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A Novel View of Cement Failure with Application to Geothermal Well Construction

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ABSTRACT

Geothermal wells are designed following oil and gas practice but have a longer expected life span, and thus their integrity evaluation is based on the same standards and requirements of hydrocarbon wells. Thermal cement degradation is known to occur at temperatures higher than 110°C and many researchers have focused their efforts to develop new recipes that will withstand the high temperatures encountered in these wells. Although other scholars have focused on cement compression and tension strength and its evolution with time and temperature, a closer look at geothermal wells will show that the major load on the cement is generated by the inevitable casing expansion and its effects at the cement-casing contact.

Several works have related geothermal well failures to the casing-cement debonding process. However, field data have shown that the casing movement does not correlate with the debonding theory. The major assumption is that the cementing hardware such as centralizers or collars do not restrict casing movement. If in some situations this might be the case, the casing couplings behavior could be the answer to improve the understanding of geothermal wellbore failure.

This paper proposes a cement strength investigation setup, aimed at identifying the cement strength under a special shear load, simulating the coupling-cement interaction. Although cements are tested for shear through standardized bending tests, such test is not truly relevant for the annular cement, and as a result a new procedure to test this load on well cements is necessary and defined in this paper. The new method replicates the interaction between the casing couplings and cement, and results will help engineers improve their well design and increase the well integrity for the life of the geothermal well.

1. INTRODUCTION

Securing the world's energy needs while addressing the low carbon challenge has become one of the crucial topics in the future energy aspect. Geothermal energy is a known reliable energy suitable for baseload power generation because it is available at all times throughout the year, whereas the availability and energy density of other renewable energy forms is in general lower (Kömürcü, 2009). Since drilling principles in geothermal wells are the same as the ones of the oil and gas industry, drilling engineers and researchers from the oil and gas industry have been interested in technical issues in geothermal wells. One of these issues is loss of well integrity, a major concern which may cause safety issues, environmental risks, lost time and additional cost. A successful cementing job is known as one of the most important parts in achieving long term well integrity (Alber, Ehringhausen, 2017).

Wellbore cementing is the process of placing cement in the annular space between the well casing and the geological formation surrounding the wellbore to provide zonal isolation (Shahruar, 2011), or between two strings of casing. The main objectives of well cementing are (Joshi and Lohita, 1997):

- providing axial and collapse support to the casing,
- protecting well casings from corrosion,
- reducing the risk of ground water contamination by oil, gas or saltwater,
- preventing crossflow (exchange of gas or fluids among different geological formations).

Wehling stated that cementing plays an important role in terms of well stability and introduced three mechanical issues affecting wellbore integrity, or cement failure types as radial cracks, de-bonding cracks, and shear failure (see **Figure 1**). As Wehling (2008) stated, the major mechanical issues affecting wellbore integrity are compressive, bonding and shear failure. The same principle is applied to the interaction between coupling and cement, and this paper is introducing laboratory test results achieved through a customized testing setup of a coupling and the surrounding cement.

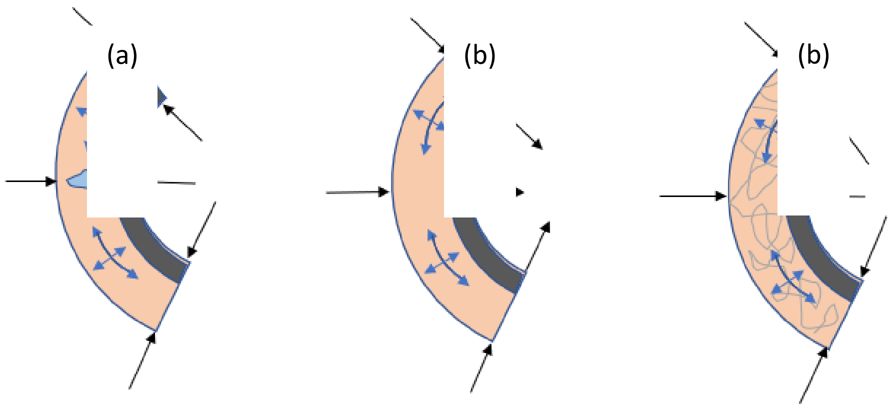

Figure 1. Types of Mechanical Cement Failure a) Radial Crack b) De-bonding c) Shear Failure (Wehling, 2008)

In both the hydrocarbons and geothermal industry, investigations on compressive strength of various cement samples with variables such as thermal variation, added additives, and curing time have been of interest to observe their relationship with well integrity issues. Teodoriu (2012) introduced the possibility of cement failure caused by shear failure, but unlike numerous compressive strength studies of cement, the well integrity issues caused by shear and bonding strength haven't been spotlighted as much. This issue has been readdressed by Ichim and Teodoriu (2017). In addition, Thiercelin et al. (1997) and Philippacopoulos et al. (2001) also mentioned that compressive strength might not be the main factor that secures zonal isolation in oil, gas, or geothermal wells. These studies suggested that other mechanical properties of the cement, such as shear stress, bonding stress, Young's modulus, and Poisson's ratio can also be important factors to consider when evaluating causes of well integrity issues. For a better understanding, we must mention that the shear strength is a cement mechanical property similar to the unconfined compressive strength and the tensile strength. The bonding strength (also known as interface bonding strength) is an interfacial property that depends on cement and the other material that comes in contact with it (i.e. between casing and cement).

Because of its importance to the construction industry, concrete shear bonding strength has been studied in various fields other than the energy industry. A common setup for simulating shear stress and measuring this property in civil engineering is usually a beam shaped structure, different from the annular shaped cement placed in a geothermal well. The results of such a measurement are purely related to the cement and do not consider cement-pipe interaction. Bejar and Rushing (2017) examined the shear strength of a cylinder model of Class H Cement with added silica fume through a finite element analysis approach.

Evans and Carter (1962) conducted bonding studies of cement to pipe, introducing the variables for different tests to obtain shear bonding strength and hydraulic bonding strength between casing and cement. They distinguished experiments between shear bonding and hydraulic bonding (which is not affected by shear stress). The shear bonding test is performed by measuring the force required to push a cylinder that was previously cemented inside of a cylindrical shape container. The hydraulic shear bond is measured by pumping water in the middle of two concentric cylinders that were cemented in place. Figure 2 shows both experimental setups used by Evans and Carter.

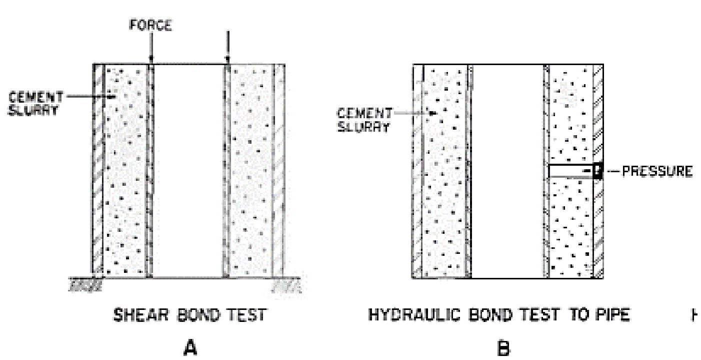

Figure 2. Shear bonding test and hydraulic test between pipe and cement setup (Evans and Carter, 1962)

Evans and Carter (1962) have shown the influence of curing conditions to hydraulic bond stress of an API Class A cement inside of a 2 in. pipe (inside diameter) of 10 in. length. These are presented in Table 1.

Table 1. Relationship of curing conditions to hydraulic bond strength of API Class A cement

Curing Conditions			Failure Pressure, PSI
Time, h	Temperature, °F	Pressure, PSI	
24	80	0	500
48	80	0	500
24	120	0	500
24	140	2000	600
24	120	3000	800
24	80	0	600

Other experimental work was performed by Zhao et al. (2015), Salehi et al. (2016), Lavrov and Torsaer (2016). Through Finite Element Analysis, Teodoriu (2015) and Kaldal et al. (2015) have shown the importance of casing coupling – cement interaction, in which the maximum stresses in a temperature loaded well will always appear between the coupling edges and cement. **Figure 3** shows the stress distribution around the edges of an API Buttress coupling.

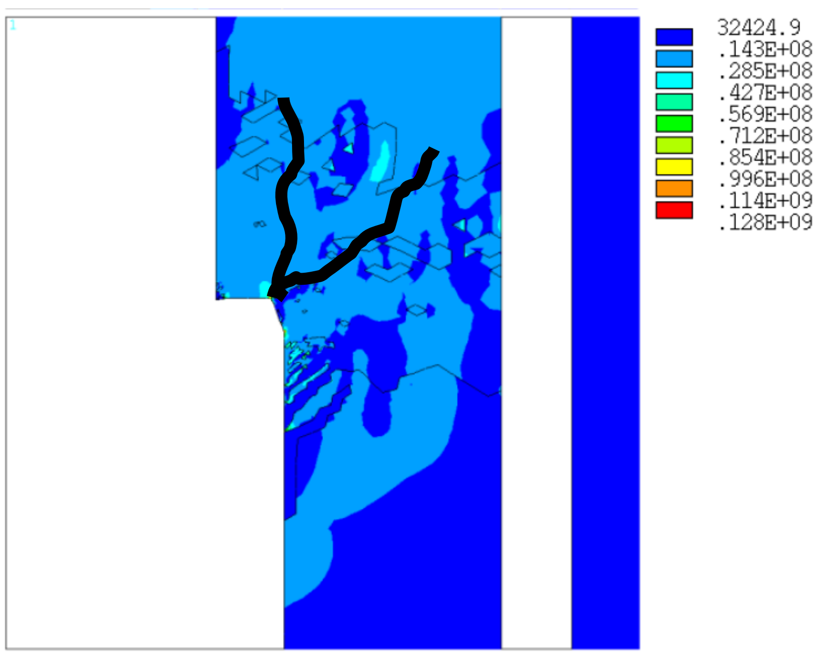

Figure 3. von Mises stresses [MPa] in the cement around a Buttress type casing coupling (Kaldal et al. 2015)

Although shear stresses are not shown in Figure 3, the likely failure mode of cement is shear, and as mentioned by Teodoriu (2015) the shear stress will propagate vertically or diagonally (see the marked lines in Figure 3). Due to the thin cement layer, it is to believe that the shear failure will most likely propagate vertical.

The experiments presented in this work simulate the shear bonding strength between cement and casing coupling, showing which shear failure will appear first and then comparing this with cement ultimate compressive strength. To resemble the annular shape that represents casing/coupling, each test cell was customized accordingly. A standard API recipe of Class H cement has been used and samples were tested for shear/bonding stress at different ages.

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

2.1 Sample Preparation

Class H cement was used for this study without any additives included. The amount of water used to make the 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 distilled water were used. The mass of distilled water is measured directly in the mixing container, after which the mixer motor is powered on. The mixing speed must be maintained at 4000 RPM while the cement is added within 15 seconds. After all the cement is added to the water, the mixing rate is 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, 35 days, and 82 days for 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

The experimental setup consists of a 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. Each cell has its own cap adapter to apply force only on the cement, see **Figure 4**. A cutaway view (**Figure 5**) shows the shear cell with a similar shoulder as the one generated by the casing coupling. The shear bonding strength cell is using a slightly different principle as the cell presented in Figure 2, in which the cement has only one contact area with the pipe. For all tests, the material used for pipe was a zinc plated structural pipe, as obtaining a good bonding between pipe and cement was intended. For the pure shear strength cell, the material is stainless steel with low pipe roughness, and the entire inner surface of the cell was greased in order to avoid cement bonding.

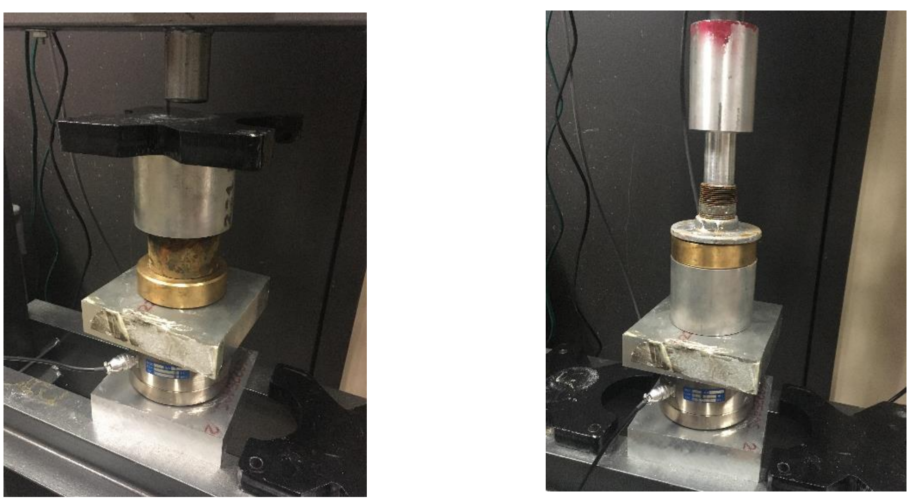

Figure 4. Views of the testing cells mounted in the press, left the shear strength and right the shear bonding strength

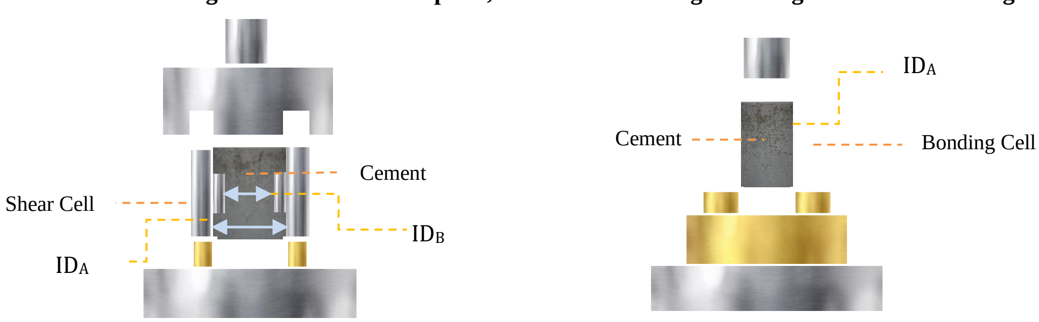

Figure 5. Shear (left) and bonding (right) test cell used in the present study

Table 2 below shows the cells' length, outer diameter, and inner diameters (ID_A, ID_B). The shear strength cell has two inner diameters in order to create the square shoulder of an equivalent coupling.

Table 2. Geometries of the shear and bonding cells

Item	Cell 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 6 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 7** shows the shear bonding strength cell before and after testing.

Figure 6. Shear strength cell before testing (B, C) and after testing (A)

Figure 7. Shear bonding strength cell before testing (B, C) and after testing (A)

Figure 8 shows the recorded maximum applicable loads and 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.

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.

The obtained data is in line with previously published data by Salehi et al (2016), Lavrov and Torsaer (2016), and Zhao et al (2015). Nevertheless, only the interfacial debonding data could be compared since no previous work has proposed a pure shear test comparable with the ones performed in this work. It must be noted that commonly, interfacial bonding strength is evaluated at 24 hours only, therefore the Table 3 compares the found values for this curing time.

Table 3 – Comparison of literature values with obtained data

Author	**Salehi et al. 2016**	**Lavrov and Torsaer 2016**	**Zhao et al. 2015**	**Zhao et al. 2015**	**This work**	**This work**
Comment	After 24 h	-	After 5 days mixed Temp.	Added sand to casing	After 24 hours	After 82 days
Shear bonding strength (PSI)	81	14.5 to 145	14.5 to 362	362 to 1090	68	1450
Shear Bonding Strength (MPa)	0.56	0.1 to 1.0	1.0 to 2.5	2.5 to 7.5	0.47	10

Figure 8 shows a comparison of the experimentally determined shear and interfacial bonding shear strength using the two proposed methods for 1 and 35 days of curing for pure shear and 1 and 82 days for bonding shear strength respectively. The bonding shear strength values for 1 day curing time are close to those reported by other authors, while the high values obtained after 82 days of curing above the range reported by Zhao et al. (2015). this can be explained by the extended curing time used for the experiment: 82 versus 5 days curing at room and elevated (75°C) temperature.

Figure 9 shows the cement pushed out of the interfacial shear bonding strength. It is visible from the left figure that the cement after 24 hours still exhibits an elastoplastic behavior, being pushed or extruded out of the test cell, whereas the probe cured for 82 days shows a clear brittle cement behavior (see Figure 9, right).

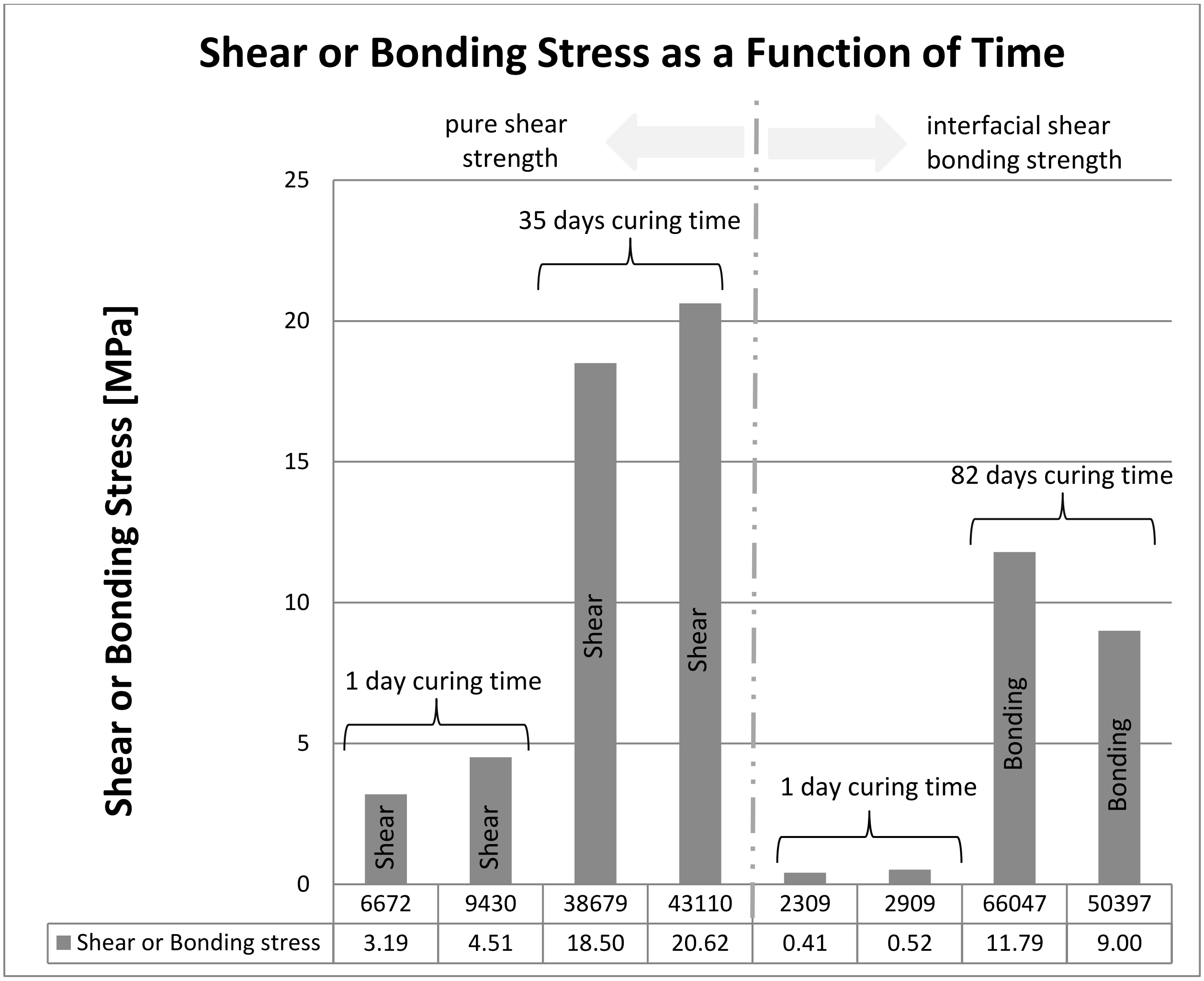

Figure 8. The measured shear(left) and debonding (right) strength for class H cement

Figure 9. The bottom part of the shear test cell after testing at 24 hours (left) and 82 days (right)

4. CONCLUSIONS

This paper presents an experimental method to address lack of data related to cement shear and bonding strength in well integrity investigation. To better understand the cement behavior in geothermal wells, a new testing procedure was designed. The approach yields convincing results, comparable to some extent to previously published data. The novelty of this work is the cell designs and the time span in which tests were conducted.

The tests have shown that the shear strength is typically higher than the interfacial shear bonding strength, which confirms that under certain downhole conditions of a geothermal well, the casing will first debond, then fail in shear in the vicinity of the couplings with a square external shoulder. The simple test performed for the interfacial bonding strength shows similar results with those performed by other authors, confirming the presented experimental work.

It is recommended that for future work, curing temperature and pressure effects will be considered together with additional cement formulations and different simulated coupling geometry.

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