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Experimental Study of Stability and Integrity of Cement in Wellbores Used for CO_2 Storage

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Abstract

This paper examines the results obtained from lab experiments on cement deterioration in sulfate and CO_2 environments. The experimental work consisted of preparing several sets of samples, placing them in environments at different conditions, and monitoring change in various properties once every two months for a period of one year. The parameters investigated were:

- Permeability
- Compressive strength
- Effect of diffusion using the scanning electronic microscope
- Shear and hydraulic bonding strength

Lab results showed that the effect of sulfates and CO_2 can be beneficial for the plugging purposes due to the reduction of permeability. However, reduction of compressive strength under CO_2 environment was observed.

Keywords: Wellbore Stability; Cement Deterioration; Geological Storage; Risk Assessment; CO_2 Leakage

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1. Introduction

Geological storage of CO_2 in depleted or partially depleted oil fields has gained increasing interest around the globe as an economically viable means of reducing emissions of CO_2 while recovering extra oil. In these projects, CO_2 is injected into the oil-bearing formations through injection wells, and oil is produced via production wells. An example of such CO_2 EOR/storage projects is the IEA GHG Weyburn CO_2 Monitoring and Storage Project, where it is predicted that about 20 million tons of CO_2 will be stored underground in Weyburn oilfield throughout the life of this project, while producing over 100 million barrels of additional oil.

One of the major challenges encountered for any CO_2 storage project is to understand the risk of CO_2 leakage back to surface. Although there are a variety of potential pathways for CO_2 leakage, it is widely accepted that the

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single most important path of CO_2 leakage is through wellbores. There are hundreds of thousands of wellbores, both operational and abandoned, in North America. For instance, over 360,000 active oil and gas wells are registered with the Railroad Commission of State of Texas[1]. It is estimated that the total deep holes in Texas are around 1.5 million. Therefore, it becomes clear that understanding the magnitude of potential risk and developing suitable mitigation responses for CO_2 leakage, when CO_2 is stored in oil reservoirs, would be directly related to our understanding of the prospective of CO_2 leakage through wellbores.

Several research groups have focused on investigating CO_2 leakage through wellbores, and one of the main areas of interest has been the stability and integrity of the cement used in wellbores. The goal of these studies has been to quantify the changes in physical and chemical characteristics of cement in environments similar to those found in CO_2 storage operations.

Krilov reported a series of experiments designed to evaluate the stability and integrity of cement in sour gas wellbores. These researchers conducted experiments at conditions similar to the actual environmental downhole impact (high reservoir temperature, BHST>180°C, sour gas: 22% CO_2 and 150 ppm H_2S)[2]

Krilov also concluded that the cement used in oil wells, under hostile reservoir conditions, could loose its mechanical integrity after long-term exposure. Some researchers believe the dominant mechanism of cement deterioration is caused by CO_2 corrosion process in the form of carbonic acid leaching. Application of various logging tools, such as cement bonding log, has verified the existence of the casing cement disintegration behind 7-in. casing after 15 years of well production period.

Since in majority of CO_2 storage projects the injected CO_2 is at supercritical state, some researchers have studied the chemical reactions and physical degradation of cement in presence of supercritical CO_2 at reservoir conditions.[3]

The cement degradation is not only a function of the presence of supercritical CO_2, but also degradation could be intensified depending on the rate of injection of CO_2. A series of studies have focused on the effect of high rate acid gas injection on cement integrity. There are specialty cements designed for withstanding environments of high injection rate for sour gas injection operations, such as high alumina cements.[4]

Other examples of experimental procedures and methodologies to study chemical reactivity of CO_2-water-cement systems by interacting the set cement with injected supercritical CO_2 at reservoir conditions have been reported too. In many of these cases the investigations have been focused on Portland cement and experiments have been continued for few months[5]. Duguid *et. al* conducted a series of experiments and investigated the effect of CO_2 on cement in abandoned oil wells[6]. It was observed that significant damage, indicated by complete loss of the calcium hydroxide phase, can occur for experiments conducted for time periods as short as 7 days.

2. Experimental Setup and Procedures

Several sets of experiments were conducted during this study. Each type of experiment required specially designed experimental setup and procedure. A list of various tests conducted is as follows:

- Permeability tests
- Compressive strength tests
- Diffusion tests, using Scanning Electron Microscope
- Shear and hydraulic bonding strength tests

Two classes of cement were used for these experiments, Type 10 and class G. The Type 10 is the Canadian denomination for the cement Class A in the API standard. These classes of cements were selected due to their common applications in the oil industry for plugging purposes.

The cement Type 10 is intended for use from surface to 6,000-ft depth, when special properties are not required. It is similar to ASTM C 150, Type I. Depth limits are based on the conditions imposed by the casing-cement specifications tests. Lafarge cement was used for this class and acquired from local vendors. Cement Type 10 is made-up according to the standard CAN/CSA-A3001-03 & CAN/CSA-A5.

The cement class G is intended for use as basic well cement from surface to 8,000-ft depth as manufactured, or can be used with accelerators and retardants to cover a wide range of well depths and temperatures. It is available in moderately and highly sulphate-resistant types. The cement Class G was obtained from Lehigh Inland Cement Ltd., Edmonton, Alberta, Canada.

Total of 300 cubic and 400 cylindrical cement samples were prepared and placed at various sulphate concentrations for several months. Another set of 40 cylindrical samples were placed in a pressure vessel where they were exposed to a mixture of brine and supercritical CO_2 at 2,200 psi and 55°C. All cement samples were prepared according to the standards API 10A[7] and API 10B[8]

3. Results

Permeability Tests

The objective for this set of tests was to investigate the extent of change in cement structure with time through measuring permeability of cement samples over time. The equipment used for this test was a special cement permeameter. Cement samples were placed in sulfate environments with sulfate concentrations of 3,000; 6,000 and 30,000 ppm. Figures 1, 2, and 3 present the change in permeability of cement samples in three different temperatures for up to twelve months (one year). It is clear that the permeability of cement is first reduced and after few months starts increasing. However, the permeability of all samples remained less than their initial values throughout these tests. The change in permeability of the cement samples in presence of water and supercritical CO_2 is presented in Figure 4. The results indicate that the cement permeability is reduced, for the duration of these experiments, in CO_2 environment.

Results of Compressive Strength Tests

An indirect method of measuring the effectiveness of plugging wellbores with cement is by means of compressive strength test. A value higher of 500 psi is considered as acceptable for plugging[9]. The net result of placing cement samples in presence of sulfate and CO_2 for prolonged periods of time is the leaching of cementitious material from the cement matrix that leads to decrease of compressive strength. A total of 300 cubic samples were used for compressive strength experiments. Figures 5 and 6 present some experimental results of change in compressive strength of cement in sulfate and CO_2 environments, respectively.

Results of Scanning Electron Microscope (SEM)

The diffusion of sulfate in cement leads to a series of chemical reactions and change in chemical structure of cement. Here, two types of chemical reactions are assumed to occur due to sulfate attack[10, 11]:

- Decalcification
- Formation of expansive products (mono-sulfate and ettringite)

Measurements were taken every two months using the SEM. Figures 7 – 9 illustrate the diffusion of the sulfate ions in the cement paste. The measurements showed a rapid diffusion at the early stages of the experiments, while the rate of diffusion slowed down at later times. It is believed that a chemical compound is formed in the capillaries inside cement that leads to reduction of cement permeability in the first few millimetres from the exposed surface. In average and after ten months of exposure, only two centimeters of the cement were reached by sulfates ions.

Results of Shear and Hydraulic Bonding Strength

In a wellbore, shear and hydraulic bond to the casing are the two forces to be considered for effective isolation between the cement and casing interfaces. Shear bond mechanically supports the plug in the hole, and it is determined by measuring the force required to initiate pipe movement in a cement sheath. This force divide by the cement contact surface area yields the shear bond in pounds per square inch. The hydraulic bond strength is a measure of the hydraulic pressure required to initiate leakage of fluid between the plug and casing. Hydraulic bonding blocks the migration of fluids or gas in a cemented annulus.

Special core holders were built to investigate the shear and hydraulic bonding strength between cement and the casing. Figures 10 and 11 show the schematic diagrams for these tests. The initial values of shear bonding and hydraulic bonding strengths were 1,240 psi and 315 psi, respectively. The final values after two months were very low for shear bonding strength in such a way that the device (hydraulic jack) was not able to detect it. The same happened with the hydraulic bonding strength, but in this case the device (manual pump) measured values of 30 to 40 psi for both classes of cement. The explanation for these results may be related to the shrinkage of cement in the casing. These findings clearly indicate that the most possible path for CO_2 leakage in a wellbore might be between the cement plug and casing.

4. Conclusions

Based on the results of above experiments the following conclusions are made:

- The permeability of the two types of cements tested during these experiments reduced initially, but it increases after few months.
- Increase in permeability occurs sooner and at a faster rate for experiments conducted at higher temperatures or/and higher sulfate concentrations.
- The compressive strength of the two types of cement tested is increased initially, but after few months it decreases.
- The hydraulic and shear bonding was reduced severely after few months. This behavior suggests that the space between cement plug and casing could be the most plausible path of CO_2 leakage in the wellbore.

5. Acknowledgements

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7. Appendices

Figure 1. Change in cement permeability in sulfate environment (30°C)

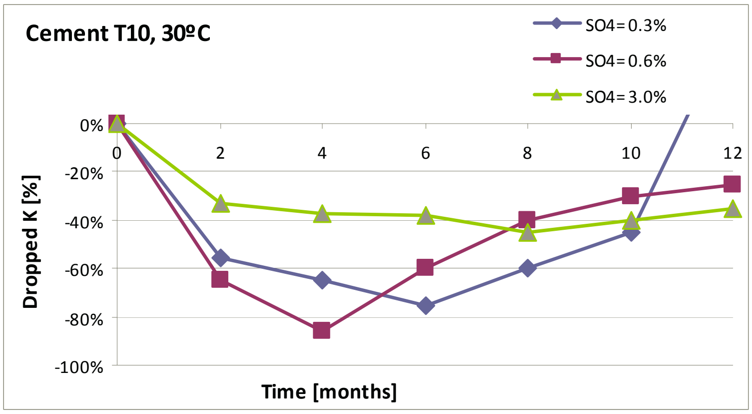

Figure 2. Change in cement permeability in sulfate environment (55°C)

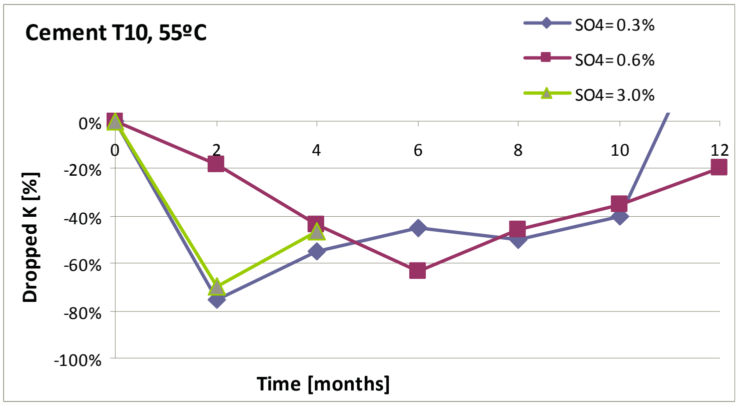

Figure 3. Change in cement permeability in sulfate environment (75°C)

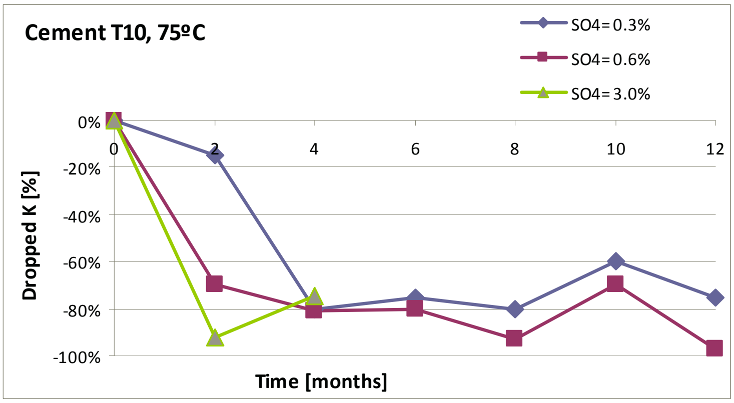

Figure 4. Change in cement permeability in CO_2 environment (2200 psi and 55°C)

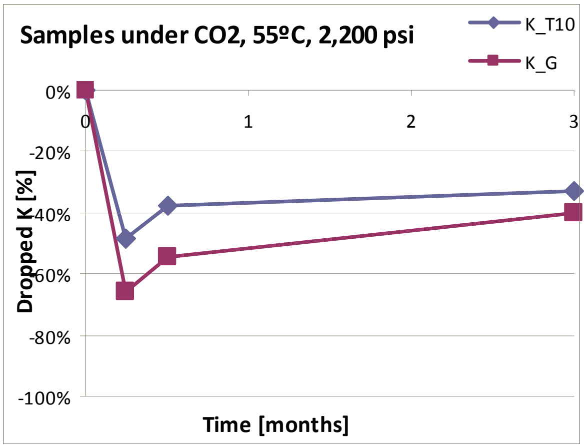

Figure 5. Change in compressive strength in sulfate environment

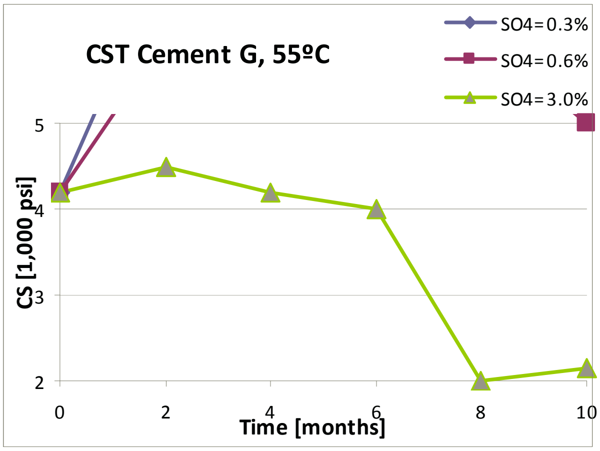

Figure 6. Change in compressive strength in CO_2 environment (2200 psi and 55°C)

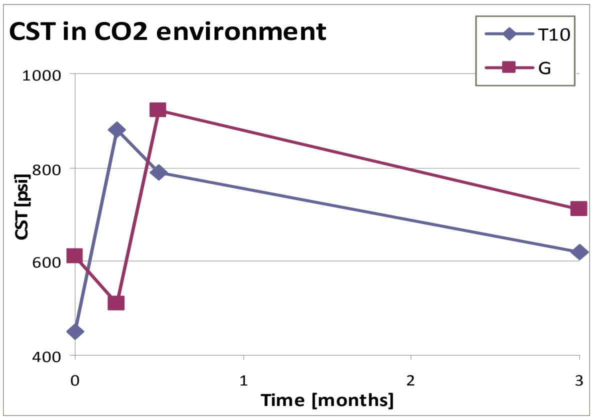

Figure 7. Diffusion of sulfate in Cement type 10, $SO_4^=$ 0.3% and 30°C

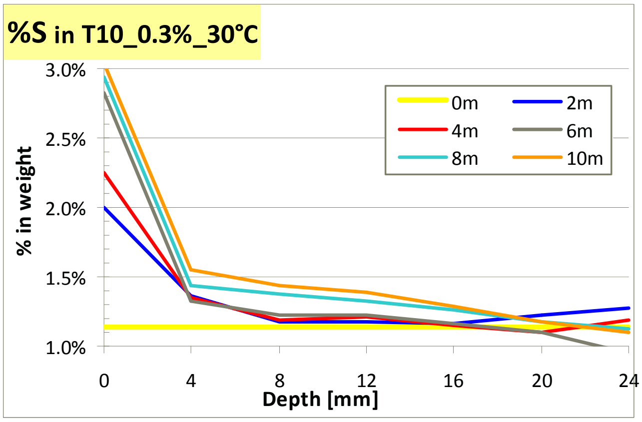

Figure 8. Diffusion of sulfate in Cement type 10, $SO_4^=$ 0.3% and 55°C

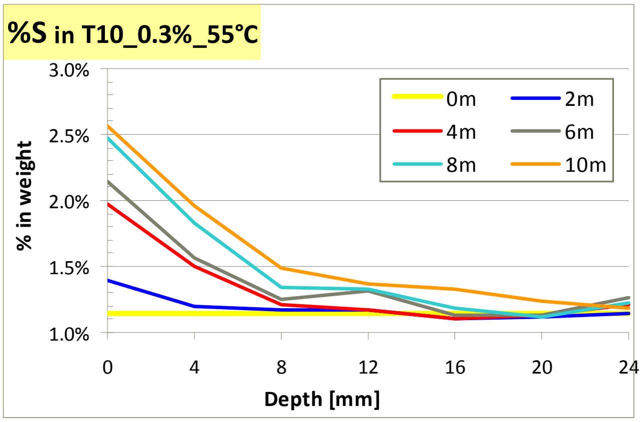

Figure 9. Diffusion of sulfate in Cement type 10, $SO_4^=$ 0.3% and 75°C

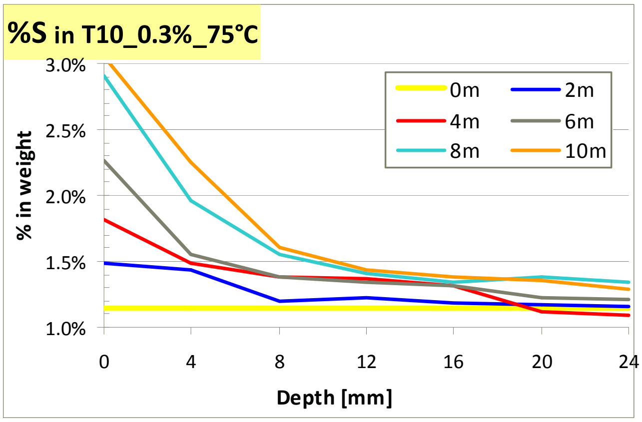

Figure 10. Experimental set up for measuring shear bonding strength

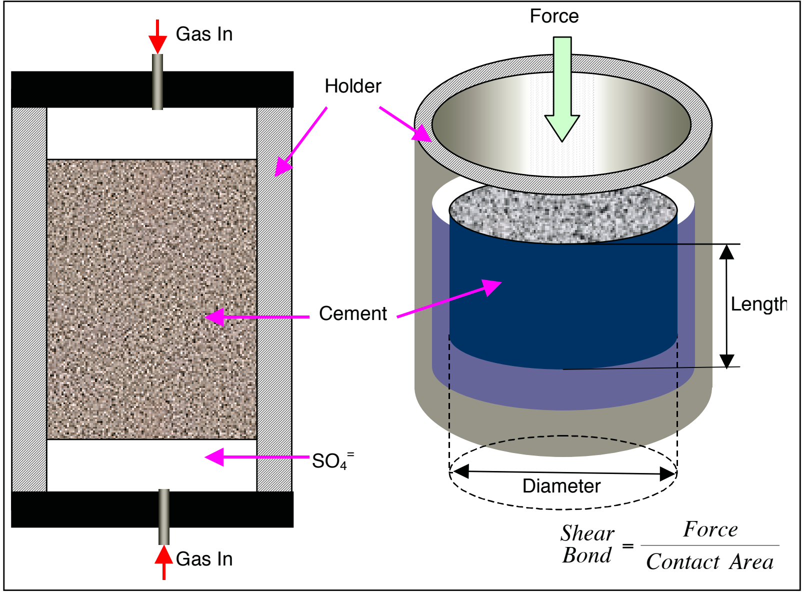

Figure 11. Experimental set up for measuring hydraulic bonding strength