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A Discussion on Geothermal Well Integrity Using Long Term Experimental Bonding and Re-bonding Data

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ABSTRACT

Geothermal wells are by default exposed to thermal loads which can induce thermal degradation of the well construction materials and also affect the wellbore integrity in various ways in time.

Surface casing rising is one of the effects of thermal expansion. Generally, the use of cement or similar products is meant to seal the space behind the casing and formation but is also intended to hinder the casing movement. Thus, casing – cement bonding has been recently acknowledged as one of the important parameters to estimate and evaluate the wellbore integrity, including geothermal wells. Information about casing-cement bonding is relatively scarce, so many publications have been focusing on how to measure bonding experimentally and quantify it mathematically lately.

This paper shows the results of some recent experiments carried out on the so-called casing-cement interfacial bonding shear strength and focuses then on the post debonding phenomenon. The post debonding analysis is trying to consider the possible effect of the casing-cement friction on one side as well as the so-called re-bonding process that has been observed in laboratory tests.

Finally, the paper concludes with a discussion on how the geothermal well integrity can be evaluated in the light of new experiments. The new results will highly impact the future geothermal well construction solutions.

1. INTRODUCTION

A first rigorous attempt to evaluate cement shear bonding and pure shear properties with respect to wellbore conditions using a simple cement testing setup has been proposed in two previous papers presented at the Stanford Geothermal Workshop (Teodoriu et al. 2018, 2019). This novel research approach allows to compare the cement interfacial shear bonding strength for various cement types and different surface roughness of the samples. With the validation of the data showing very promising results, an additional large-scale setup has been built and used in order to understand the upscaling options of the laboratory data to real wells.

The bonding between cement and casing has undoubtedly a massive impact on the well integrity. The bonding of cement and steel can be described as adhesion because the material surfaces are in contact and stick together whereby the adhesive must lead to an intimate, molecular contact with the substrate surface for forces to develop a strong bond (Bwala, 2015). The surface roughness is a crucial factor that affects the adhesion due to the change of contact area between adhesives and the adherent. Kaldal et al. (2015) also pointed out in a finite element study the importance of casing-cement bonding and friction in order to understand the casing movement in geothermal wells.

In an attempt to standardize these parameters, Teodoriu (2020) has introduced a new definition of the cement interfacial interactions and properties. Accordingly, the following cement properties are important for the interfacial cement – casing interactions:

- Shear Bonding Stress (Interfacial Bonding Shear Strength - IBSS) is an interfacial property that shows the force to shear the cement at the interface. (i.e. between casing and cement)
- Tensile Bonding Stress (Interfacial Bonding Tensile Strength - IBTS) is another interfacial cement property that shows the force to axially remove the cement from interface.
- Shear Stress (Pure Shear Strength - PSS) is a mechanical property like Unconfined Compressive Strength and Tensile Strength. The pure cement shear stresses occur because of the difference between the outer diameters of casings and couplings.
- Ultimate Unconfined Strength (UCS) is the cement resistance to compression and it is commonly used for reference purposes only.

Figure 1 shows a compilation of various IBSS values as reported by other authors. The data is shown as minimum and maximum reported values. Please note that the Yang et. Al. (2020) and this work are also reporting long term IBSS results, that show higher values. The data shows a rather scattered range of values that most likely can be attributed to the testing methodology used. The experiments shown by Yang et al. (2020) and in this paper shows that the use of highly polished samples leads to lower IBSS values, but this will be also affected by the cement composition and curing time. Reviewing the data published it has been found that there is a mutual understanding of measuring the IBSS after 24h, however, this measurement might not be relevant for the life of the well integrity.

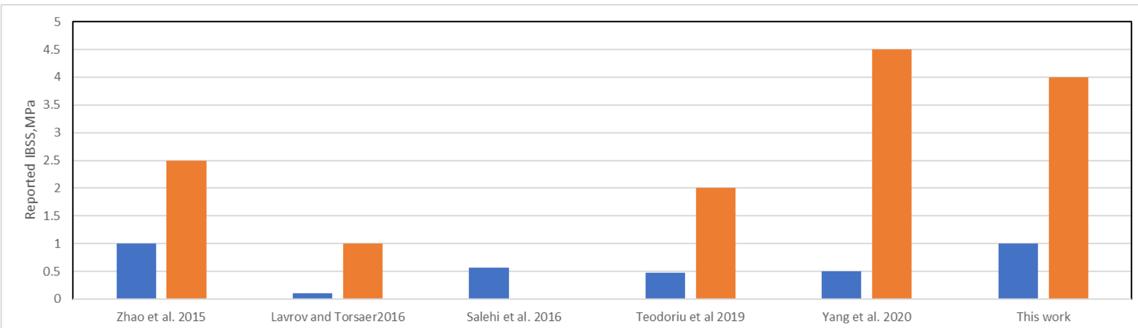

Figure 1. A comparison of minimum and maximum reported values for IBSS

The experiments presented in this work are taking the casing and cement bonding concept to the next level, namely, to investigate the effect of an initial debonding on the casing-cement system. As in the previous papers (Teodoriu et al. 2018, 2019), the same standard API recipe of Class H cement was used, and the samples were tested for IBSS at different cement ages. The samples were first de-bonded after 1 or 3 days of undisturbed curing and then retested after 3 or 7 days of waiting.

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

2.1 Sample Preparation

Neat class H cement without any additives was used for this study. 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 de-ionized water were used. The 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 bonding stress tests: small-scale samples and large-scale samples. The cement mixture was poured into the customized cells. The samples cured in distilled water for 24 hours, respectively 3, 7, and 14 days before the actual bonding tests. Finally, each test cell was tested to obtain bonding stress values. Two samples were used for each experimental data set: one sample was initially de-bonded, then placed back in the curing container and tested again after 3 days. A second sample was maintained unaltered until the de-bonded sample was tested. For example, one sample was cured for one day, then de-bonded and placed in the curing chamber for another 2 days. This resulted in a 3 days total curing. The reference sample was kept in the curing chamber for three days and was fully tested thereafter.

2.2 Experimental Setup

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 post debonding measurement.

The interfacial shear bonding strength (MPa) is calculated as:

$$\sigma = \frac{F_{max}}{\pi * D_A * CL} \tag{1}$$

Where F_{max} is the maximum recorded force[N], D_A is the diameter of the cell[m] and CL is the interfacial bonding shear strength cell length [m]. The only difference consists in measuring the de-bonded sample initial cement – cell contact length (CL) and adjusting the final value. The value CL was measured before every experiment.

The cells used for the experiments shown in this paper are presented in **Figure 2**. For the small-scale samples, the cement is poured inside the casing used for the experiments. The cement is pushed out using a piston with a diameter equal to the inner diameter of the cell. For the large-scale samples, the cement is poured between a stainless-steel pipe and a smaller steel pipe that represents the material to be tested. The smaller pipe is pushed out while the cement and the outer stainless-steel pipe are hold in place with a special flange. The cement – casing contact is measured for both experiments. For the large-scale setup, the parameter DA is equal to the outer diameter of the small pipe, while for the small-scale setup it will be the inner diameter of the cell. The samples used for the experiments shown in this paper are grouped in 4 sets: set 1 and 2 consist of small-scale samples using stainless steel for the material that will then bond to the cement. The samples had been polished with 400 grid size to achieve low roughness. For each data point 3 experiments were carried out and the average values were reported. Set 3 consists of galvanized steel small-scale cell. These samples have a higher roughness than the samples used for sets 1 and 2. Finally, the set number 4 refers to the large-scale sample. For reference only, cement cubes were used to measure the UCS and they were retrieved every time a new set was prepared. All UCS data was very consistent within less than 5% variation for all tested samples. This was the indication that the cement preparation was done uniformly.

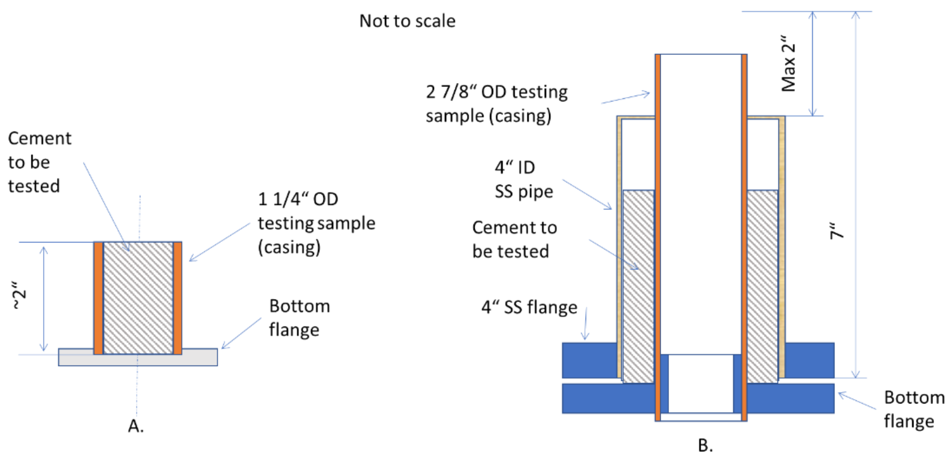

Figure 2. Schematic view of the small-scale setup (A.) and large-scale setup (B.)

2.3 Process mimicking

The new testing procedure is proposing to simulate the following geothermal wellbore situation: the well is cemented and ready for the next phase. Casing expansion or contraction will result into axial movement which will lead to casing cement debonding. The cement continues its hydration process and thus, a re-bonding takes place. This re-bonding process is hereby simulated. The casing-cement relative movement is simulated by pushing out the cement (small-scale setup) or the small pipe (large-scale setup) for a pre-set value of the axial motion (~7.5 mm) This value has been selected after intensive experiments that have shown that once this travel length is achieved the push out force remains constant. This process is investigated for early cement hydration phase (within 14 days after cementing). For example, it is very common to start the drilling of next casing section after less than 24 hours of waiting on the cement.

3. RESULTS AND DISCUSSIONS

Figure 3 shows a comparison between small-scale and large-scale IBSS, clearly indicating that the small-scale setup shows higher values for the IBSS when compared with the large-scale samples. This phenomenon was also noticed by Toersaen et al. (2015) and they indicated that the casing size will affect the readings and thus, the laboratory experiment can be used for comparison only of various cement recipes but not directly extrapolated to the field scale. While this observation has been also proved by the experiments shown in this paper, we believe that the bonding process and particularly the de-bonding experiments that will be shown as follows are still valid when looking at the general trend of the results and not at actual numbers. **Figure 4** shows the bonding and re-bonding strength values (IBSS equivalent) for set 3 which is made of galvanized steel and hence has a higher roughness. The cement is pressed from the top using the special designed cap, while the evolution of load and displacement is measured. **Figure 5** shows the bonding and re-bonding strength values (IBSS) for samples sets 1 and 2 which are made of stainless steel with much lower surface roughness. The reason for using lower roughness is that several published papers have shown results obtained using polished stainless-steel products. **Figure 6** shows the bonding and re-bonding strength values (IBSS) for large-scale samples used for this experiment; this samples have an intermediate surface roughness. The first observation is that all tested samples hereby divided in three sets have shown clearly the same trend: after day 1 when the cement is mechanically de-bonded it will re-bond to the steel surface, but the resulted IBSS value is lower compared with the undisturbed sample. If the de-bonding is performed after 3 days, a decrease of the re-bonding strength has been noticed, as shown in **Figure 7** for the large-scale experiments. These experiments show that the casing cement bonding is important within the first few days of cement hydration. If de-bonding occurs within the first 24 hours, a re-bonding is possible;, however if the de-bonding takes place after 3 days or later the process is irreversible. Also, previous tests have shown that the IBS will increase with curing time but will very fast reach a plateau after 3 to 14 days. Elevated temperatures will speed up the process while the IBSS values are much lower than those obtained under room temperature.

	Large Scale	Small Scale
Sample	3Days	3 Days
S1	1.19	3.72
S2	1.55	3.69
S3	1.37	3.70
S4	0.81	4.12
S5	1.01	3.86
S6	1.13	3.99
S7	1.06	4.16
S8	1.35	3.85
S9	1.08	4.01
S10	0.95	4.63
S11	1.20	4.14
S12	1.08	4.39
	1.15	4.02

Bonding Strength in MPa

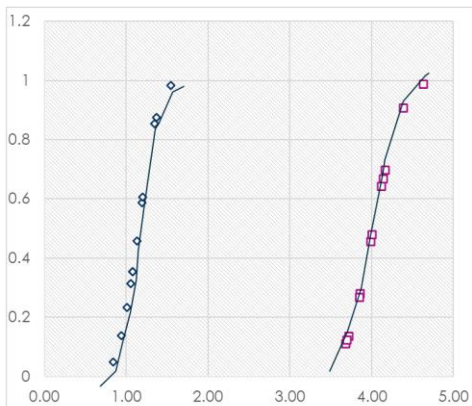

Figure 3. A comparison between small-scale and large-scale cement bonding strength experiments, indicating that the IBSS for large-scale is smaller than that obtained using small-scale.

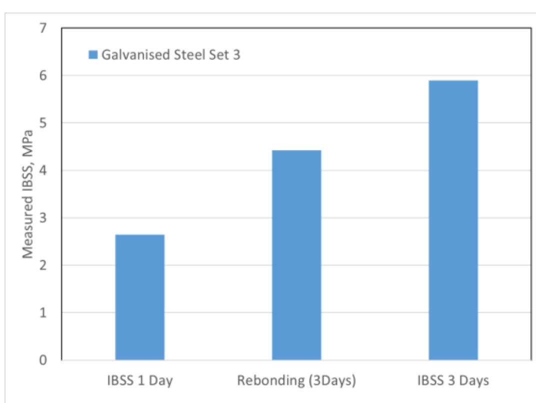

Figure 4. Measured IBSS of galvanized steel cells using class H cement, showing that the IBSS will not be restored to 100% once a de-bonding took place.

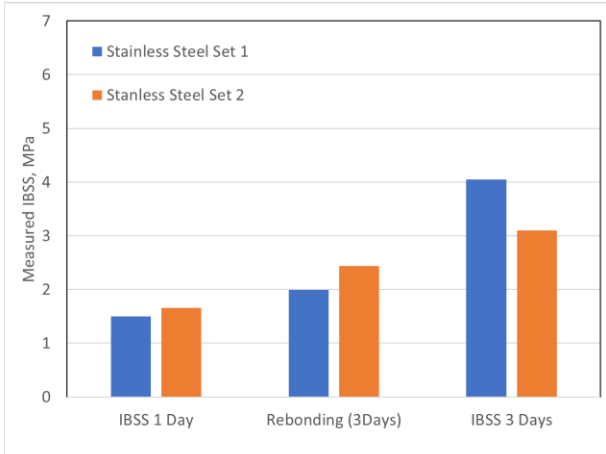

Figure 5. Measured IBSS of stainless-steel cells using class H cement, showing that the IBSS will not be restored to 100% once a de-bonding took place.

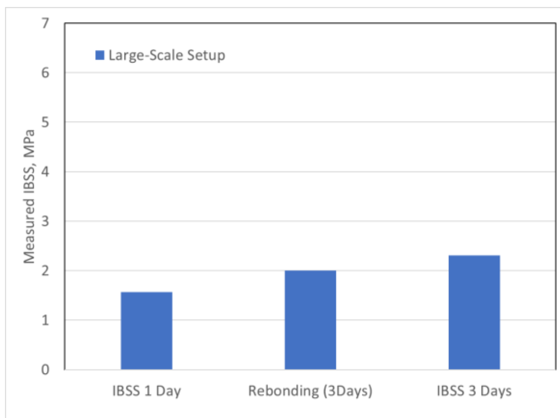

Figure 6. Measured IBSS of large-scale cells using class H cement, showing that the IBSS will not be restored to 100% once a de-bonding took place.

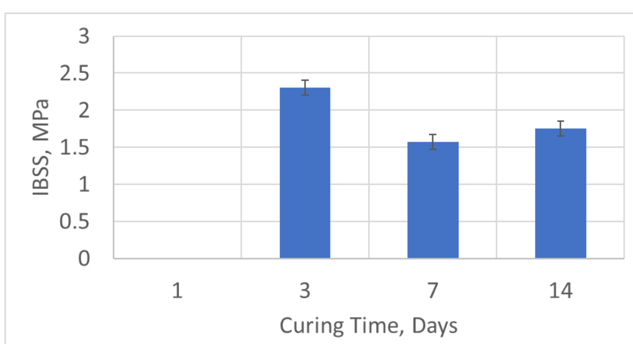

Figure 7. Measured re-bonding IBSS of large-scale cells using class H cement, showing that if the de-bonding takes place after 3 days of undisturbed curing the re-bonding IBSS is lower than before.

4. THE EFFECT ON WELL INTEGRTY

In lieu of the new experiments we can conclude that any debonding that will take place after the hydration of the cement will inevitably lead to a permanent loss of the casing cement bond. The experimental data shows that what is measured after day 7 can be associated to a friction between casing and cement rather than bonding.

In particularly, these findings could explain why some surface casing expansion cannot be fully explained by the simple thermal expansion estimations. Kaldal and Thorbjornsson (2016) have estimated that 1000 m of free casing (no cementing) exposed to a 160°C differential temperature will expand approximately 1.96 m. If this expansion will be fully stopped by a good cement behind the casing, then the resulted axial stress in the casing will be 379 MPa. This stress is independent from pipe size.

According to the definition of the IBSS, the geometry of the pipe will highly affect the axial force that can be hold by the casing cement interfacial stresses. This force can be estimated as follow:

$$F = IBSS * \pi * OD * Length \quad (2)$$

Where OD is the outer diameter of the casing in [m] and Length is the fully cemented length of the casing in [m].

If we calculate the axial force induced by 379 MPa in a casing with a size of 7 inch and 9.19 mm wall thickness we will get about 1.85 MN axial force. Replacing this in the equation 2 we can estimate the minimum fully cemented length that could hold such axial load. Assuming an IBSS value of 1.5 MPa this length is 2203 m which is longer than the initial length of 1000 m assumed for the casing in this example. As such it will be impossible for an assume IBSS of 1.5 MPa to hold the casing in place.

This simple calculation shows that wells exposed to high differential temperature changes will inevitably result in casing – cement debonding and thus additional solutions needs to be applied to maintain a good annular well integrity.

5. CONCLUSIONS

This paper presents an experimental method to address the lack of data related to cement bonding strength and introduces for the first time the re-bonding concept.

It has been found that all samples (small and large-scale) have shown the same trend: if the cement is de-bonded after day 1, the equivalent interfacial bonding shear strength after 3 days is higher than its initial value. However, if the de-bonding takes place after 3 or more days, the measured re-bonding strength is clearly lower than the initial one. This implies that the re-bonding process will only take place during early stages of cement hydration.

Casing-cement debonding might be inevitable if casing axial movement exists after 3 das since cement job.

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