MONITORING OF CO_2 WELL PLUG INTEGRITY. ELECTRICAL RESPONSE OF CEMENT/CNF SENSOR TO MECHANICAL LOAD, WATER SATURATION AND CARBONATION

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Abstract

CO_2 storage wells will eventually need to be permanently plugged and abandoned. Subsidence, fault/fracture reactivation or chemical degradation can all adversely affect well plug integrity leading to CO_2 leakages. Thus, monitoring of well plug integrity should be of high priority for CO_2 storage.

There are materials whose properties change upon application of mechanical stress or chemical alterations that could be tested for well plug integrity sensing. One of them is cement with conductive fibres. In this paper we summarize SEP FARAWELL project results describing electrical response of conductive composites made of well cement and carbon nanofibers (CNFs) in response to load, carbonation, and water saturation changes.

The results show that bulk resistivity of well cement/CNF composites changes upon application of the three stimuli mentioned above thus the material proves promising for monitoring applications.

Keywords: *well, plug, monitoring, integrity, sensor*

1. Introduction

CO_2 storage wells will eventually need to be permanently plugged and abandoned. Subsidence, fault/fracture reactivation or chemical degradation can all adversely affect well plug integrity leading to CO_2 leakages. Taking responsibility for the storage projects for posterity should not only rely on better understanding of leakage mechanisms but also on taking measures to detect and prevent any future leakage events. To this end monitoring of the well plug integrity in the long perspective is needed. It is in vain to look for long-term monitoring technology in oil and gas industry. In contrast to CO_2 storage wells, the oil/gas wells are plugged when the reservoir has been depleted from gas/oil thus the system left under-pressured and not prone to further leakage. Moreover, the long-term monitoring in oil and gas industry is a controversial topic due to difficult decision making on defining responsible authorities. Defining responsibility in CO_2 storage legislation is easier.

The plugging upon abandonment aims on long term sealing of the well (preferably for infinity) in order to prevent leakage of the fluids from the reservoir to the environment [1]. This is done by setting cement plugs within the well. After the cement plug is set the plug quality is assessed by pressure testing and if no leakage at this stage is detected the well is regarded as sealed. Although the requirement for long-term (eternal) sealing seems to be very strict, there is no commercial monitoring technology for abandoned wells that could prove that the well plug is indeed intact long after the plug was set. This implies that the responsible authorities do not know whether or not installed well plugs are fulfilling their role, or have stopped acting as barriers, as a result of chemical or mechanical degradation. The chemical degradation can be a result of interaction between the plug and reservoir fluids, while the mechanical degradation can result from e.g., subsidence or shear displacement along discontinuities (e.g., rock interfaces, fractures). Continuous in-situ monitoring of well barrier materials could allow for early stage warning of any loss of sealing capacity and intervention before any leakage occurs. Chemical or mechanical degradation processes may be detected by incorporating into the cement plug a sensor whose transducer is sensitive to both stress and changes in chemical environment. This important goal represents the main scope of the work performed within the SEP FARAWELL project at SINTEF Industry. Within this project we have proposed that electrically conductive cements with carbon nanofibers can be tested in view of plug integrity sensing.

2. Concept description

Cement materials with well-dispersed conductive fillers such as metal fibers, graphite powder, carbon nanofibers, carbon nanotubes, may show piezoresistive properties [2-9]. Piezo-resistivity is a physical property of materials defined as the change in electrical resistivity upon exposure to stress. The physical mechanism underpinning this phenomenon is associated with the connectivity between the conductive particles. When a uniaxial compression is applied to the material with embedded electrically conductive fillers, the inter-particle distance in the filler decreases, and new conductive paths are created. The closer the conductive particles are and the more interparticle connections are created, the easier an electrical current can flow, and the resistivity of the material decreases. Provided there is no plastic deformation of the material, by unloading the composite material it returns to its primary state and the initial resistivity is recovered. The resistivity changes can also be utilized to follow irreversible changes within material occurring at higher load ranges.

The response of the material to stress takes place only above a critical concentration of conductive particles called percolation threshold. This phenomenon is well explained by the percolation theory [10, 11]. Due to their stress sensitivity, piezoelectric cement materials are considered as excellent sensors in structural health monitoring of reinforced concrete structures [3, 12] and traffic monitoring [13-15]. The SEP FARAWELL project, aimed at utilizing the stress sensitivity of cement composite materials containing carbon nanofibers in the sensing of stress changes that may occur in a permanently plugged well as a result of subsidence, fracture reactivation etc. The monitoring of a well would rely on measurements of electrical resistivity of the sensor whose transducing material is made of stress sensitive cement. It was expected that stress imparted on the cement plug with an embedded sensor would result in changes of electrical resistivity of the transducer. To prove the feasibility of the concept, the resistivity changes associated with stress changes relevant for well conditions were assessed. As the resistivity was expected to be sensitive to the water content in cement and to the temperature, the effect of the two parameters was also evaluated.

The plug being in contact with reservoir fluids may also, upon long time exposure, undergo chemical degradation. Downhole brines commonly contain carbonate and sulphate ions that tend to react with cement. The reactions are associated with density changes within the cement [16]. The density changes were expected to affect the resistivity of cement/CNF composites. This topic has not been previously researched. Therefor we also studied how the carbonation process (as an example of degradation processes) affects the signal of the potential transducer material.

Our results are also relevant for other applications where the sensing material is exposed to humidity and an environment that contains sour gases such as CO_2 and H_2S, e.g., traffic monitoring or structural health monitoring.

3. Discussion of main findings

Figure 1. shows two types of samples used to study the behavior of conductive cement composites. Cubic samples were used to study response to load while cylindrical samples were used to follow resistivity changes upon carbonation and changes in pore saturation with water.

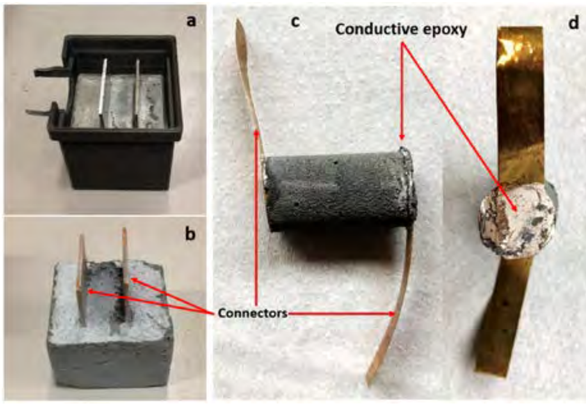

Figure 1**:** Photography of different samples: (1) cubic sample in a 3D printed mold before (a) and after (b) removal from the mold, and (2) cylindrical sample, side view (c) and top view (d), indicating metal connectors. (From [17])

3.1 Water saturation sensitivity

Our results (Figure 2) [17] showed that an increase in the water to cement ratio in cement slurry resulted in increased bulk resistivity.

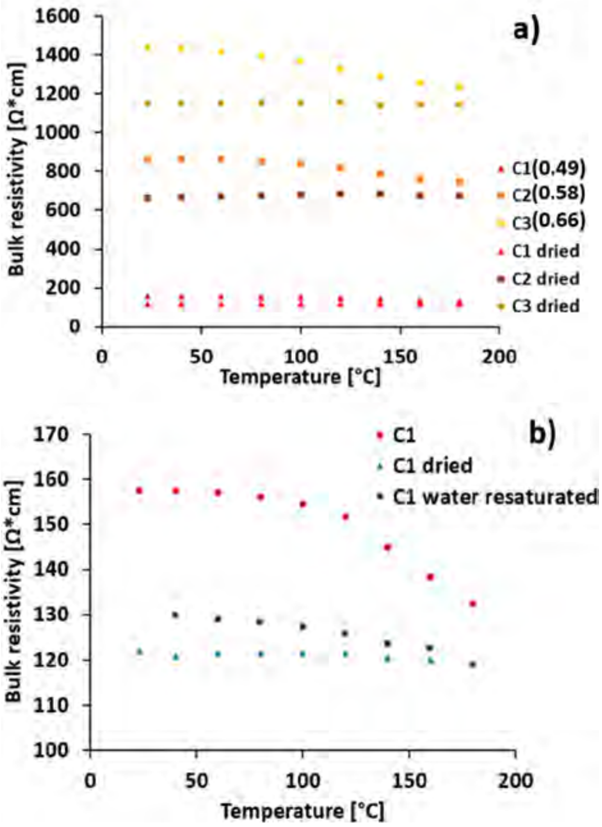

Figure 2**:** Resistivity changes upon temperature increase for samples with (a) different water to cement ratio: C1 (w/c: 0.49), C2 (w/c: 0.58), C3 (w/c: 0.66) and (b) different pore volume water saturation. From [17]

The decrease in nanocomposite resistivity upon a stepwise temperature increase up to 180 °C was ascribed to free water release from cement pores. The dry materials were relatively insensitive to temperature changes and had much lower resistivity compared to wet materials. The re-saturation of pores with water did not reverse electrical resistivity. The results also highlighted the importance of the type of electrical connection. Application of electrically conductive epoxy as electrode material resulted in two orders of magnitude larger bulk resistivity compared to the same material.

3.2 Chemical changes sensitivity

We have shown that carbonation processes affect material bulk resistivity [18], thus electrical resistivity measurements may be applied to sense chemical degradation of conductive cements.

3.3 Stress sensitivity

Stress sensitivity of cement/CNF composites was studied. The samples were gradually brought to failure and resistivity changes along with acoustic emission events being followed and correlated [19]. Figure 3 presents schematically experimental setup that was used to follow changes in sample resistance and acoustic emission upon application of mechanical load.

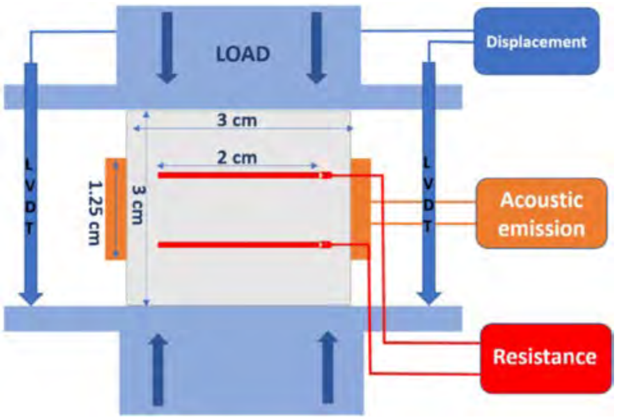

Figure 3: Schematic illustration of experimental setup (not to scale). From [19].

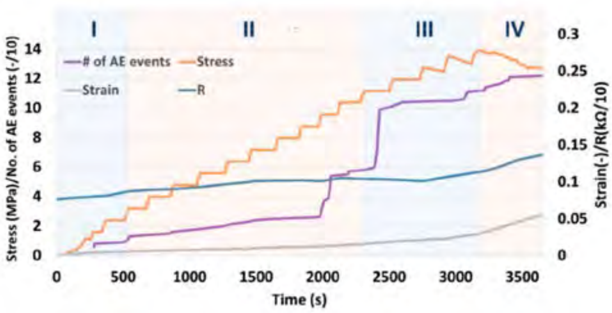

Figure 4: Resistivity changes (R) and cumulative acoustic emission events (# of AE events) upon application of mechanical load to the sample similar to that shown in Figure 1 b. The load was applied in a direction perpendicular to the surfaces of electrical connectors. Mechanical failure takes place at time of 310 seconds. From [19].

Our results (Figure 4) [19] showed that complementary acoustic emission recording and resistivity measurements can clearly indicate the onset of material mechanical failure. The increase in resistivity starts long before failure which implies that the method can be used as indicator of increasing load.

3.4 Sensor and signal readout

In order to monitor the state of the temporary or permanent well plug, the transducer material has to be embedded within the cement plug or be used as a plug itself. There are at least two readout systems utilizing conductive cements that can be consider for sensing application: (1) direct resistivity measurements with two or four point probe methods or (2) electromagnetic EM method.

For direct resistivity method the transducer material needs to be physically connected with a power source and a signal transmitter. Signal transmission can be done in a wireless manner using e.g., radio communication. The system of many wells can likely be monitored by just one radio signal receiver. The direct measurement method can be easily used to monitor the state of the top i.e., environmental plug, however monitoring of the deeply situated plugs seems more challenging.

The electromagnetic method nowadays used as a complementary geophysical method to seismic surveys could be extended to monitor the state of permanent cement plugs containing CNF. The method requires electromagnetic transmitter and receiver that does not have to be in a direct electrical contact with the transducing material which makes the method noninvasive and thus promising.

The design of the readout system and power source was however beyond the scope of this project, and the topic requires a separate spin-off project.

3.5. Interpretation of the data

Detection of stresses that are close to the compressive strength of cement may suggest that the plug is close to failure. The increasing stress followed by sudden unloading or continued loading above the material failure threshold may suggest failure of the plug. Modelling of different mechanical failure scenarios is needed to aid in the data analysis. Both stress (close to failure) and carbonation contribute to increased resistivity of cement/CNF composites. Decoupling of the two effects as well as the effect of changing water saturation and salinity may be the biggest challenge for the field application of cement/CNF composite as selective transducers. What poses a challenge is simultaneously a benefit as the materials can sense both mechanical and chemical stimuli which makes them promising.

3. Conclusions

Project findings suggest that cements with carbon nanofibers are good candidates for transducer materials capable of transforming changes in stress as well as chemical alterations into electrical signal. The cement/CNF composites showed to be sensitive to mechanical load and chemical degradation. As the materials have been shown to be sensitive also to other factors like water saturation, the signal readout needs to be carefully designed and the interpretation of data should consider all factors.

Cement/CNF composite materials are good candidates for ccontinuous in-situ monitoring of well barrier materials. Such monitoring could allow for early-stage warning of loss of plug integrity due to chemical or mechanical degradation. Early detection of such degradation processes could allow for leakage preventive intervention before any leakage occurs.

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