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Stiff cement, soft cement: Nonlinearity, arching effect, hysteresis, and irreversibility in CO_2-well integrity and near-well geomechanics

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ABSTRACT

During geologic CO_2 storage, integrity of injection wells is of utmost importance. Tensile radial stresses at casing-cement and cement-rock interfaces caused by relatively cold CO_2 flowing down the tubing may induce debonding and create microannuli. Microannuli represent potential leakage paths. Thermal stresses can be reduced by using softer cement ("flexible cement"). Numerical simulations show that benefits of soft cement are more pronounced in relatively hard (stiff) rocks. In a very soft rock, there might be as good as no effect of lowered cement stiffness on thermal stresses, while tensile strength of such cement might be severely reduced. Thus, to fully benefit from soft (flexible) cement in CO_2-injection wells, such cement should be set against sufficiently stiff rock. Effect of rock stiffness on tensile radial stress build-up during cooling is stronger than that of cement stiffness. As a result, the benefits of carefully adjusting the cement stiffness might be offset by natural variation in the rock properties. Soft cement also reduces the stress build-up in the cement sheath caused by far-field in-situ stress variation during injection. The mechanism here is the arching effect in the near-well area: the rock effectively shields the cement sheath from in-situ stress changes. In order to fully exploit benefits of soft cement here, the rock again must be sufficiently stiff.

1. Introduction

Geologic storage of CO_2 requires that there be no leakage from the storage reservoir. Well integrity is thereby of utmost importance since wells may provide a continuous path from the reservoir to the upper strata or even to the Earth's surface.

An essential component of well integrity is integrity of the cement sheath. During well construction, the drilling process is periodically suspended, the drill bit is pulled out of the hole, and a steel pipe called casing is run in hole. The casing's purpose is to prevent rock from falling into the hole as the holes gets deeper. It also enables drilling with heavier mud in deeper sections of the hole without fracturing the formation in the upper sections (Bourgoyne et al., 1991; Lavrov, 2016b).

In order to keep the casing string in place and stable, cement is pumped up the annular gap between the casing and the formation after the casing has been set in place. After the cement hardens, the drill pipe is run back in hole, and drilling is resumed with a new drill bit that has a smaller diameter than the previous one. Once the next casing point is reached, the drill string is pulled out again, and the whole procedure is repeated. This cycle is repeated until the target depth is reached, at which point the drill pipe is pulled out, the drilling mud is replaced with a completion fluid, and the well is completed by installing a tubing (Fig. 1).

The main functions of well cement placed in the annulus are as follows (Lavrov and Torsæter, 2016; Nelson and Guillot, 2006):

- Cement should hold the casing string stable.
- Cement sheath should prevent aggressive formation fluids from reaching the casing easily.
- Cement should provide zonal isolation, i.e. should prevent formation fluids from flowing up along the well to shallower horizons or to the Earth's surface.

The last item in the above list is the focus of this study. In order to ensure zonal isolation, the cement sheath must be in contact with the casing and the rock at all times. During CO_2 injection, the temperature of CO_2 flowing down the tubing is lower than the formation temperature. As a result, the casing is cooled down during injection periods and gradually warms up during shut-in periods. According to some estimates, the casing may cool down by ca. 20–25 °C during injection (Aursand et al., 2017). This induces contraction of casing and of the adjacent cement. As a result, thermal stresses are induced in cement. In particular, tensile radial stress is induced at the casing-cement interface. If the initial stresses in the cement sheath were zero, such tensile radial stress could induce tensile failure at the interfac since the interface is normally weaker than the bulk cement.

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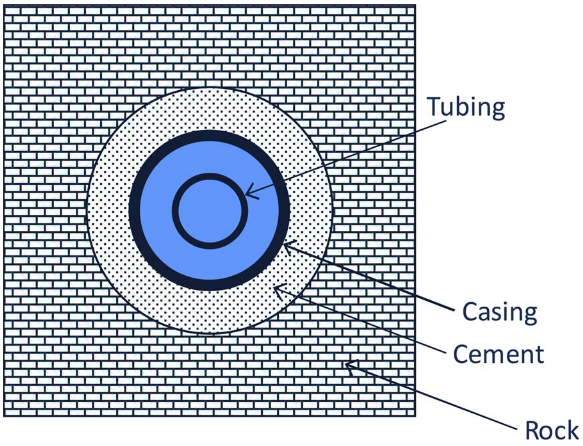

Fig. 1. Schematic sketch of cross-section of a completed vertical well (not to scale).

Tensile failure at casing-cement interface is known as debonding, i.e. loss of bonding between steel and cement. Debonding leads to the development of microannulus along the casing. Microannulus represents a potential leakage path along the well (Carey et al., 2010). Microannulus is essentially a fracture or a zone of increased permeability. It is schematically depicted in Fig. 2 as a perfect circular ring. It should be understood, though, that real microannuli have much more complex structure, with multiple spots of intact (bonded) material, where the aperture of the microannulus is effectively zero. This increases the flow tortuosity in (and increases the flow resistance of) microannulus (Kjøller et al., 2016; Skorpa and Vrålstad,2016).

A microanulus *per se* does not mean that there will be leakage along the well yet. A leakage path can only be formed if there is a *continuous* microannulus along a substantial length of the well. However, since the structure and extent of the microannulus is beyond our control once the microannulus is formed, well construction experts strive to prevent the formation of microannulus in the first place. In wells subject to thermal loading (cooling, as in CO_2 wells, or heating, as in geothermal wells or wells with thermal stimulation in oil industry), the risk of microannulus formation could be reduced by improving the properties and behaviour of well cement. In particular, two approaches have been pursued in the industry in the past two decades:

- use of expanding cements in order to create compressive initial stresses in the cement sheath;
- use of softer (“flexible”) cement to mitigate the build-up of thermal stresses.

The benefits of expanding cements are due to cement failure being governed not by the thermal stresses alone, but rather by a superposition of thermal stresses *and* initial stresses in the cement sheath. When cement slurry, in liquid state, is first placed in the annulus, its stress state at any given depth is hydrostatic and is determined by the slurry density and the height of the cement column at that depth. As cement sets and builds the yield stress, the vertical stress in the cement column gradually decreases because cement now can “hang” on the walls exposed in the annulus (Chenevert and Jin, 1989; Prohaska et al., 1993). In addition, neat Portland G cement that was commonly used in well cementing before the advent of expanding cements shrinks and the horizontal (radial and circumferential) stresses in cement decrease, too (assuming the well is vertical). During subsequent lifetime of the well, lower initial stresses mean easier failure in tension. To illustrate this, we follow the explanation laid out in (Therond et al., 2016): Imagine a cement sheath with the initial radial stress (i.e. radial stress acting in cement after hardening) being equal to 10 MPa. If cooling during CO_2 injection induces tensile radial stress of 6 MPa, the radial stress after cooling is still compressive and equal to 4 MPa. No debonding will occur, and there will be no microannulus after cooling. Now imagine a cement sheath with the initial radial stress (i.e. radial stress acting in cement after hardening) being equal to 2 MPa. If tensile radial stress induced by cooling during CO_2 injection is again equal to 6 MPa, the radial stress after cooling will be tensile and equal to 4 MPa. This almost certainly exceeds the bonding strength between cement and casing. Thus, microannulus will develop in this case. From this illustrative example, it is evident that increasing initial compressive stresses in cement should be beneficial for well integrity.

Another approach that may work against tensile failure is reducing the thermal stresses in cement. This could be achieved either by pumping warmer CO_2 (which is likely to reduce efficiency of injection) or by reducing the cement stiffness. By stiffness we mean Young's modulus in this text. The importance of cement stiffness has been recognised in well construction for a long time, see e.g. (Boukhelifa et al., 2005; Thiercelin et al., 1998). Thermal stresses indeed scale with the Young's modulus, so reducing the latter should help against the build-up of thermal stresses, both during cooling and during heating (Therond et al., 2016). Consequently, cement products with lower stiffness in set state are offered on the market. From simple dimensional analysis, it is, however, evident that the cement stiffness alone should not matter. In order to build a dimensionless group describing the problem, at least one other parameter with dimension $M/(L \cdot T^2)$ should enter the group. Only one such parameter is found in our system, i.e. Young's modulus of the rock. Young's modulus of steel (casing material) is on the order of 200 GPa and is thus an order of magnitude higher than that of the normal Portland G. For our purposes, casing can thus be assumed rigid (infinitely stiff).

From this simple argument, we deduce that a combination of cement stiffness and rock stiffness rather than the cement stiffness alone should affect the build-up of thermal stresses in the cement sheath.

The same argument applies to stresses induced in cement by variation of far-field or reservoir-scale in-situ stresses. During depletion, horizontal total stresses in the reservoir decrease as the pore pressure goes down (Fjær et al., 2008; Lavrov, 2016a; Zoback, 2007). During subsequent injection of CO_2 (or any other fluid), horizontal stresses in the reservoir may somewhat increase, albeit their full restoration to the pre-depletion state is unlikely (Santarelli et al., 1998; Vidal-Gilbert et al., 2010). Increasing compressive total stresses in the reservoir will effect an increase of compressive stresses in the cement sheath and thus will counteract debonding. However, this increase is a much slower

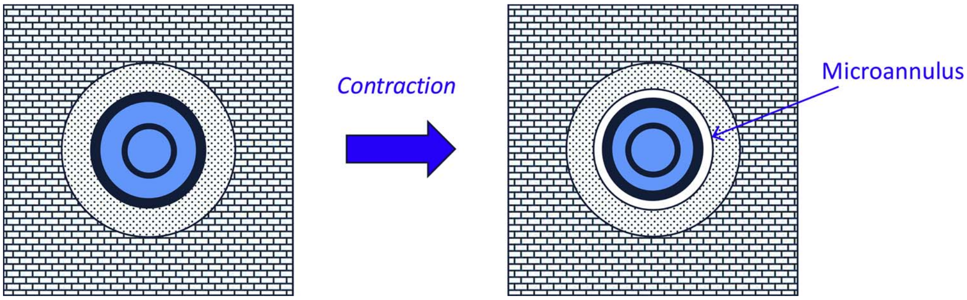

Fig. 2. Schematic plot of microannulus developing when cold fluid is pumped down the tubing. Left-hand panel: intact well. Right-hand panel: well integrity has been breached after casing contracted and detached from cement.