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Deformation mechanics and acoustic propagation in reservoir rock under brine and oil saturation: An experimental study

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Abstract

Deep saline aquifers and depleted oil fields have been identified as two main potential geological sinks for CO_2 sequestration due to their preferable geological conditions. However, correct understanding of their in-situ chemico-mechanical properties (prior to CO_2 injection) is necessary to evaluate their safe and long-term CO_2 storage potential. This study therefore investigated the effect of brine and oil saturations on the mechanical and acoustic properties of reservoir rock by performing a series of strength tests using acoustic emission technology. According to the test results, the mechanical responses of reservoir rocks vary with the saturation condition, and the existence of brine and oil in water-saturated reservoir rocks causes their mechanical properties to be noticeably enhanced.

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Keywords: Compressive strength; CO_2 sequestration; deep saline aquifers; oil fields

1. Introduction

Full understanding of the mechanical behaviour of reservoir rock under various saturation conditions is required in many civil, mining and petroleum engineering applications, including waste disposal, tunnelling, oil recovery, and CO_2 sequestration. CO_2 geo- sequestration in depleted oil reservoirs and deep saline aquifers offers one of the most promising solutions to the continuously increasing anthropogenic

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CO_2 emissions into the atmosphere. Table 1 shows the worldwide capacity of potential CO_2 storage reservoirs [1].

Nomenclature

EOR	enhanced oil recovery
AE	acoustic emission
GtC	billion metric tons of carbon equivalent

Although geological sequestration is a technologically feasible and verifiable option to mitigate anthropogenic CO_2 emissions [1], dumping vast quantities of CO_2 into deep geological reservoirs may have harmful effects on their hydro-mechanical properties, and the possibility of CO_2 leakage into surrounding fresh water aquifers raises questions regarding long-term integrity of the process. To correctly identify such risks, it is necessary to have a precise understanding on the in-situ chemico-physical properties that may significantly differ from those of normal water- saturated rocks due to the presence of brine and oil. This study was carried out to identify such effects by conducting a series of compressive strength tests using acoustic emission (AE) technology, in which the fracturing processes of oil-and brine-saturated reservoir rocks were characterised. It is believed that the findings will be highly useful in understanding the effect of wetting by oil/brine on reservoir rock fracturability during EOR and sequestration processes.

Table 1. The worldwide capacity of potential CO_2 storage reservoirs [1]

Sequestration option	Worldwide capacity
Deep saline aquifers	100s-1000s GtC
Depleted oil and gas reservoirs	100s GtC
Un-mineable coal seams	10s-100s GtC

2. Sample preparation

The sandstone blocks were collected from the Sydney basin in New South Wales, Australia and belong to the Triassic geological age. The mineralogical structure of this sandstone is 80% quartz, 10% calcite, 5% kaolinite, 2% anatase, 1% siderite, 1% mica, and 1% amphibole, and the main cementing phases are quartz, calcite, and kaolinite. Homogeneous sandstone blocks were first carefully selected and then cored to the required size to produce samples 38mm in diameter and 76mm high, maintaining the required ASTM standard (2:1 height-to-diameter ratio) [2]. Both ends of the specimens were then ground. The prepared samples were first oven-dried at 30^0C for 48h (a temperature of 30^0C was selected to avoid micro-structural damage). Ten sets of three samples were then kept in distilled water, brine (15% NaCl by weight) and oil solution- filled desiccators and saturated for one year under vacuum to ensure maximum saturation (see Fig. 1). The specimens were removed from the desiccators just before being tested.

3. Experimental procedure

Forty AE compressive strength tests were performed (see Fig. 2(a)) to study the fracture propagation patterns in oil-and brine-saturated reservoir rock samples. The test series was conducted at Monash

University's Deep Earth Energy Research Laboratory, following the ASTM standards [2]. A SHIMADZU AG 9 type compression machine with maximum load capacity of 300kN was used for the experiments, and a 0.1 mm/min loading rate was used for all the samples. An AE system coupled with a peripheral component interconnection (PCI) 2-channel data acquisition system was used to study the fracture propagation patterns. This AE monitoring system consists of a band-pass filter with a frequency range of 1–2000 kHz and a 500 kHz frequency nominal resonance. The hardware included six sensors and external amplifiers (see Fig. 2(c)). During each test, six sensors were connected in series to the sample on either side of the specimen (see Fig. 2(b)) to precisely measure the fracture propagation in the sample, and amplifiers were used to measure the low frequency acoustic waves.

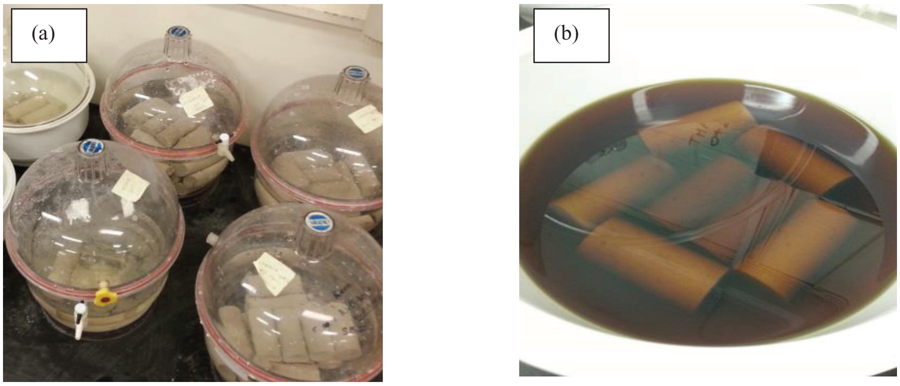

Fig. 1. Desiccators used to achieve (a) brine-saturated and (b) oil-saturated conditions in sandstones

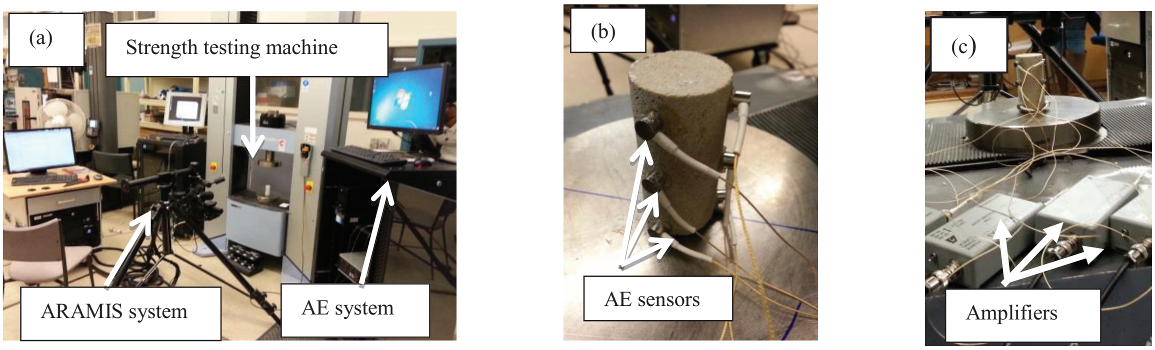

Fig. 2. (a) The strength testing set-up with AE machine and ARAMIS system, (b) the locations of AE sensors mounted on the sample and (c) the set of amplifiers used to amplify the low frequency AE waves

4. Results and discussion

The evaluation of the failure strength of reservoir rocks under brine- and oil-saturated conditions offers useful information related to the in-situ mechanical properties of deep saline aquifers and oil fields. Fig. 3 below shows the stress-strain curves of the specimens under different saturation conditions.

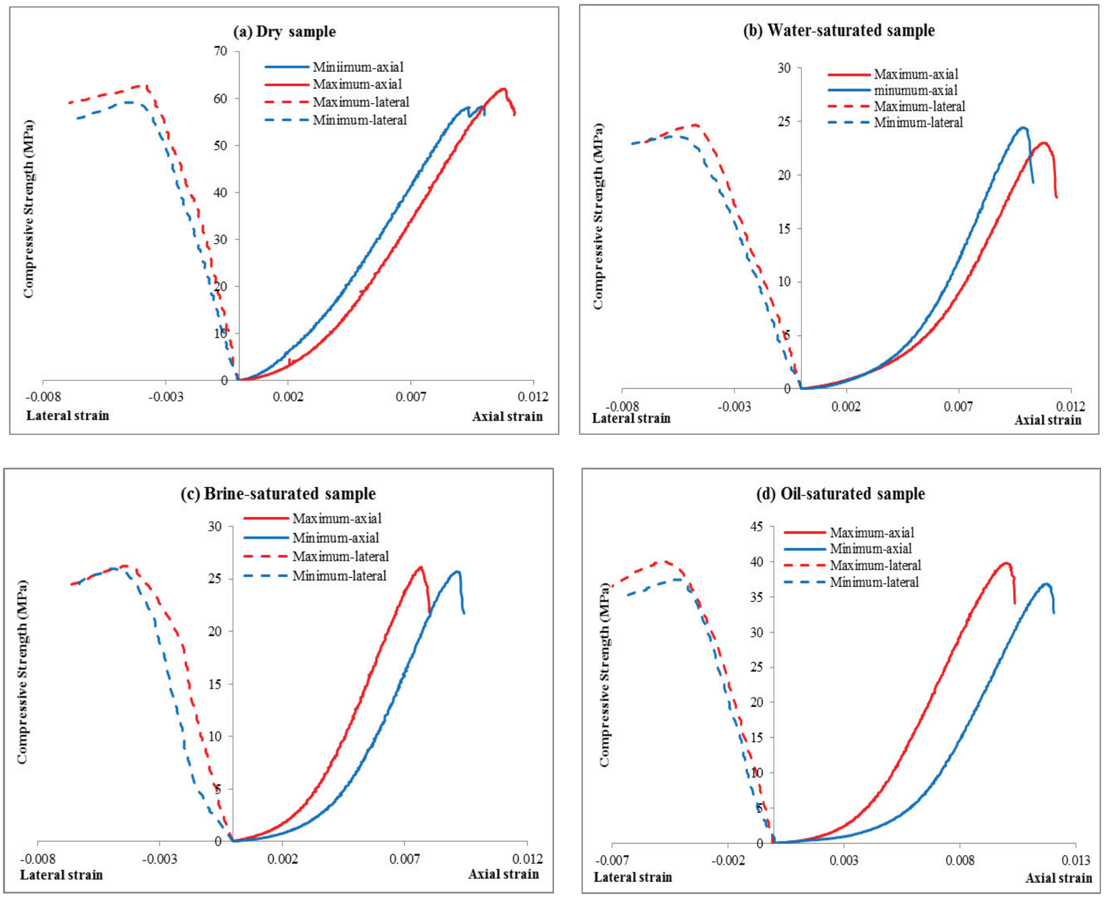

Fig. 3. Stress-strain curves for tested specimens.

Fig. 4 shows the mean compressive strength values of dry, water-saturated, brine-saturated, and oil-saturated reservoir rock samples. According to Fig. 4, dry reservoir rock has the greatest mechanical strength, with the highest mean compressive strength of 63.21MPa with standard deviation of 1.0234 MPa, and its greatest strength reduction occurs with water saturation (water-saturated samples have a minimum mean compressive strength of 23.78MPa with standard deviation of 1.763 MPa). This significant strength reduction in reservoir rock in the presence of water is mainly due to the grain softening effect [3, 4]. The most important observation is that the introduction of oil- and brine- saturation causes the strength of water- saturated reservoir rock to be clearly enhanced, and the oil-saturated reservoir rock samples show a mean strength value of 39.09MPa with standard deviation of 2.124MPa and brine-saturated samples exhibit a compressive strength of 23.78MPa with standard deviation of 1.873MPa. According to Rathnaweera et al. [5], the greater strength gain in brine-saturated samples compared to water-saturated samples is due to the NaCl crystallisation process which occurs in the rock mass pore space. These crystals add additional strength to the rock mass by reducing the effective pore space in the rock mass. As explained by Ying et al. [6], the density and viscosity of the pore fluid have a significant influence on rock mechanical properties. Compared to water and brine, oil has the highest density and viscosity properties under the given conditions. Therefore, when the rock sample is saturated with oil, there is always a fluid film between the asperities on each grain, resulting in well-lubricated grain contacts compared to water- and brine-saturated samples. Therefore, the bonds between grain-to-grain contacts are stronger in oil- saturated sample than water- and brine-saturated samples, which increases the strength of oil-saturated rocks compared to water- and brine-saturated rocks.

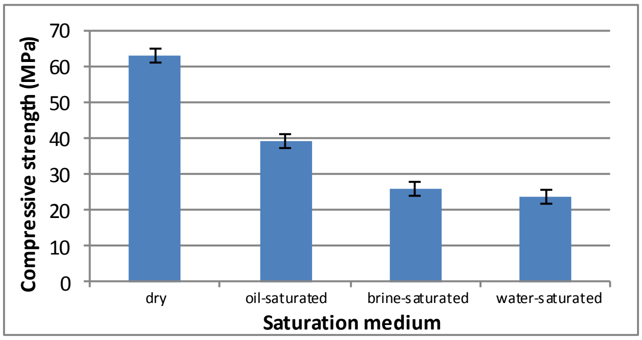

Fig. 4. The mean compressive strengths of dry, water-saturated, brine-saturated and oil-saturated reservoir rock samples

Table 2 shows the variation of reservoir rocks' mechanical properties with brine and oil saturation, compared to their dry and water-saturated conditions. The significance of these variations was statistically evaluated by performing T-tests, and the results indicated that the overall effect is statistically significant.

Table 2. Variation of reservoir rocks' mechanical properties with brine and oil saturation compared to dry and water-saturated conditions

Specimen	Mean compressive strength (MPa)	Percentage reduction compared to dry sample	Percentage increment compared to water-saturated sample
dry	63.21	-	165.8116
oil-saturated	39.09	38.15852	64.38183
brine-saturated	26.04	58.80399	10.2341
water-saturated	23.78	62.37937	-

After evaluating the compressive strength of oil- and brine-saturated reservoir rock, a comprehensive AE analysis was carried out to understand the different fracturing processes. AE data can be used to identify the rock failure threshold stresses including the crack closure stress range, crack initiation, stable crack propagation, and unstable crack propagation. In the crack formation process, at the beginning of load application, no significant AE energy emission can be seen, and this stage is called the crack closure stage. However, with the gradually increasing compressive load on the rock mass, crack initiation begins, which is indicated by the gradually increasing AE energy release. The further increase of the load causes unstable crack propagation in the rock mass, which is revealed by the exponential increase in the AE energy release. This stage of the load application leads to crack damage and the rock eventually fails.

As Table 3 and Fig. 5 show, the crack initiation stress value decreases from 17.82 MPa (the dry rock mass value) to 7.25, 11.41 and 16.57MPa with water, brine and oil saturations, respectively.

Table 3. Crack propagation stress values from AE analysis

Specimen	Crack closure range (MPa)	Crack initiation stress (MPa)	Crack damage stress (MPa)
Dry	0-17.73	17.82	45.94
Water-saturated	0-7.16	7.25	17.46
Brine-saturated	0-11.37	11.41	19.32
Oil-saturated	0-16.41	16.57	28.76

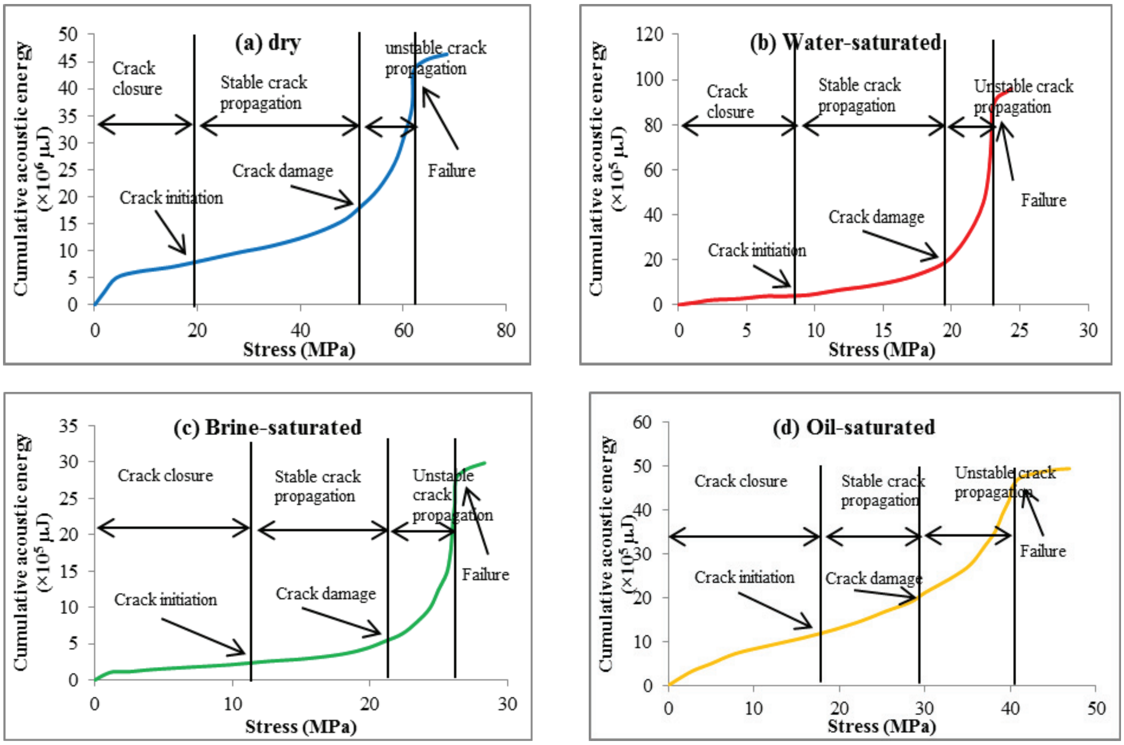

Fig. 5. The variation of cumulative acoustic energy versus compressive strength

Interestingly, the crack initiation value increases with the introduction of brine and oil into water-saturated rock. As mentioned earlier, the NaCl crystals deposited during the long-term saturation of rock in brine clog the existing micro-cracks in the rock pore space and an additional resistance to crack initiation occurs in the rock microstructure (see Fig. 6). The crack initiation values observed in oil-saturated samples do not show any significant deviation from the dry value, possibly due to the previously mentioned strong lubrication process of the saturated oil in the rock microstructure. Similar trends were observed for crack damage stress values, with the dry value of 45.94MPa decreasing to 17.46, 19.32 and 28.76MPa with saturation with water, brine and oil respectively.

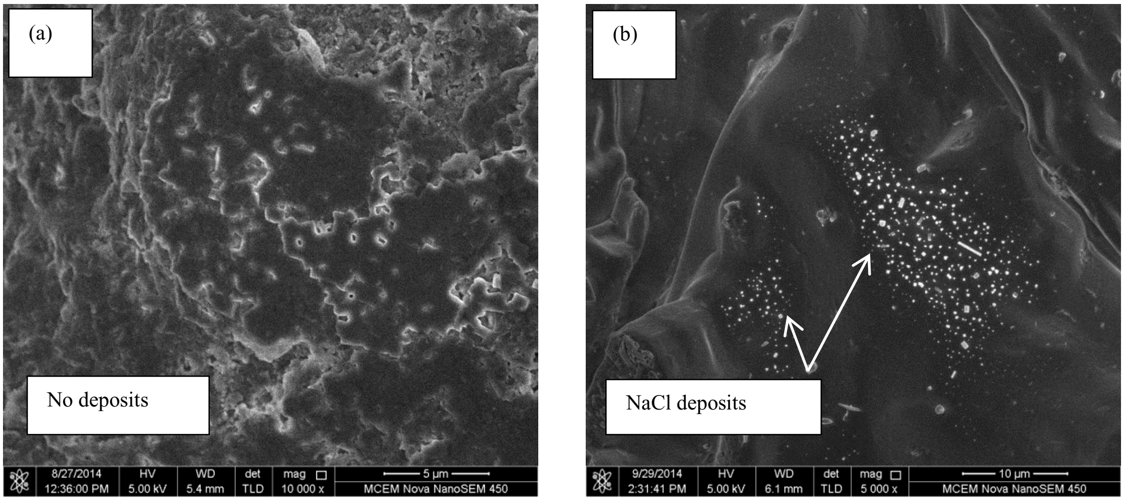

Fig. 6. SEM test results of (a) water- and (b) brine-saturated samples

5. Conclusion

Based on the results of strength tests on brine-, oil- and water-saturated and dry reservoir rock samples, the following major conclusions can be drawn:

- Although the presence of any kind of pore fluid causes reservoir rock to be weaker, the existence of oil in the pore fluid causes a considerable strength gain in the reservoir rock compared to both brine- and water- saturation conditions. This is a favourable for the long- term safety of the EOR process.

- Brine saturation also creates considerable strength gain in the reservoir rock mass compared to water-saturation, although the extent of strength gain is much less than that created by oil. This strength gain confirms saline aquifers to be safer for CO_2 sequestration.

- The failure-related stress threshold values obtained in this study can be used to identify the fracturing behaviour of undisturbed formations, to prevent unnecessary fractures due to an accidental increase in injection or the build-up of reservoir pressures.

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Biography

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Ranjith is a Professor of Monash University, Australia and Future Fellow of Australian Research Council. His main areas of research interests are sequestration of carbon dioxide in geological formations, deep geothermal energy extractions, and well-bore stability in complex geological conditions.