Effects of Thermal Shocks on Sealant Integrity for CCS Applications

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Abstract

In wells for carbon capture and storage (CCS), cracks can develop in the cement sheath due to strong thermal shocks when cold pressurized CO_2 is injected into the warm subsurface (Carey et al., 2007). The network of these cracks may form leakage pathways that can impair sealant integrity, thus impeding safe and sustainable storage of CO_2. In this study, we investigate how thermal shocks affect four sealants of different compositions under unconfined conditions. This study is a part of Cementegrity project funded by ACT (Accelerating CCS Technologies) initiative.

Experimental Materials, Setup, and Methodologies

In our study, cylindrical sealant samples (Φ3 x 7 cm) and samples of the same size but with a Φ4 mm central borehole along the vertical axis are used. The latter mimics a sealant with a pre-existing leakage pathway. To create thermal shocks, we either quench pre-heated solid samples into a cold 6 L water bath (type 1), or we flow cold water through the pre-heated samples with the central borehole (type 2). Figure 1 shows schematics for the two approaches. Sealant samples are of four compositions, namely S1: OPC (ordinary Portland cement) blend, S2: Ultra-low permeability OPC blend, S3: OPC blend with CO_2-sequestering agent, and S4: CAC (calcium aluminate cement) blend, and are prepared by Halliburton AS Norway, in accordance with API specification 10B-2.
In type 1 quenching experiments, we first heat the sample to 120°C in the oven, and then quench the sample in 20°C water. After that, the sample is reheated to 120°C in the oven for the next shock. This is repeated eight times. In type 2 flow-through experiments, the whole sample assembly is placed in the oven at 120°C. We use a syringe pump to inject 160 mL 20°C water through the sample in 2 minutes to apply the strongest thermal shock possible. We then halt for 12 minutes before the next injection to allow the sample to heat up again. As shown in Figure 1 (right), a thermocouple is mounted on the outer surface of the sample to measure the temperature, T1, during the experiment. Also in type 2 experiments, we carry out eight cycles of thermal shock. To study the effects of thermal shocks on the sealants, we perform micro-computed tomography (μ-CT) scans on samples and use Avizo software to characterize the network of voids and cracks in samples before and after experiments. In addition, we measure unconfined compression strength (UCS) to study how these thermal-induced cracks affect sealant integrity.

Comparison of Results Between Quenching and Flow-through Experiments

Figure 2 shows the structure of voids and cracks in sealant samples of S1 composition before and after quenching and flow-through experiments. The voids displayed in samples before thermal shocks are due to trapped air during cement casting. Both quenching and flow-through experiments induced cracks after thermal shocks. This means both experiments generate sufficient thermal stresses to cause cracking in cement. By quenching, multiple cracks developed at different orientations. However, by flow-through, only two major longitudinal cracks were created. The cracks are intersected with the flow hole, where most thermal stresses are built up. Figure 3 shows the UCS and volume ratio of voids and cracks before and after experiments. The volume ratio of voids and cracks increases to 2.74% by quenching and 1.29% by flow-through respectively, from 0.40% on average. In both experiments, samples are weakened due to these cracks. The UCS decreases from 99.2 MPa for intact sample to 53.9 MPa after quenching, and to 90.3 MPa after the flow-through experiment, separately. The thermal shocks induced during quenching are greater than those achieved during the flow-through experiment. This means more thermal stresses are generated through quenching, hence creating more cracks and resulting in a greater decrease in strength.

Similarities and Differences in Thermal-Shocking Effects on Four Sealants

Figures 4 and 5 show the structure of voids and cracks in samples of all four sealant compositions before and after quenching and flow-through experiments, respectively. Figure 6 shows how quenching and flow-through experiments affect the UCS of samples of all four sealant compositions. Like samples of sealant composition S1, in those of S2 and S4, cracking due to thermal shocks occurred during the experiments. This in turn weakened the samples by decreasing their strength. Quenching displays more jeopardizing effects compared to flow-through experiments. By quenching, cracks develop throughout the samples and cause an average 50% decrease in strength. However, by flow-through, cracks only initiate longitudinally and intersect with the borehole. Strength decreases by 9%, 28% and 39% for sealants S1, S2 and S4, respectively. On the contrary, as shown in Figures 4 and 5, we have not observed any thermally-induced cracks in samples of sealant S3 by either quenching or flow-through. Instead, quenching appears to have strengthened the sample, while flow-through caused no significant changes in UCS. Figure 7 shows T1 temperature drop during flow-through experiments for all four sealants. At each shock, S3 undergoes the biggest temperature drop, on average 7.3°C, at the outer surface of the sample. The drop is 5.1, 6.7, and 4.5°C for S1, S2 and S4, respectively, giving the same amount of cold water flow-through within the same time. This possibly means sealant S3 conducts heat more efficiently. Compared to the other three sealants, thermal stresses are less in the sample of S3 after thermal shocks, and insufficient to cause cracking behavior in our experiments.

Future Work

In this study, we conducted experiments without confinement. De Andrade et al. (2015) reported that confining pressure reduced thermal-cycling-induced cracks in cement. We expect the presence of confining pressure would mitigate the adverse effects of thermal stresses on cement integrity. In our Rock Mechanics Laboratory, we prepared a triaxial deformation setup (Figure 8) capable of loading confining pressure and axial stress on the sample to study effects of thermal shocks on sealants. In addition, we will cast sealant samples with a steel pipe along its axis to mimic a wellbore section with cement sheath and casing. We will use the traxial setup to study how thermal cycling affects the bonding between the cement and casing in these samples.

References

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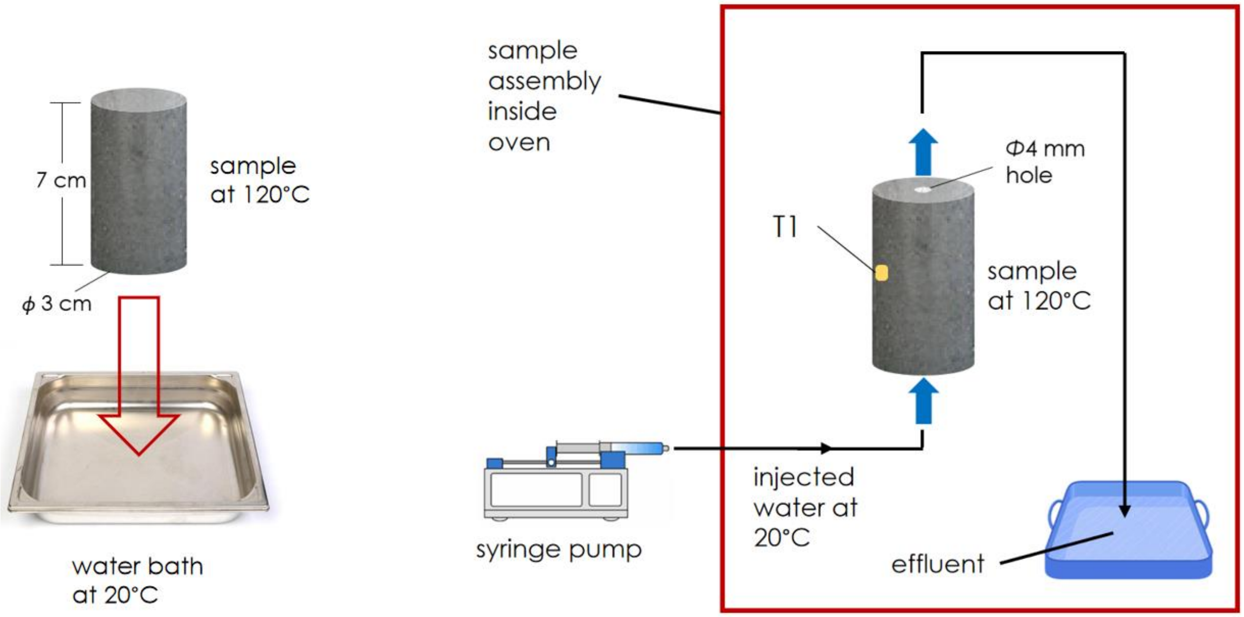

Figure 1 left: schematic of quenching; **right**: schematic of flow-through setup.

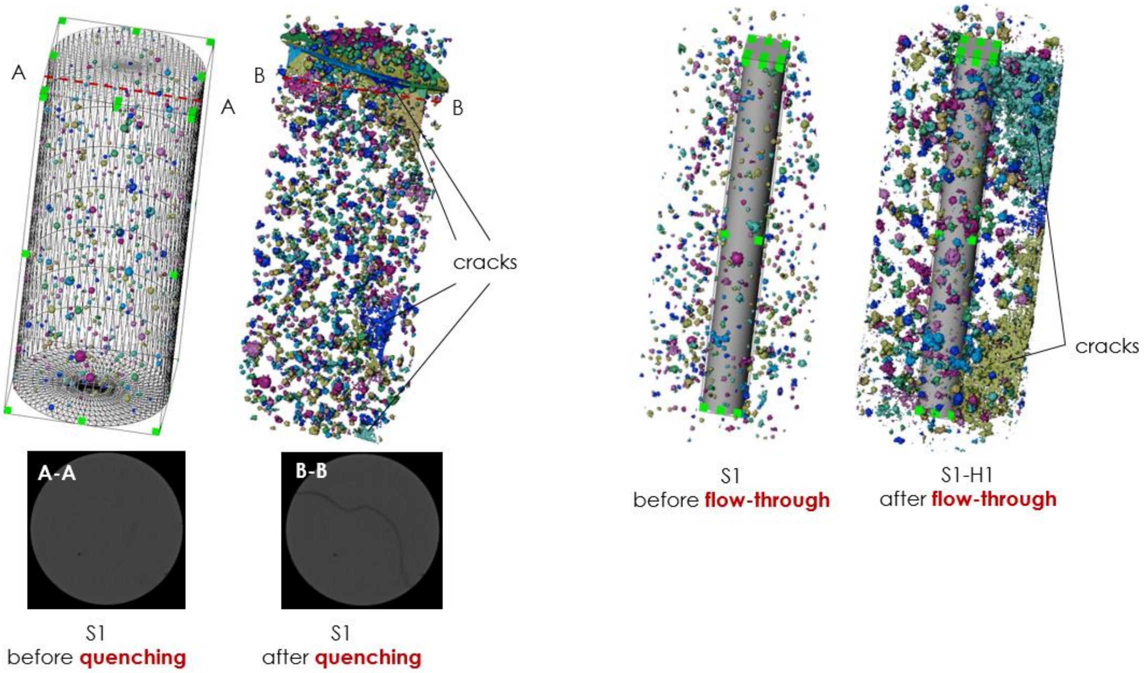

Figure 2 structure of voids and cracks in samples of sealant S1 composition before and after quenching (**left**) and flow-through experiments (**right**). This shows both quenching and flow-through experiments create cracks.

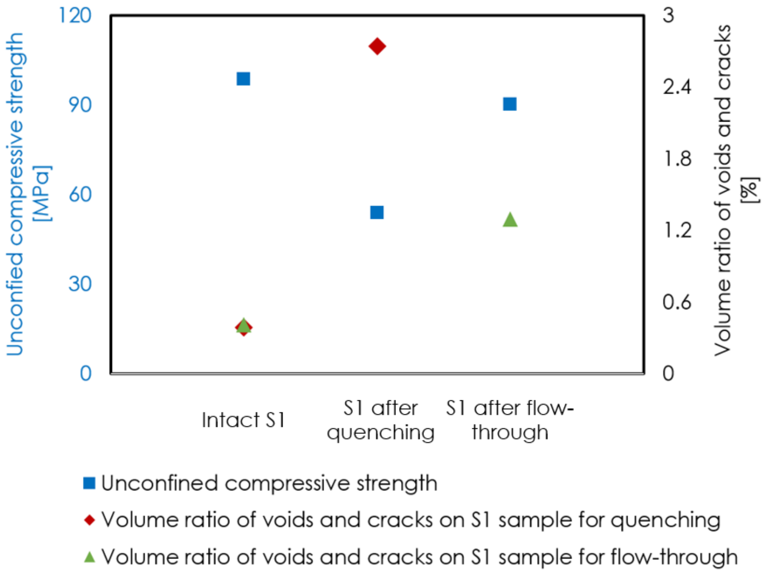

Figure 3 UCS and volume ratio of voids and cracks in samples of sealant S1 composition before and after experiments.

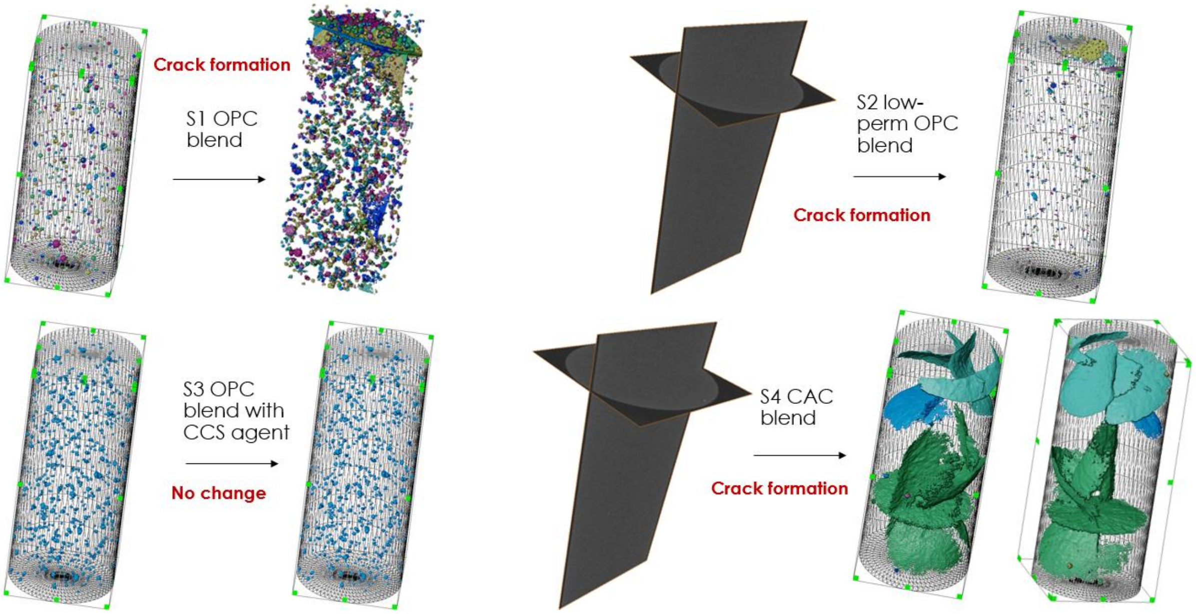

Figure 4 structure of voids and cracks in all four sealant samples before and after quenching experiments. This shows quenching create cracks at different orientations throughout samples of sealant S1, S2 and S4 compositions. We have not observed any cracks for the sample of sealant S3 by quenching.

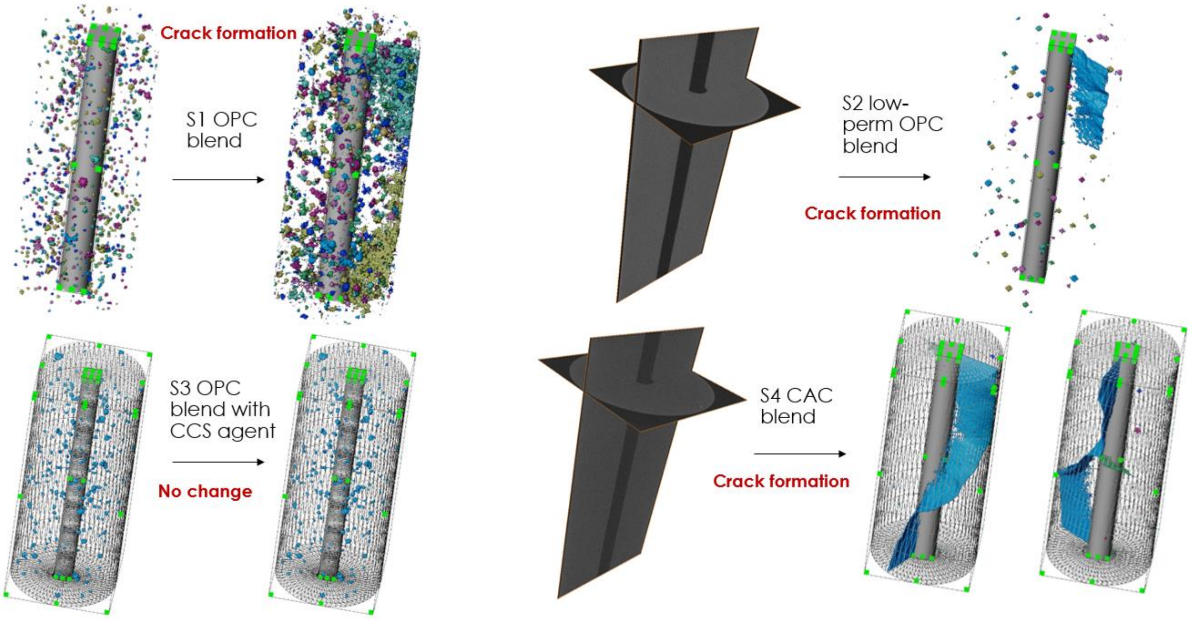

Figure 5 structure of voids and cracks in all four sealant samples before and after flow-through experiments. This shows flow-through experiments create longitudinal cracks that intersect with borehole for samples of sealant S1, S2 and S4 compositions. We have not observed any cracks for the sample of sealant S3 by flow-through experiment.

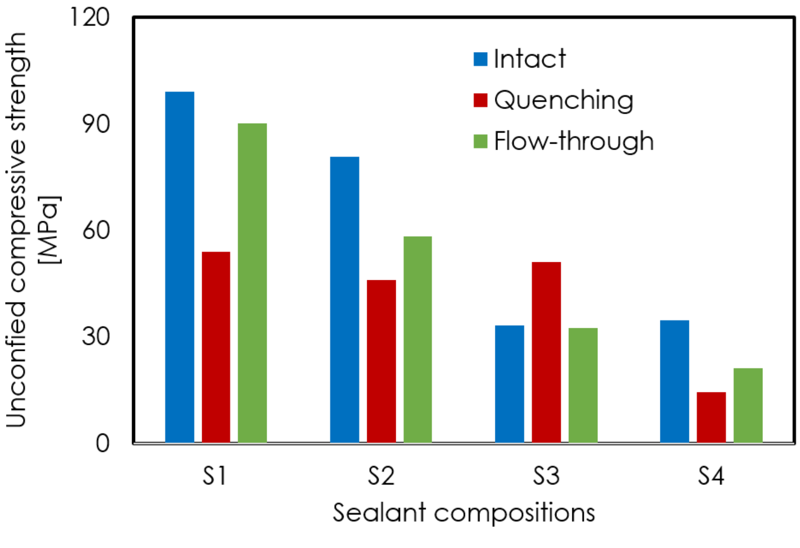

Figure 6 UCS of samples of four compositions before and after quenching and flow-through experiments. This shows both quenching and flow-through experiments weaken samples of sealant S1, S2 and S4 compositions. The decrease in the UCS by quenching is greater than that by flow-through. On the contrary, qunching strengthen the sample of S3 composition, while flow-through makes insignificant changes in the UCS.

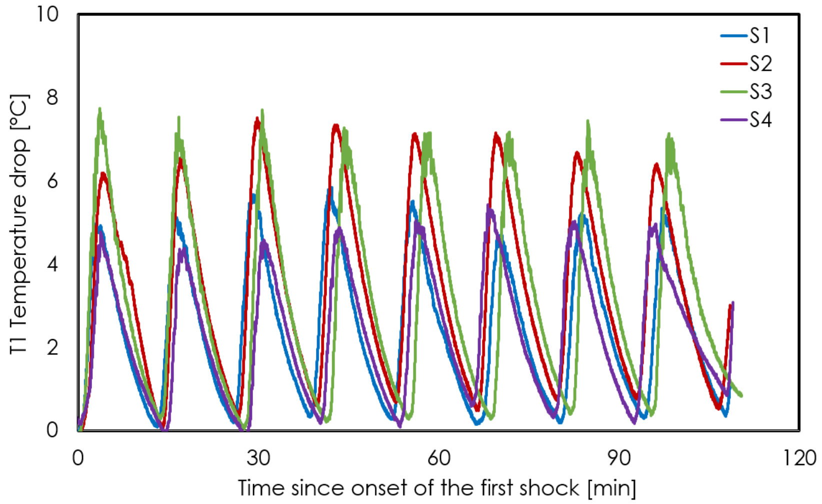

Figure 7 T1 temperature drop during flow-through experiments for all four sealants. T1 is the temperature in the middle of the outer surface of the sample (see Figure 1 right). Note there is a temperature gradient along the vertical axis direction on the outer surface of the sample during the experiments. The temperture near the inlet is lower than that near the outlet.

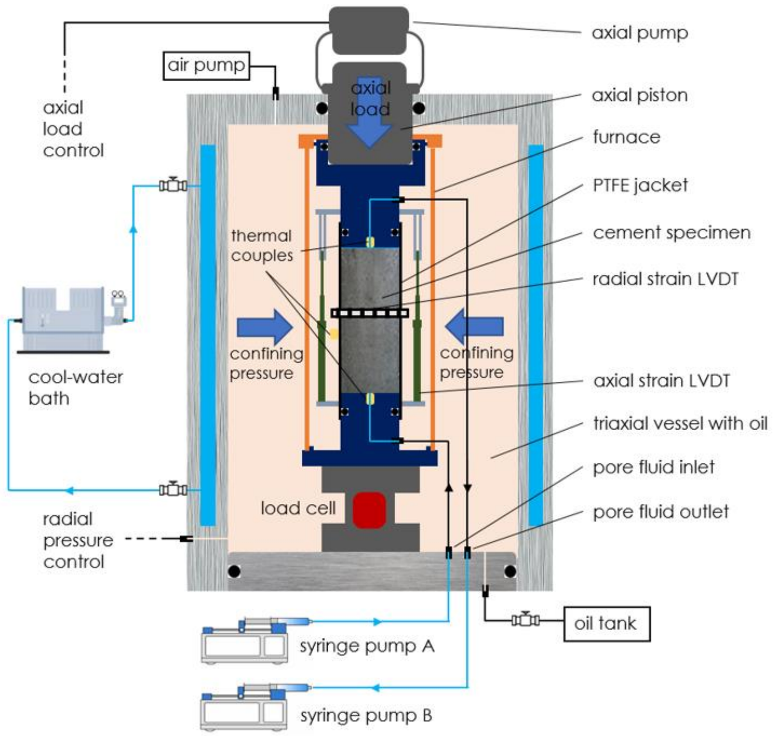

Figure 8 schematic of triaxial deformation setup.