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Cement de-bonding under elevated temperature conditions: what is different?

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ABSTRACT

Geothermal wells rely on hydraulic fracturing in order to enhance the heat exchange downhole. However, when hydraulic fracturing is performed the injection fluid typical lowers the temperature in the near wellbore area, which might lead to a possible loss of the wellbore integrity. Moreover, thermal cycles induce casing-cement relative movement that must be evaluated. A very controversial aspect is the effect of heating and cooling on cement properties, particularly related to interfacial bonding strength.

A novel experimental setup has been developed to compare cement interfacial de-bonding with cement shear during the geothermal well exploitation. This setup allows the evaluation of bonding and shear stresses between cement and casing, and could help the improvement of casing movement models. The samples are cured at elevated temperature (~65 deg C) and then cooled down by immersing them in water bath at room temperature. After the sample temperature stabilizes, the samples are then tested.

This paper shows the latest results of interfacial cement shear stress and pure cement shear stress that were performed at elevated temperatures mimicking the natural cycle of a geothermal well: drilling, cementing, wait on cement, fracturing, production. The results will be compared with reference samples kept at room temperature.

1. INTRODUCTION

In a previous paper presented at the 2018 Stanford Geothermal workshop, Teodoriu et al. (2018) made a first rigorous attempt to evaluate cement shear bonding and pure shear properties with respect to wellbore conditions. Our new research approach is a result of the latest Finite Element data published by Teodoriu (2015) and Kaldal et al. (2015). They show the importance of casing coupling – cement interaction, in which the maximum stresses in a temperature loaded well always appears between the coupling edges and cement. Figure 1 shows the stress distribution around the edges of an API Buttress coupling.

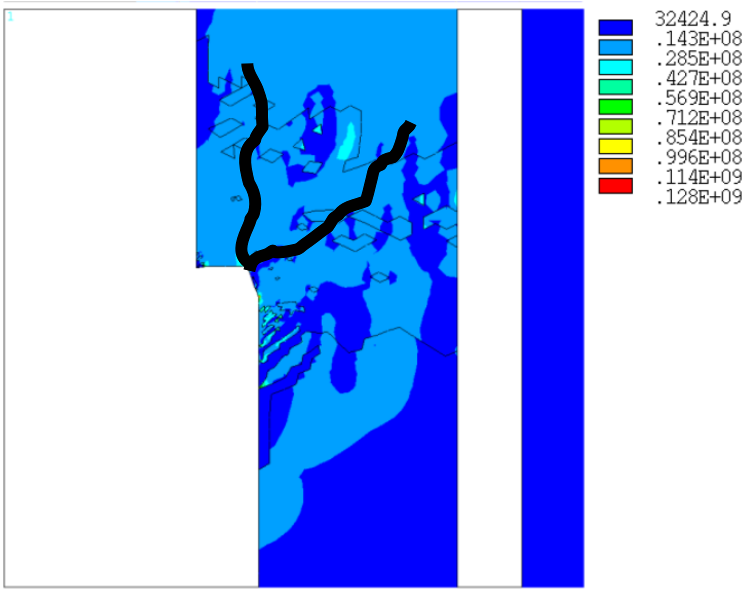


Figure 1. von Mises stresses [MPa] in the cement around a Buttress type casing coupling (Kaldal et al. 2015)

Although shear stresses are not shown in Figure 1, the likely failure mode of the cement is shear, and as mentioned by Teodoriu (2015) the shear stress will propagate vertically or diagonally (see the marked lines in Figure 1). Due to the thin cement layer, it is to believe that the shear failure will most likely propagate vertical.

The experimental setup used in this paper is identical with that presented in the previous paper by Teodoriu et al. (2018) and will not be further detailed. Figure 2 shows a schematic of the two setups used for bonding and shear strength measurement.

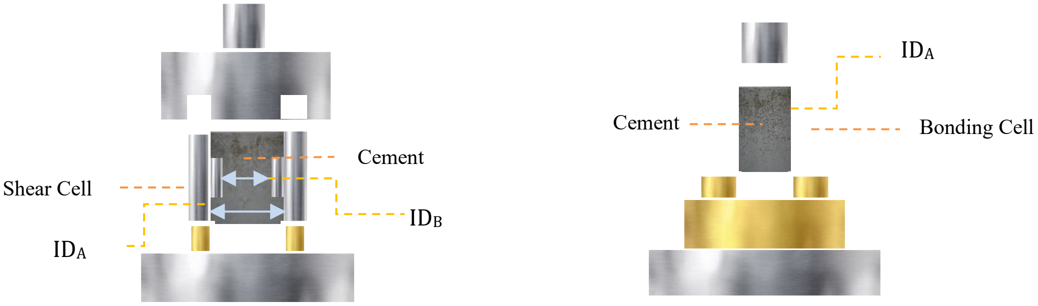


Figure 2. Shear (left) and bonding (right) test cell used in the present study

As already presented in the previous paper by Teodoriu et al (2018), the pure shear strength (MPa) is calculated using the following equation:

$$\sigma = \frac{F_{max}}{2\pi * ID_B * SL} \tag{1}$$

Where F_{max} is the maximum recorded force, N; ID_B is the inner diameter of the shoulder, m; SL is the shear length of cement in the cell, m. The interfacial shear bonding strength (MPa) is calculated as:

$$\sigma = \frac{F_{max}}{2\pi * ID_A * CL} \tag{2}$$

Where F_{max} as the maximum recorded force, N; ID_A is the inner diameter of the cell, m, and CL is the is the interfacial bonding shear strength cell length, m.

Bonding between cement and casing is a crucial factor for the well integrity. Bonding of cement and steel can be described as adhesion because the material surfaces are in contact and stick together. Various adhesion mechanisms will be introduced in the next paragraph, that could be considered for the cement casing interaction. Intermolecular bonding which is known as van der Walls forces is caused by molecular contact between two materials and the surface forces. Bwala (2015) states that the adhesive must make intimate, molecular contact with the substrate surface for forces to develop. "Wetting' is a term of maintaining continuous contact between an adhesive and an adherent. According to Bwala (2015), permanent adhesion results in molecular attraction forces after contact between adhesive and adherent through wetting. The "wetting" effect is the critical factor that can explain why poor wellbore cleaning and spacer selection will lead to poor cement bonding. Chemical bonding of adhesion includes ionic, hydrogen bond or covalent formed at an interface. Surface pores generated by the roughness that are occupied by adhesive materials allow surfaces to attach together. In general, especially in the adhesive industry, adhesion occurs when adhesive fills on surface voids. As adhesive gets harden, it holds the substrates together. This is a mechanical bonding theory. Surface roughness is a crucial factor that affects the adhesion due to the change of contact area between adhesives and the adherent depending on surface roughness.

The experiments presented in this work are taking this concept to the next level: investigate the effect of elevated temperature on the shear bonding strength between cement and casing coupling, showing which shear failure will appear first and then comparing this with the cement ultimate compressive strength. As in the previous paper, the same standard API recipe of Class H cement has been used and samples were tested for shear/bonding stress at different ages. The value of the temperature was selected in order to mimic the conditions at the surface casing, since a cement debonding at this string will lead to catastrophic well integrity issues with respect to water sources protection. In previous papers, Ichim and Teodoriu (2016, 2017) have documented the importance of surface casing integrity and hence the importance of this paper experimental results.

2. METHODOLOGY (EXPERIMENTAL SETUP FOR THE INVESTIGATION OF SHEAR AND BONDING STRESS OF CEMENTING)

2.1 Sample Preparation

As mentioned above, Class H cement was used for this study without any additives included. The amount of water used to make cement mixture (or slurry) was 38% by weight of well cement (Class H, according to API Spec 10A). According to this ratio, 860 g of Class H cement and 327 g of de ionized water were used. Water was measured directly in the mixing container, and the mixer motor was powered on. The mixing speed was maintained at 4000 RPM while the cement was added within 15 seconds. After all the cement was added to the water, the mixing rate was increased to 12000 RPM and maintained for 35 seconds. Two different cell shapes were customized for the shear and bonding stress tests. The inside of the cells for shear stress was coated with a non-reactive release agent before the cement mixture was poured, whereas no grease was applied for cells used in bonding stress tests. The cement mixture was poured into the customized cells and these were placed in the curing vessel. This was filled with distilled water at atmospheric pressure and room temperature, where the samples cured for 24 hours, respectively 3, 7, and 14 days before the actual shear and bonding tests. Finally, hydraulic pressure was applied to each test cell to obtain shear stress and bonding stress values.

2.2 Experimental Setup

Curing at elevated temperature is the major difference in the proposed experimental approach. To do so, a hot water bath with temperature controller was used. The samples were cooled down to room temperature before testing. The mechanical load was applied using the hydraulic press with a maximum capacity of 20 tons. A force gauge placed at the bottom measures the axial load applied on the samples, while the attached displacement sensor measures the cylinder displacement. The temperature was set at 65 deg C. The precision of the water bath was ± 3 deg C. The cells geometry was identical as in previous experiments, and Table 1 shows once again their dimensions.

Table 1. Geometries of the shear and bonding cells (Teodoriu et al. 2018)

Item	Length (mm)	Outer Diameter (mm)	Inner Diameter (ID$_{A}$) (mm)	Inner Diameter (ID$_{B}$) (mm)
Shear Cell	49.2	75.6	61	54
Bonding Cell	50	40	35.1	-

3. RESULTS AND DISCUSSIONS

Figure 3 shows the shear strength specimens before and after testing. The cement is pressed from the top using the special designed cap, while the evolution of load and displacement is measured. **Figure 4** shows the shear bonding strength cell before and after testing.

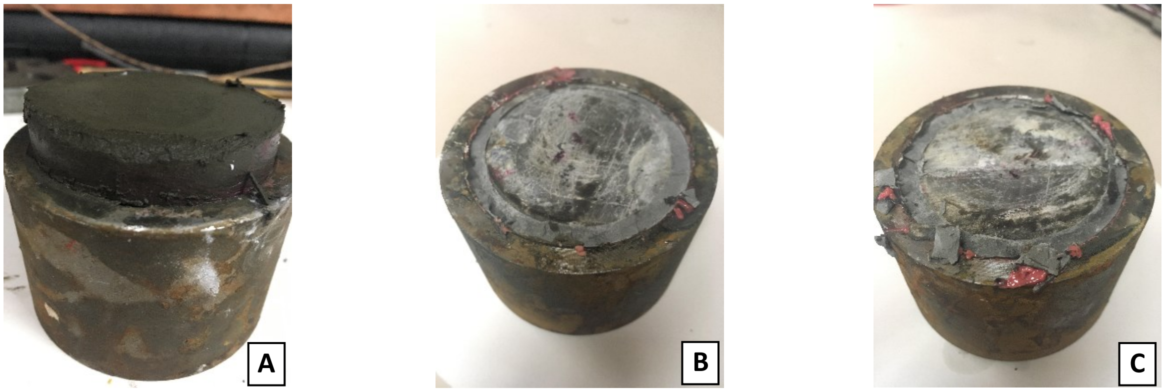


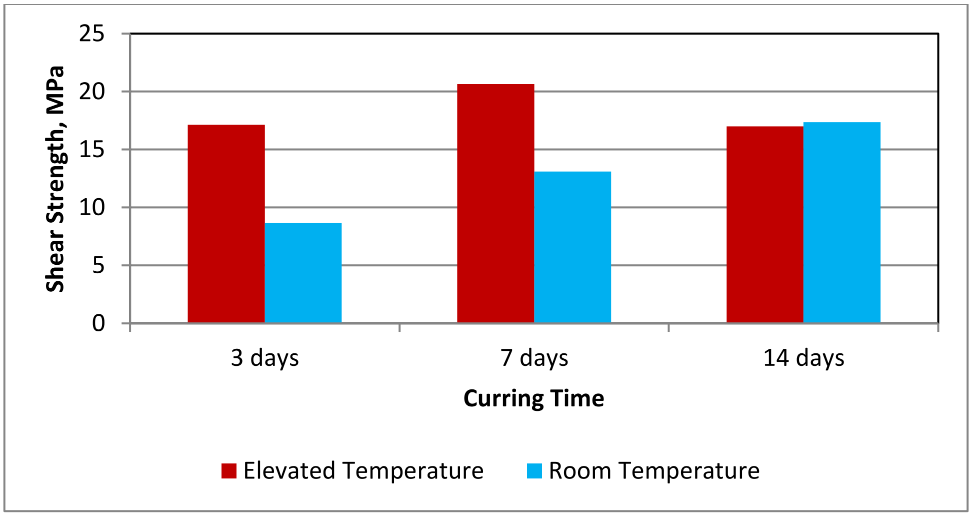
Figure 3. Shear strength cell before testing (B, C) and after testing (A)

Figure 4. Shear bonding strength cell before testing (B, C) and after testing (A)

Figure 5 shows the calculated equivalent shear and bonding strength for the samples used in this work. The shear strength is higher than the interfacial shear bonding strength in all cases, which implies that the cement will first debond from the pipe prior to shear failure. However, at elevated temperatures the shear bonding seems to be affected, showing lower values than for the room temperature. We believe that this is also due to different expansion coefficients between cement and steel, resulting in a lower contact. Furthermore, the chemical bonding process may be affected by the temperature as well. By looking at the UCS increase due to temperature we believe that the fast hydration process will impede the surface strong bond. The shear bonding strength values are shown in Table 3. We also observed a decrease of shear strength after 14 days. To further understand this behavior, the unconfined compressive strength (UCS) has been measured.

Table 2 – Comparison of literature values with obtained data

Author	**Salehi et al.** **2016**	**Lavrov and Torsaer** **2016**	**Zhao et al.** **2015**	**Previous work** **2018**	**This work**	**This work**
Comment	After 24 h	-	-		After 72 hours @room Temp	After 72 hours @ 65 deg C
Shear Bonding Strength (MPa)	0.96	0.1 to 1.0	1.0 to 2.5	0.47	6.79	6.11



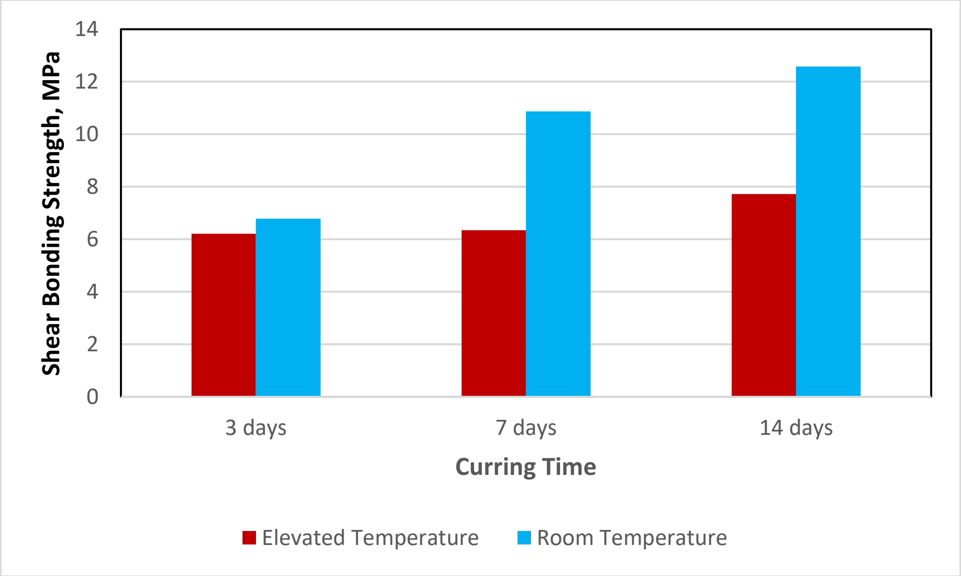


Figure 5. The measured shear(top) and bonding (bottom) strength for class H cement

Figure 6 shows the evolution of unconfined compressive strength (UCS) of the cement measured for room and elevated temperature. As expected, the UCS of the cement increases with time, and temperature leads to a higher UCS for the same day compared with room temperature. Please note that we are investigating plain class H cement, and especially room temperature values are low. A continuous increase of the cement UCS will automatically lead to the idea that all other properties such as interfacial shear bonding and shear strength will also follow the trend. However, the interfacial shear bonding strength seems unchanged when exposed to elevated temperatures, especially day 3 and 7. Day 14 shows a slightly increase of interfacial shear bonding, but the value still remains lower than that at room temperature. Although no similar tests have been found in the literature, the closest experiments we found were from civil engineering, related to rebar cement bonding that also showed a lower bonding at elevated temperatures.

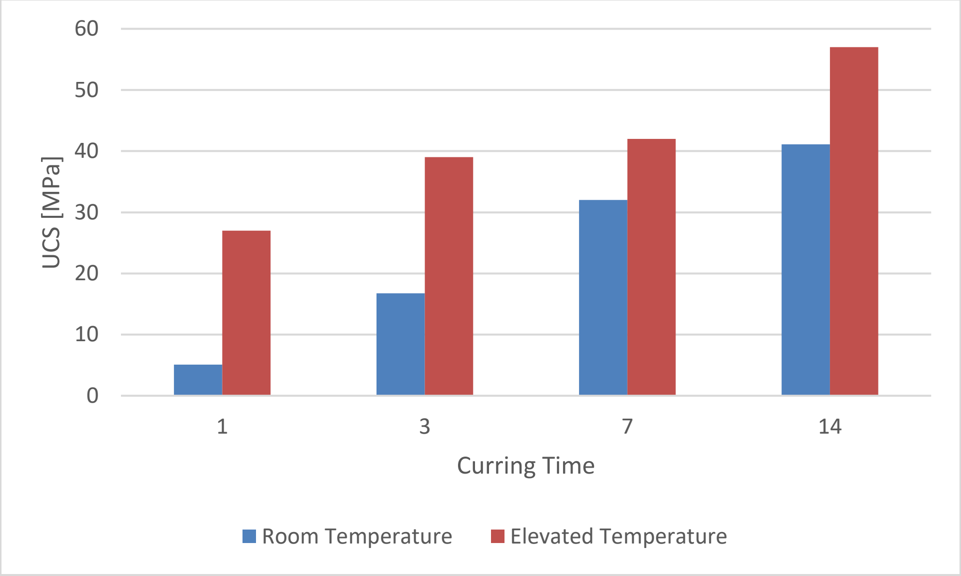


Figure 6. The measured UCS at room and elevated temperatures for class H cement

4. CONCLUSIONS

This paper presents an experimental method to address the lack of data related to cement shear and bonding strength in well integrity investigation. This time, cement was cured at elevated temperature (~65 deg C). The following main results can be noted:

- Shear strength for specimens cured at elevated temperature is higher than that for specimens cured for the same days at room temperature.
- Bonding stress for specimen cured at elevated temperature appeared slightly smaller than it was at room temperature and does not increase as we observed for room temperature conditions. Also there is no increase of the bonding strength with curing time.
- Shear strength for specimens cured at elevated temperature appeared as 17.1 MPa and it was 2.1 times higher than it was at room temperature for day 3. On day 14 of the curing timewe observed a decrease of the shear strength, although the UCS was still slightly increasing. Further investigations are needed to clarify this behavior.

5. Acknowledgments

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