. The aim is to have a consistent fracture aperture geometry and brine permeability in tests, and to show the impact of the acid treatment on the fracture surface asperities. The digital models are also hoped to be useful in characterising the surface roughness of the natural samples to allow some comparison between samples and for possible finite element modelling of fracture surface interaction.

Further testing of samples with lower carbonate content will also be carried out, to determine the effectiveness in other shales, and the water outflow chemistry and structure and deformation of the altered fracture zone will also be investigated. The potential for, and extent of carbonate re-precipication will also be investigated.

9. Conclusions

The effectiveness of a viscous acid treatment in reducing the permeabiltiy of a caprock fracture is demonstrated in this study, with at least an order of magnitude reduction in permeability observed during an acid treatment programme. The reduction in permeability appears to be controlled by the development of an altered fracture region along the fracture, which is more compliant than the host caprock. However, the mechanism of permeability reduction is not fully understood, CT investigations show closure in the fracture region after acid treatments which indicates deformation of the altered region and fracture surface resulting in fracture sealing. SEM analysis shows dissolution of carbonate material within the altered region along the length of the fracture. Other examples in the literature show increases in the permeability in caprocks when exposed to acidic conditions, however confining stress is not considered in these studies. Further work involving comparison of fracture permeabilities in un-altered caprock, and acid treatment in different material types with a lower carbonate content is planned, along with investigation of the structure and behaviour of the fracture surface and altered region.

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