



# Mechanical behaviour of wellbore materials saturated in brine water with different salinity levels



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## ABSTRACT

In any carbon capture and sequestration (CCS) project, well cement plays a vital role as it provides the required zonal isolation and well integrity. Typical wellbore materials including well cement and formation rock will be exposed to a range of saturation mediums such as water and brine with different salinity levels. To date, ordinary Portland cement (OPC)-based well cement has been used. However, its survival has been questioned under CO<sub>2</sub> sequestration conditions, as it experiences cement degradation and strength reduction in saline water. Therefore, this experimental work investigates the mechanical characteristics of geopolymer (G) as well cement and sandstone (S) as formation material. The mechanical behaviours of G, S and G–S composite materials in fresh water (W) and two concentrations of brine water (BW), 5% NaCl (5% BW) and 15% NaCl (15% BW), were studied. Based on the results, it was found that G, S and G–S samples experience strength reduction in W and BW. However, the reduction rate of G is almost half of that of OPC-based oil well cement. In addition, the strength reduction rates of G and G–S were less in 15% BW compared to W and 5% BW, due to the lower alkali leaching rates from G in BW compared to W. Therefore, saline aquifers with high NaCl content are always favourable for G well cement. The S samples showed constant strength reduction regardless of the saturation medium, and hence NaCl does not show any significant effect on the mechanical behaviour of quartz-rich sandstone. The crack propagation stress thresholds were higher for G and G–S saturated in 15% BW compared to 5% BW. The S samples did not show major variation in crack propagation stress thresholds in W and BW. The ARAMIS strain measurement results showed that the maximum strain that wellbore materials experience at failure reduces with the introduction of brine. In addition, G and G–S undergo splitting failure, whereas S experiences shear failure in W and BW.

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## 1. Introduction

There have been many scientific studies focussing on the reduction of global warming, and carbon dioxide (CO<sub>2</sub>) is one of the main greenhouse gases causing global temperature rise. The major threats of global warming will be the inundation of low-lying coastal zones due to the melting of polar ice caps, regional decreases in food production, the deterioration of eco-systems, and the spread of diseases [1]. Of all greenhouse gases, CO<sub>2</sub> is responsible for 64% of the greenhouse gas effects [2]. Geo-sequestration of CO<sub>2</sub> is considered to be one of the largest scale mitigation methods

to combat greenhouse gases produced from coal-powered plants, petroleum and oil recovery projects, cement production and iron and steel production [3–5]. The sequestration wells play a major role in the success of any sequestration project, as well as integrity should be maintained for efficient sequestration. Well integrity can be obtained by providing zonal isolation, which depends on the well cement as it is used for primary cementing (between the casing and the caprock) and secondary cementing (inside the casing).

To date, ordinary Portland cement (OPC) has been used as well cement. However, there are many problems associated with the current practice, such as cement degradation, lack of chemical and acidic resistance, durability concerns, leakage, and strength reduction in high salinity environments [6,7]. According to an enhanced oil recovery (EOR) survey, of the total of all CO<sub>2</sub> EOR wells (16,348) only 0.15% use non-Portland cement CO<sub>2</sub> zones. In North America, there are tens of thousands of abandoned, inactive, or

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active oil and gas wells, including gas storage wells that currently leak to the surface. Another portion enters shallow ground water aquifers, causing problems for flora and fauna [8]. In contrast, it has been discovered that geopolymer possesses higher compressive strength, has high acidic resistance, is durable, does not undergo alkali aggregate reaction (AAR), possesses higher pumpability compared to OPC, and consumes less energy and costs less for its production [9–11]. The development of high early-age strength of well cement is important to ensure structural support for the casing and the hydraulic/mechanical isolation of the wellbore [12]. Normally, CO<sub>2</sub> is injected in its super-critical state (pressure >7.3 MPa and temperature >31.8 °C), and a minimum depth of 800 m is suggested for super-critical conditions [13]. At such depths, CO<sub>2</sub> is injected into sedimentary rocks and the salinity of the brine in such rocks is usually high [14]. Therefore, sedimentary rocks (sandstone) and well cement are exposed to brine water with different salinity levels.

The behaviour of OPC in saline water has been studied by many researchers [15–19]. Barlet-Gouedard [15] found that OPC samples saturated in CO<sub>2</sub>-mixed water and brine solutions for a period of 6 months were degraded. However, the degradation rate was 10 times lower in brine as an increase in the salinity of water reduces the solubility of CO<sub>2</sub>. In addition, CO<sub>2</sub>-mixed water samples showed 65% strength reduction, although the extreme deterioration of the samples did not allow further compressive strength measurements. Lecolier et al. [16], studied the durability of class G well cement cured at 80 °C for one month, and then aged in water, brine and crude oil at 80 °C. It was observed that samples aged in water and crude oil did not show any considerable strength reduction after one year, whereas the uniaxial compressive strength of the samples aged in brine fell to 50% of the initial strength due to the leaching of portlandite from the cement matrix.

Kondo et al. [17], studied the influence of chlorides (Cl<sup>−</sup>) on the hydration of OPC by monitoring the diffusion rates of anions and cations (K<sup>+</sup>, Li<sup>+</sup> and Na<sup>+</sup>) through the cement. It was found that the diffusion rates of Cl<sup>−</sup> ions were higher than that of cations such as K<sup>+</sup>, Li<sup>+</sup> and Na<sup>+</sup>. In addition, the counter diffusion of Cl<sup>−</sup> and OH<sup>−</sup> between the solution and the cement formed insoluble Ca(OH)<sub>2</sub> crystals. The counter diffusion process in hardened cement paste accelerates the dissolution of Ca(OH)<sub>2</sub> leading to coarser pore structure and extensive diffusion of ions. When Susuki et al. [18], studied the effect of NaCl on the formation of calcium silicate hydrate (C–S–H) gel in OPC, it was noted that the Na<sup>+</sup> ion is adsorbed on the surface of C–S–H gel, reducing the Ca/Si molar ratio of C–S–H. A similar action takes place on C–S–H with the Cl<sup>−</sup> ion in NaCl promoting leaching rates of Ca from C–S–H. Zhou et al. [19], studied the effect of salinity level (0–36% NaCl concentration) on the properties of oil well cement (class G) cured under high pressure and temperature conditions. It was noted that low NaCl concentration (<10%) accelerates the hydration process, whereas high NaCl concentration (>10%) delays it. In addition, the strength of the cement reduces substantially as the concentration of NaCl in brine increases, and reduction is more pronounced for prolonged curing periods. It can be seen that higher NaCl content saline water is not favourable for OPC, as it retards hydration and accelerates the leaching process.

To date, there have been limited studies [20,21] focussing on the behaviour of geopolymers in saline water. Lee and Deventer [20] tested the durability of two different types of geopolymers with different KOH molarities in salt water. The inorganic salts (KCl, CaCl<sub>2</sub> and MgCl<sub>2</sub>) were added in the mixing stages and curing was done at room temperature. They noticed an increase in strength in the early ages (up to one month), although strength deterioration was observed after 9 months. The long-term strength reduction was related to hydrolytic attack on aluminosilicate gel in salt water.

**Table 1**

The composition of ASTM class F fly ash used for the study [4].

| Element as oxide | Al <sub>2</sub> O <sub>3</sub> | SiO <sub>2</sub> | CaO | Fe <sub>2</sub> O <sub>3</sub> | K <sub>2</sub> O | MgO | Na <sub>2</sub> O | SO <sub>3</sub> | Loss on ignition |
|------------------|--------------------------------|------------------|-----|--------------------------------|------------------|-----|-------------------|-----------------|------------------|
| Percentage       | 30.5                           | 48.3             | 2.8 | 12.1                           | 0.4              | 1.2 | 0.2               | 0.3             | 1.7              |

Giasuddin et al. [21], tested geopolymer saturated in fresh water and brine water (8 and 15% NaCl concentration) under ambient curing conditions. It was observed that the strength of brine water cured samples was higher than fresh water cured samples. The alkali leaching rates and sorptivity of saline water cured samples were lower than that of fresh water cured samples, leading to higher strength in saline water. Saline water has excess Na<sup>+</sup> ions, and hence the anions (Na<sup>+</sup> and Ca<sup>+</sup>) present in geopolymer are less prone to leaching in saline water. These excess cations help to enhance the reaction kinetics in saline water.

In relation to formation rocks, it has been found that the compressive strength of rock reduces drastically when cured in water [22–25]. The reduction ranges from 6% to 85%, depending on the saturation level [25]. Moreover, it was observed that the compressive strength of the water-saturated samples, which were oven-dried prior to saturation, was similar to those saturated without drying [23]. Dyke and Dobereiner [26] concluded that parameters such as water content, mineralogy and texture of rocks contribute to the mechanical properties of rocks. Weaker sandstones are more sensitive to moisture content changes than harder rocks because of the larger pore networks in weaker sandstones. Clay minerals in sandstone are highly water-sensitive and this may result in changes in porosity, permeability, modulus of elasticity, uniaxial compressive strength and tensile strength [27]. Shukla et al. [14], tested feldspathic greywacke (S type comprising matrix and quartz clasts in equal amounts) and lithic greywacke (M type with 75% of quartz) sandstones saturated in 0–15% NaCl brine water for 45 days. The water saturation caused a strength reduction of 61 and 24% for S and M type sandstones, respectively. In addition, it was observed that the UCS values of both the sandstones reduced with the initial increase in NaCl concentration from 0 to 5%, and then UCS values increased from 5 to 15% NaCl concentration. However, they concluded that the strength variation in different NaCl concentration is less pronounced for M type sandstone (higher quartz content) compared to S type sandstone.

The experimental programme reported here investigates the mechanical behaviour of geopolymer (G), sandstone (S) and G–S composite wellbore materials exposed to different curing mediums and two concentrations (5% NaCl and 15% NaCl) of brine for periods of 14, 30, 60 and 90 days. The NaCl salinity level may vary from 0 to 36% depending on the geological conditions [19]. In the present study 5% and 15% NaCl concentrations were chosen to represent low and medium salinity environments. Giasuddin et al. [21], used geopolymer made by partial replacement of fly ash with slag and the curing was done at room temperature. However, the present study uses fly ash-based geopolymer cured at elevated curing temperatures (50 °C). The G–S composite material was tested to study the composite behaviour of a typical wellbore. Acoustic emission testing (AET) was used to study the crack propagation behaviour, while ARAMIS image photogrammetry was used to study the macro–micro behaviour of material deformation under various test conditions.

## 2. Experimental programme

G, S, and G–S composite samples were prepared for testing. The G paste was prepared using ASTM (American Society for Testing

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