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Effects of Thermal Cycling on Sealing Ability of Sealant Surrounding Steel Pipe for CCS Applications

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In wells designed for carbon capture and storage (CCS), leakage pathways may develop due to thermal cycling when injecting cold CO2 into the warm subsurface, for example, debonding between cement and casing, or fractures in the cement itself. These leakage pathways can impede the permanent geological storage of CO2. In this study, we investigate how thermal cycling affects the sealing ability of cement surrounding steel wellbore casing under unconfined conditions. To this end, cylindrical sealant samples (OD 30 mm, Length 70 mm) with a steel pipe (ID 4 mm, thickness 1 mm, length 110 mm) in the middle, are used to mimic the cement sheath surrounding the casing in the wellbore. We adopt sealants of five different compositions. S1 is ordinary Portland cement (OPC)-based, S2 is OPC-based with ultra-low permeability, S3 is OPC-based with CO2 sequestering additives, S4 is calcium aluminate cement(CAC)-based, and S5 is geopolymer-based.
In the experiments, we mount PVC caps at each end of the sample to isolate the flow channel through the pipe from another flow channel toward the top surface of the sealant. Three thermocouples are installed at the surface of the sealant, inlet, and outlet of steel pipe, separately. The entire sample assembly is placed in an oven. Before thermal cycling, we apply 3 bar N2 on the sealant and monitor its penetration rate through the sealant for 1 hr. Subsequently, we heat the sample at 60 for 1.5 hr. To apply thermal cycling, we inject 5℃ water through the pipe at 80 ml/min for 2 mins, then stop the injection and allow the sample to reheat for 12 mins before the next injection. We repeat this for 12 cycles.
In our study, we haven't observed any cracking in the sealant material itself. This is because the induced thermal stress upon thermal cycling is smaller than the tensile strength of the sealant. Among the five sealants, we found that the bonding performance of S3 on steel is the best. All other sealants were negatively affected by thermal cycling: S1 and S5 experienced more debonding than others, while S2 and S4 experienced minor debonding. The bond strength of all five sealants (including S3) decreases after thermal cycling, further indicating that debonding has occurred. We attribute the magnitude of debonding to be due to a combination of thermal expansion coefficient and Young's modulus. Steel has a high expansion coefficient compared to sealant. Of the tested sealants, S1 and S5 have the lowest thermal expansion coefficients, while S2 and S4 have the largest, i.e. closer to that of the steel. We hypothesize that, during thermal cycling, S2 and S4 expand and shrink with a more similar rate as steel, resulting in a small mismatch in strain and hence less debonding compared to S1 and S5. Additionally, S1 has the largest Young's modulus, whereas S3 and S4 have the lowest. This indicates that S3 and S4 are more compliant, so S3 and S4 can more easily elastically deform upon thermal cycling, resulting in less damage to the bonding.

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References

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