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Salinity-dependent strength and stress–strain characteristics of reservoir rocks in deep saline aquifers: An experimental study

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HIGHLIGHTS

- Salinity effects on mechanical properties of deep saline aquifers are investigated.
- AE counts, SEM and ARAMIS analyses on varying brine saturated sandstone are performed.
- Crystals develop in the rock's pore structure, depending on the bine concentration.
- Increased salinity enhances rock brittleness and reduces crack initiation stress.

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ABSTRACT

This paper presents an experimental study of the effects of salinity on the mechanical properties of reservoir rocks in deep saline aquifers. Nineteen sandstone specimens saturated in NaCl brines of varying salinity concentrations (0%, 10%, 20%, and 30% NaCl by weight) were tested in a uniaxial compression testing machine and the corresponding fracture propagation patterns were recorded using an advanced acoustic emission (AE) system. The stress–strain curves were analysed, with the simultaneous recording of the acoustic signals and the failure mode. In addition, a digital image correlation system, ARAMIS, was used to measure the lateral and axial strains during the loading period. Scanning electron microscopy (SEM) analysis was performed to understand the changes observed in the uniaxial compressive strength (UCS) and stress–strain behaviour of the rock specimens. According to the experimental results, the UCS and stress–strain behaviour of the rock specimens change with the increasing NaCl concentration of the host fluid. The SEM results show only minor changes in mineral structure during immersion. However, some depositions of NaCl crystals in the rock's pore space were observed. Interestingly, the growth of the NaCl crystals depends on the brine concentration, the amount of growth increasing with increasing brine concentration. The observed changes in AE analysis are also explained by the crystallisation of NaCl in the pore space, which transfers more acoustic energy from the cracks to the AE sensors due to the crushing of NaCl crystals during the compression process.

1. Introduction

Geosequestration in deep saline aquifers has recently attracted the attention of the scientific community and the general media, as it is one of the most promising means of reducing anthropogenic CO_2 emissions in the atmosphere. Deep saline aquifers have the largest storage capacity, which has been estimated to be between 320 Gt CO_2 and 200,000 Gt CO_2, with the potential to store the world's anthropogenic CO_2 emissions for hundreds of years [24,7]. Geosequestration in deep saline aquifers involves a number of steps including CO_2 capture, transport and injection deep underground via wells. Of these, the injection of CO_2 plays an important role in the CO_2 storage process. Typically, CO_2 is injected into the aquifer in a compressed form via a pipeline as a super-critical phase fluid, which exists in the super-critical phase at a temperature of 31.48 °C and a pressure of 7.38 MPa. CO_2 injection involves injecting CO_2 into a reservoir rock via a single well or array of wells. Normally, the most preferable aquifers for CO_2 sequestration lie at depths between 800 and 2000 m. Most are highly saline and situated in sedimentary basins, and can host large amounts of carbon dioxide safely due to the high formation pressures. According to past studies, it is clear that the high overburden pressure (high formation pressure) significantly affects CO_2 storage capacity during sequestration. Generally, high overburden pressure can prevent the decrease in the effective stress in the rock formation due to CO_2 injection. On the other hand, the increase of CO_2 injection pressure can significantly reduce the effective stress at low overburden pressure zones (shallower depths) and will damage the caprock sealing and reactivate existing faults, fractures and joints, even if

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the fluid pressure is below the fracturing pressure, and this can open new pathways for CO_2 back-migration into the atmosphere. As a result of this back-migration of CO_2, the effectiveness of the storage process will decrease, reducing the storage capacity of the sequestration project [37,41,1].

The CO_2 injected into deep saline aquifers is trapped by a number of different mechanisms, including solubility, mineral, residual and mobility trapping. During the long-term injection of CO_2 into the aquifer, the sedimentary rock at the centre of the well of the aquifer becomes almost dry due to forced brine migration. However, sedimentary rocks in this area are fully CO_2 saturated. Further away from the injection well, the degree of gas saturation of the host rock becomes less than one. Generally, these areas are characterised by rocks partly saturated with brine and CO_2, and in more remote parts only brine. Therefore, it is clear that differently saturated rock masses exist at the same time during the CO_2 injection process in saline aquifers, which itself exhibits the complexity of CO_2 sequestration in saline aquifers. On the other hand, reservoir rock (sandstone) is a complex solid medium, which has many initial internal micro-cracks. Therefore, during these trapping processes, the mineralogical structure of reservoir rock is exposed to the brine in various complex ways, leading to significant changes in the hydro-mechanical properties of the host rock.

According to past studies [8–10,19,12,4,20,42,36,43,34,21], the strength of reservoir rocks mainly depends on the temperature, confining pressure, injection pressure, pore size distribution, porosity and mineralogical structure of the rock mass. The concentration of brine in the aquifer is also an important parameter in the geosequestration process, when evaluating the possible changes in the mineralogical structure of reservoir rock. The detrimental effects of NaCl concentration on sandstone properties have been studied by a number of researchers [18,17,35,38] and it is now established that high ionic strength brines can cause irreversible formation damage to reservoir rocks. For instance, [18] showed that the shear friction of sandstone decreases due to the ionic concentration of NaCl. They also revealed that the rock strength reduces, mainly due to the corrosive nature of the chemical reaction between the mineral structure and brine. Feng et al. [17] conducted triaxial tests to evaluate the risks associated with the Xiaolangdi hydraulic project due to chemical corrosion, and investigated the long-term impact of NaCl on rock strength and its fracture characteristics. They found that, under the influence of a solution of NaCl with 0.01 M, the peak stress decreased about 15% in comparison with the natural state. Swolfs [40] proposed a hypothesis to explain the effect of different pore fluids on reservoir rock fracture strength, which is that the reduction in fracture strength due to the adsorption of ions or molecules onto the rock surface reduces the surface free energy of rocks. Moreover, Dunning and Miller [13] studied the effect of chemically-active solutions on the rock strength of porous Berea sandstone and Tennessee sandstone and concluded that Berea rock's strength reduces due to the chemical solution, producing gouge more quickly, which was not observed for Tennessee sandstone. Shukla et al. [38] studied water and NaCl saturation effects on reservoir rock mass strength and found that the mechanical properties of reservoir rock change significantly with the NaCl concentration in the pore fluids, where it initially reduces, and then increases with increasing NaCl concentration. According to Shukla et al. [38], the initial reduction of the strength is due to the water sensitivity or softening of the sandstone specimens in the brine, and according to these researchers, up to about 80% of the overall reduction in the dry strength of reservoir rock may occur due to the saturation effects of the pore fluids. The additional strength gained in reservoir rock with increasing salinity concentration is related to the crystallisation effect of NaCl in the pore structure, which happens with salt evaporation [38], and the double-layer interactions of clay particles [29]. Generally, sandstones contain many pore voids which provide enough space to develop NaCl crystals during the saturation process. The growth of these NaCl crystals significantly changes the pore matrix of the reservoir rock, while adding to the compressive strength. Mohan et al. [28] also studied the effect of NaCl crystallisation on reservoir rock strength using smectitic sandstone, considering the swelling effect of the existing clay minerals in the rock samples. These researchers observed that the growth of NaCl crystals during the swelling process of clay particles causes irreversible formation damage to the reservoir rock pore structure. Probst [32] observed that aquifer hydro-mechanical properties change with increasing concentration of brine, and explained this using the evaporation effect of salt in the aquifer. In addition, this study also illustrated the salting out effect, whereby evaporation can make the water phase denser and cause formation damage. Baudracco and Aoubouazza [2] also studied the variation in aquifer properties in Triassic sandstones submitted to saline circulation. The observed changes in the mechanical properties of the aquifer were explained by the displacement of free fine particles, which block the finest pores. In addition, the swelling of clays, the interaction of colloids and the adsorption of the brine on the walls of the porous environment may be the reasons for the changes observed.

Based on these findings, it is clear that there is a direct relationship between the brine concentration and mechanical properties of the host rock. However, it is important to note that these studies were conducted for low salinity ranging between 0% and 15% (by wt) and have not presented a quantitative explanation of the salinity effect on the mechanical properties of reservoir rock. Hence, this paper aims to present the findings of a laboratory investigation into the identification and characterization of the failure patterns and damage mechanisms of fully saturated reservoir rock under high concentrations of NaCl by integrating the use of acoustic emission (AE) monitoring and ARAMIS technology. Finally, scanning electron microscopy (SEM) analysis was performed to verify the results obtained and correlate them with possible changes in the microstructure of the rock mass.

2. Experimental methodology

2.1. Sample preparation

The sandstone samples used for this study were obtained from the Gosford quarries in New South Wales and some physical and mechanical properties are shown in Table 1. The sandstone blocks were cored according to ASTM standards and cored samples were then cut into 38 mm diameter cylinders in the Monash University Civil Engineering Department Laboratory. The height was selected as 76 mm to make the diameter-to-height ratio of 1:2. Both ends of the specimen were then carefully ground to produce smooth faces, and the specimens were oven-dried for 48 h and allowed to cool before being weighed.

For the present study, the water saturation specimens were selected as control tests, and four samples were kept for saturation in distilled water. In addition, three samples were selected to deter-

Table 1
Physical and mechanical properties of the Gosford sandstone used for the test program.

Property	Value
Bulk density (ASTM C97-83)	2.22–2.5 g cm^3
Absorption by weight (ASTM C97-83)	6.57%
Modulus of rupture	8.9 MPa dry, 2.5 MPa wet
Compressive strength (ASTM C170-87)	39.05 MPa dry, 22 MPa wet