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Review

# A review of oil well cement alteration in $CO_2$-rich environments

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## HIGHLIGHTS

- Formation of four main zones within the cement matrix.
- The residence time and the aperture size determine cracks' behaviour.
- A cement matrix is damaged more than its surrounding rock.
- Self-sealing behaviour is likely, when a well is properly cemented.

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## ABSTRACT

The purpose of this study is to examine previous works undertaken that characterise the cement alteration due to its exposure to $CO_2$-bearing fluids attacking on the interfaces of cement-rock and cement-casing, or through cement cracks, and the cement matrix itself. Numerous studies have reported carbonation of well cements. The majority of studies reported self-healing behaviour of cements cracks observed under general $CO_2$ storage conditions. In addition, defective cement matrix and bonding between cement and casing were also found to be potential causes for leakage pathways. Albeit, severe conditions, such as high acidity degree of brine and high flow velocity, may negatively affect the self-healing behaviour of the cement.



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## 1. Introduction

In the course of 132 years from 1880 to 2012, the average global combined land and ocean temperature has risen by 0.85 °C [1], a phenomenon now indelibly linked to anthropogenic greenhouse gas (GHG) emissions. Carbon dioxide is accountable for 9–26% of these GHG emissions [2,3]. One amelioration technique that can be adopted is the use of carbon capture and storage (CCS), which seeks to capture released $CO_2$ from power plants and subsequent injection of them into stable underground formations. Coal beds, aquifers, and depleted oil and gas reservoirs are of considerable interest for CCS. Amongst them depleted reservoirs are preferred since their structures have been well-characterised and studied over different periods of the reservoir's lifecycle. In addition, oil and gas reservoirs have maintained their integrity and prevent fluid permeation to the surface over millions of years, indicating their proven capability of storing fluids over a long duration. One additional benefit of CCS is that the $CO_2$ injection into oil and gas reservoirs is considered as an enhanced oil recovery strategy. One of the major problems with this type of projects is that quite a high number of abandoned wells have been cemented during the last century without meeting the necessary safe storage requirements. Drilled wells are the direct connection between underground formations and the surface. Any defects in the cement and plugs may later transform into potential leakage pathways. This is illustrated by a 30-year old cement core sample recovered from a $CO_2$-flooding site in West Texas. That demonstrated $CO_2$ leakage along the cement-shale and cement-casing interfaces, even though the cement retained its low permeability to prevent $CO_2$ flow [4]. Accordingly, an investigation of cement integrity exposed to $CO_2$-bearing fluids is of great importance for determining the probability of $CO_2$ leakage to the surface.

Carbon capture and storage (CCS) projects are designed to prevent large quantities of $CO_2$ from entering into the atmosphere. This will be done by effectively collecting $CO_2$ and transporting it from large production point sources to storage sites where it can be deposited in underground formations and can remain there for thousands of years [5].

Typically, depleted oil and gas reservoir sites are the main subjects for $CO_2$ storage. The risk of $CO_2$ gas leakage to the surface from prior-drilled and abandoned wells can be assessed to speed up risk assessment [6]. It was also shown that wells which are drilled under an appropriate regulatory system for $CO_2$ and acid gas injection purpose are less probable to fail in comparison with other types of wells converted to injection wells [7]. Therefore, performing a robust drilling, completion, abandonment, and cementing under the supervision of reliable regulatory frameworks is vital to prevent $CO_2$ leakage. The cement used as well lining or plugs may have undergone an alteration process due to $CO_2$ exposure. This process may lead to either the aggravation or amelioration of leakage pathways depending on the conditions of the cement and the invading fluids [8].

The most potential leakage pathways within casing-cement-rock (rock can be a storage formation or caprock) assembly include the gap between rock and cement [9,10], the gap between the casing and cement [11,12], cracks in the cement [11,13–15], and the cement matrix by itself [14,16–18]. $CO_2$ is injected generally in a supercritical form into underground formations [19]. In this state it has the physical properties of both a liquid and a gas which dissolves materials such as a liquid and can effuse through solids like a gas. The injected $CO_2$ dissolves in brine, as a ubiquitous element in depleted oil and gas reservoirs particularly around abandoned wellbores, results in carbonic acid formation [20]. $CO_2$-saturated brine with a pH lower than 4 starts moving through well cements due to diffusion or advection [21,22]. This movement brings the pore water within the unaltered cement with a pH more than 12.5 in contact with acidic brine [23]. This process leads to a reaction between the cement and brine leading to a gradual carbonation within the cement [12,24–29]. The continuous renewal of reacted $CO_2$-saturated brine at the cement interface accelerates the degradation of the cement and causes the depleted calcium region to be converted into an amorphous silica gel [27,29].

This paper provides a review of studies that have characterised the alteration in cement due to $CO_2$–bearing fluids attacking on the interfaces of cement-rock and cement-casing, or through cement cracks, and the cement matrix itself.

## 2. Characterisation of cement matrix alteration attacked by $CO_2$-bearing fluids

### 2.1. Involved chemical reactions

The dissolution of $CO_2$ in brine decreases its pH to below 4. The subsequent flow of this mixture through a carbonate formation leads to an increase of pH by 2. It is interesting to note that if the dissolution was to flow through a sandstone formation there