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Measuring Cement Thermal Expansion Coefficient and Its Impact Towards Geothermal Well Construction

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ABSTRACT

The global energy demand is increasing worldwide, and geothermal is becoming an attractive option due to the untapped resources and being considered an important green energy source. Geothermal wells are challenging due to their depth, which makes the subsurface condition very hostile with respect to temperature and pressure. For the geothermal project to succeed, it is vital to maintain the integrity of the well so that the maximum energy can be produced from it. In that respect, cement plays a crucial role, as different studies have suggested that cement is one of the most critical parameters that control the integrity of the well. Though many cement properties have been investigated by researchers, thermal properties are the least studied parameter. Moreover, the elevated temperature in the geothermal wells makes thermal properties the most important parameter to be considered. Expansion and contraction of the cement due to temperature fluctuation can affect the cement's bonding with the formation and casing and create micro-annuli in the cement matrix. Hence, this paper focuses on measuring the linear thermal expansion of different oil well cements that have been cured for different time periods. The measurement of the thermal expansion was done with the help of a novel apparatus that works on the principle of optical shadowing. The results from this study can be used to find the integrity of the cement through simulations for geothermal wells.

1. INTRODUCTION

Geothermal energy is becoming an important energy source in the United States, aiming to reduce greenhouse emissions. Renewable energy will be an important part of the efforts to achieve the goal of net zero by 2050. In that respect, geothermal energy will be one of the biggest sources of energy production due to the untapped resources and presence in many parts of the world at certain depths (Abid et al., 2022; as cited from Lund, 2000). The energy collected from geothermal comes from the subsurface layers of the earth (Abid et al., 2022; Kagel et al., 2005), where higher temperatures are present. This is achieved by drilling the well and circulating the working fluid. Therefore, it is of utmost importance that the integrity of the well is maintained throughout the life of the project. Two main components control the well integrity during the operations in the well: casing and cement. Due to the high-temperature exposure, thermal properties, such as thermal expansion, must be considered for well integrity purposes. Thermal expansion can affect both the casing and the cement sheath. In the casing, the effects of thermal expansion are present in the form of induced stresses that might exceed the yield strength of the casing with respect to compression, which can develop a plastic strain that may end up in the collapse of the casing (Kaldal and Thorbjornsson, 2016). On the other hand, due to the thermal stress on the cement sheath, micro annuli, cracks, and debonding from the casing and formation can take place (Bu et al., 2017).

Cement plays a vital role in the integrity of the wells. The main purpose of cement is to provide proper zonal isolation to perform a safe and economical production out of a well (Teodoriu et al., 2012). Although the mechanical properties of oilwell cement have been extensively studied, the research on the thermal properties of cement is very limited. Therefore, this study focuses on the well cement's thermal expansion measurement, which is one of the most important thermal properties.

Thermal expansion refers to the dimensional variation of any material when exposed to changes in temperature, and it can be linear, areal, or volumetric (Bajpai, 2018). Linear thermal expansion, which is the scope of this investigation, refers to the change in the length, and its mathematical formula is presented in Equation 1:

$$\Delta L = L_0 \cdot \alpha \cdot (T_1 - T_0) \qquad \text{Equation (1)}$$

Where, ΔL, L_0, α, T_1, T_0 are change in length, original or initial length, coefficient of linear thermal expansion, final temperature, and initial temperature, respectively. Moreover, to calculate the coefficient of linear thermal expansion, Equation 1 has to be rearranged, as shown in Equation 2.

$$\alpha = \frac{\Delta L}{L_0 \cdot (T_1 - T_0)} \qquad \text{Equation (2)}$$

For calculating the coefficient of linear thermal expansion, two physical parameters that must be measured from Equation 2 are length and temperature. Several methods, such as dilatometry, interferometry, or thermomechanical analysis (Toledo Velazco 2023; as cited from James, 2001) have been used to measure these properties and then calculate the coefficient of thermal expansion of different materials. In this research, the length and the temperature are obtained with an experimental apparatus developed in the Well Integrity

Laboratory at OU, which operates using an optical shadowing technique. The details of the experimental apparatus are described in the following section.

2. EXPERIMENTAL APPARATUS

The experimental apparatus developed in the Well Integrity Laboratory at The University of Oklahoma allows the linear thermal expansion measurements of cylindrical-shaped samples for different materials. The advantage of cylindrical-shaped samples is the feasibility of measuring other mechanical properties. The apparatus consists of the following components, as shown in Figure 1:

- Micrometer
- Heat controller
- Aluminum block
- Thermometers
- Cylindrical sample
- Data acquisition system

As mentioned in previous publications (Toledo Velazco, 2023), the micrometer's main function is to read the sample length placed in the aluminum block. The aluminum block conducts the heat to the sample by using thermocouples connected to the heat controller. The heat controller, control the temperature during the experiment. In this research, the temperatures used were in the range of 100 – 200 ℃ (200 – 400 ℉), although greater temperatures up to 315 ℃ (600 ℉) can be achieved. The temperature is measured by thermometers, which also helps to corroborate the temperature at which the system is working.

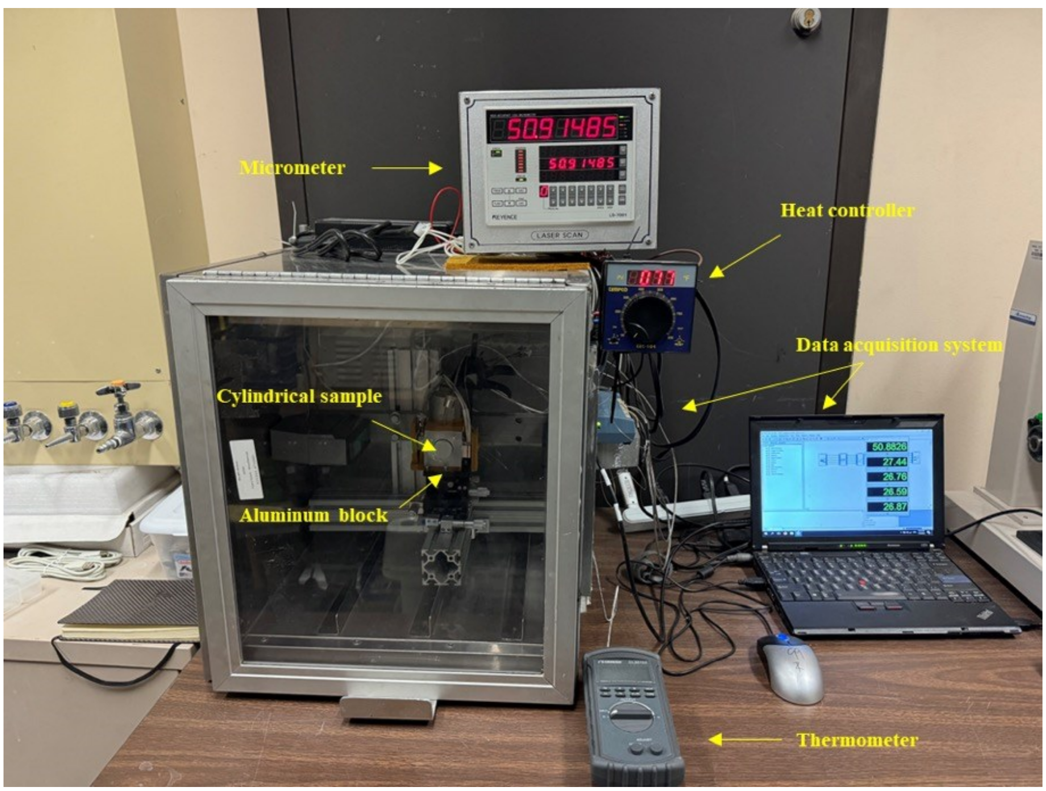

Figure 1: Apparatus used to measure the CLTE of cement samples

The data acquisition system helps collect the sample length throughout the experiment and four different temperatures measured along the apparatus. The temperatures are distributed according to the placement of thermocouples which are connected to the system in different spots. The visualization of those four different temperatures collected by the data acquisition system helps us to observe if the temperature is uniformly distributed along the length of the sample. Data acquisition is performed using DasyLAB. Figure 2 shows a plot with the measurement and distribution of the temperatures along the apparatus while measuring the change in length of a material tested versus time.

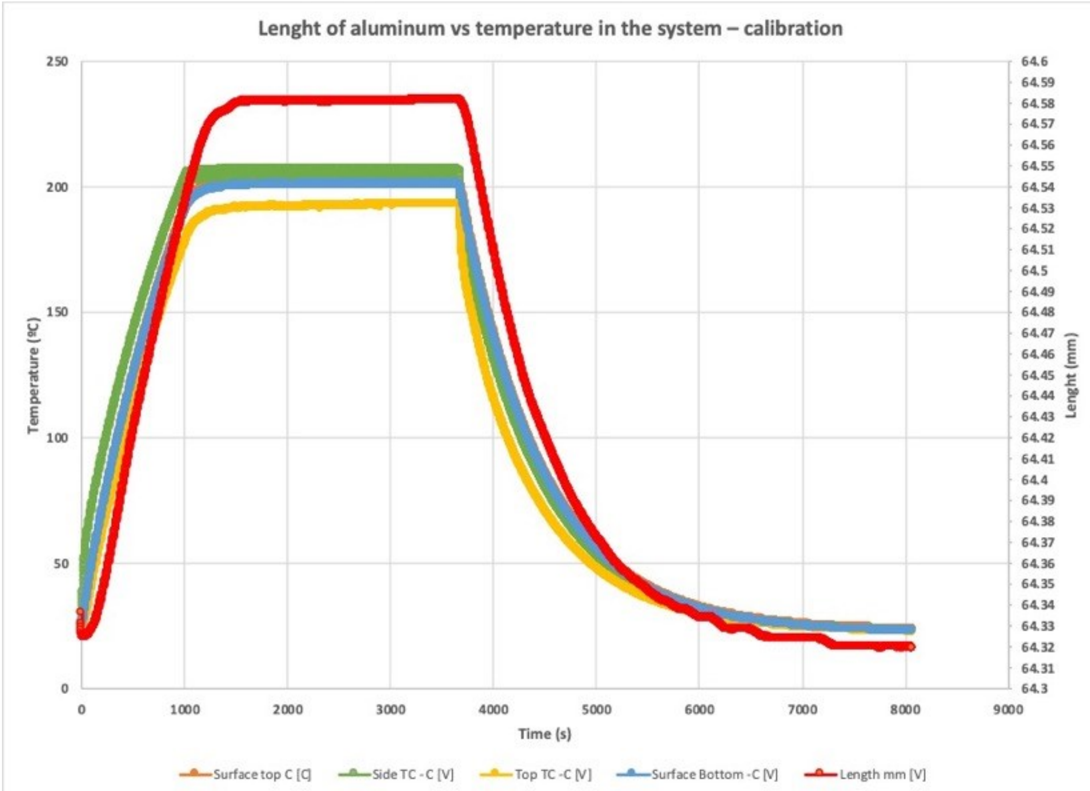

Figure 2: Temperatures around test samples and sample length measured in the apparatus and their distribution

The description of different plots in Figure 2 is as follows:

- Orange plot shows the temperature measured on the surface top of the aluminum block
- Gray plot shows the temperature on one of the sides of the aluminum block
- Blue plot shows the surface bottom temperature
- Yellow plot shows the temperature at the top of the block

From these plots, it can be noticed that the temperature reaches a steady-state point before one hour, and the system ends up with a constant temperature within the same time interval, making the measurement at high temperatures effective.

2.1 Procedure

The test starts with placing the respective sample in the aluminum block, where the micrometer reads its initial length at room temperature and atmospheric pressure conditions. Then, the desired test temperature to which the test is to be held is set with the help of the heat controller. The sample is heated for an hour while the increment in sample length is continuously monitored. Once the hour has passed, the final length and temperature are recorded. Further explanation of the procedure can be found in our previous study (Toledo Velazco, 2023).

2.2 Calibration

The calibration of the system was performed using metallic materials with a known coefficient of linear thermal expansion, which is present in the literature. The purpose of using metallic materials is their homogeneity, which could help avoid any hysteresis behavior in the measurement. The calibration is carried out with the same procedure that has been described in section 2.1. After the test, the coefficient of linear thermal expansion was calculated using the CLTE formula (Equation 2).

2.2.1 Aluminum

The first material used to calibrate the apparatus is Aluminum. Aluminum has a coefficient of linear thermal expansion of 23.6E-06 [1/ºC], according to ASM and Davis (1998). While The Engineering Toolbox, (2003) gives the CLTE of Aluminum to be in the range of 21 to 24E-06 [1/ºC]. The results of the coefficient of linear thermal expansion measured for Aluminum are shown in Figure 3.

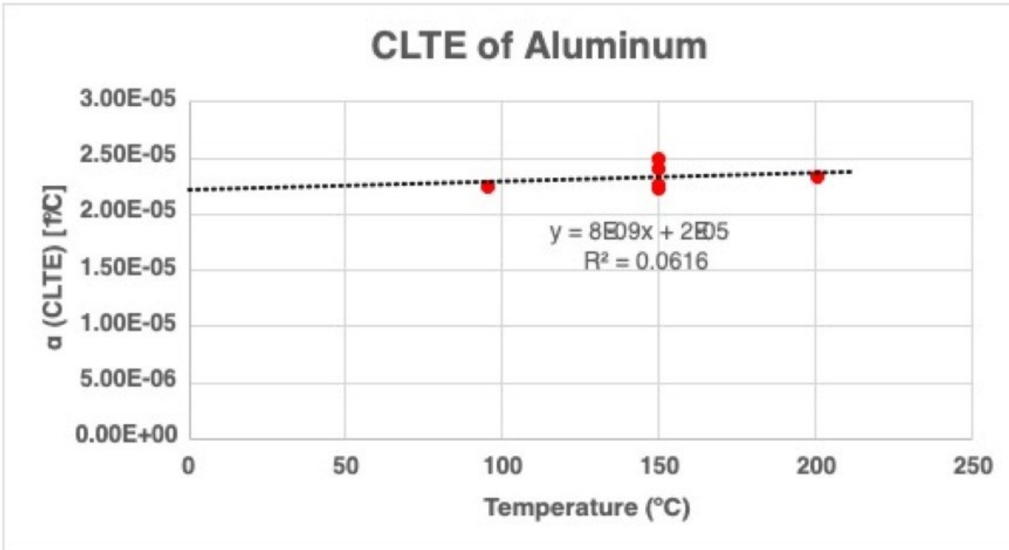

Figure 3: Coefficient of linear thermal expansion of aluminum material for calibration purposes

As can be seen from Figure 3, the values obtained from the Aluminum were 2.2E-05 [1/ºC] to 2.5E-05 [1/ºC] which was within the range of the value presented in the literature.

2.2.1 Brass

To confirm that the apparatus is fully calibrated Brass was used and its results were compared with the CLTE value present in the literature. The CLTE values of Brass provided by The Engineering Toolbox (2003) are in the range of 18 to 19E-06 [1/ºC]. Whereas, ASM and Davis (1998) give a CLTE value of 20.3E-06 [1/ºC] of Brass. Additionally, Dunn (2018) provides values of CLTE of 18E-06 [1/ºC]. The results of the measurement with the apparatus are shown in Figure 4.

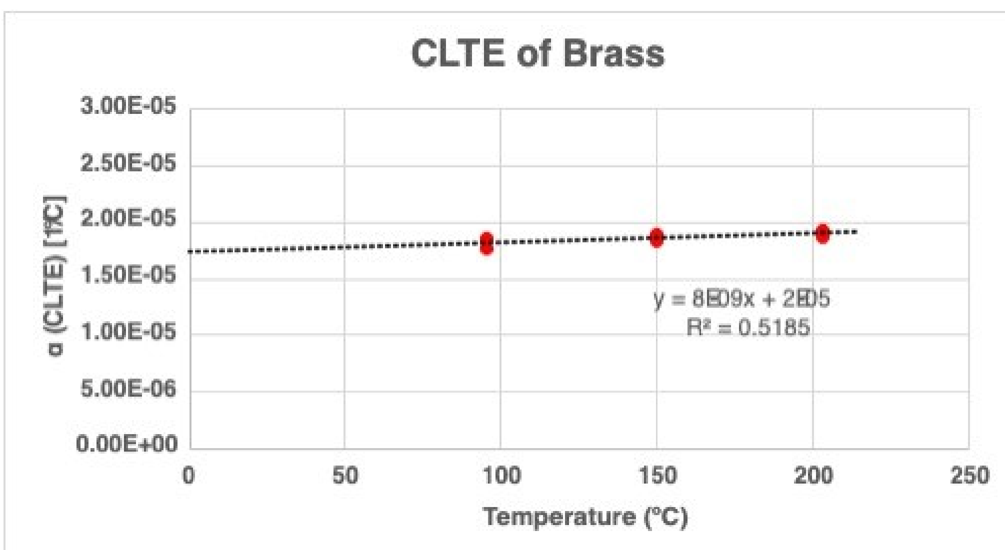

Figure 4: Coefficient of linear thermal expansion of brass material for calibration purposes

The results obtained while measuring the coefficient of linear thermal expansion of Brass were in the range of 18 to 20E-06 [1/℃] at 100 – 200 ℃ (200 – 400 ℉) which were similar to the values present in the literature.

3. RESULTS

After the successful calibration of the equipment through Brass and Aluminum, the CLTE of the well cements was conducted. The cement samples used for this study are as follows:

- Class G
- Class H
- Class C
- Class G + 40% Silica

According to the literature, the curing time is an important factor to consider when measuring any cement mixture's properties. Studies performed by Rincon et al. (2022) show how the curing time affects the UCS of the cement composites. In addition, Rincon (2023) also studies the thermal conductivity of some Class H composites, demonstrating how the curing time affects the cements. The longest curing time showed a better thermal conductivity with constant values in difference with the samples cured for shorter time. Abid et al. (2023) also mentions how important the curing time is when measuring thermal properties, such as thermal conductivity. Their study mentions how the evolution of thermal conductivity is time-dependent, hence short curing times might not give the real values of this thermal property in the samples. In this research, for CLTE purposes, each sample was cured in a water bath for 28 days at room temperature and pressure. After 28 days, the samples were taken out of the water bath and placed at ambient conditions for seven days to dry the sample properly. Figure 5 shows samples that were used in this study.

Figure 5: Samples used for this study

As previously mentioned, the temperatures in which the samples were tested are in the range of 100 – 200 ℃ (200 – 400 ℉). Samples were tested three times for each one of the temperatures and were not exposed to cycling testing. Therefore, each test at each high temperature was performed in a different sample, although the mixture and curing conditions of the samples were the same. After the test, the calculation of the CLTE was made by using Equation 2.

3.1 Class G

The first mixture to be tested was neat Class G. Figure 6 shows the CLTE obtained for each one of the Class G samples exposed to different high temperatures. It can be seen that the CLTE values vary depending on the temperature, and even when exposed to the same temperatures of 200 ℉ and 300 º (around 100 ℃ and 150 ℃), the CLTE ranges from 5E-06 [1/℃] to 2E-05 [1/℃]. Nonetheless, when exposed to 200 ℃ (400 ℉), the CLTE of the Class G sample was consistent, around 1E-05 [1/℃].

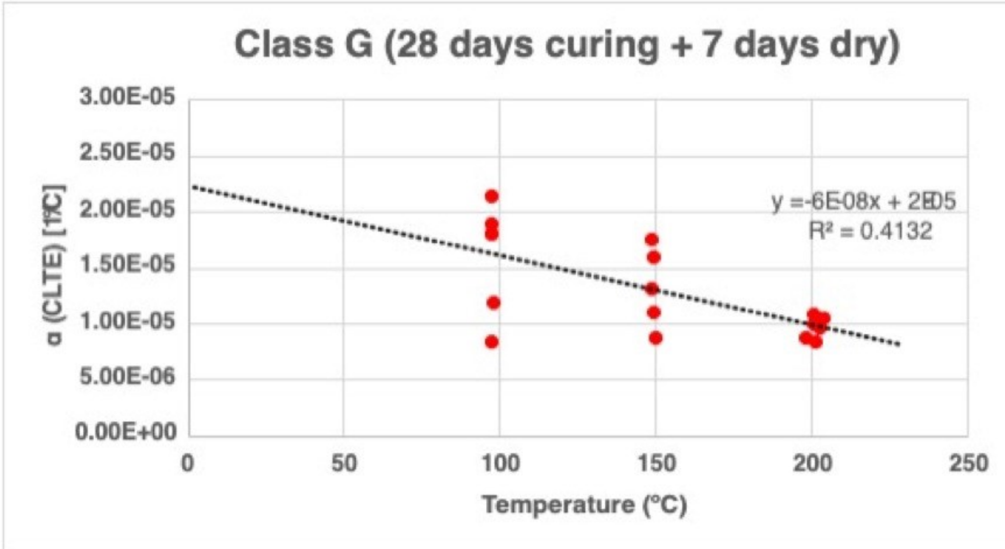

Figure 6: CLTE values of Class G samples

3.2 Class C

The CLTE values of neat Class C cement are presented in Figure 7. In contrast to Class G, the CLTE values of Class C samples were closer that ranged from 1E-05 [1/℃] to 2E-05 [1/℃]. The exposure to 200 ℃ (400 ℉) showed the highest inconsistency in CLTE values for each of the tested samples.

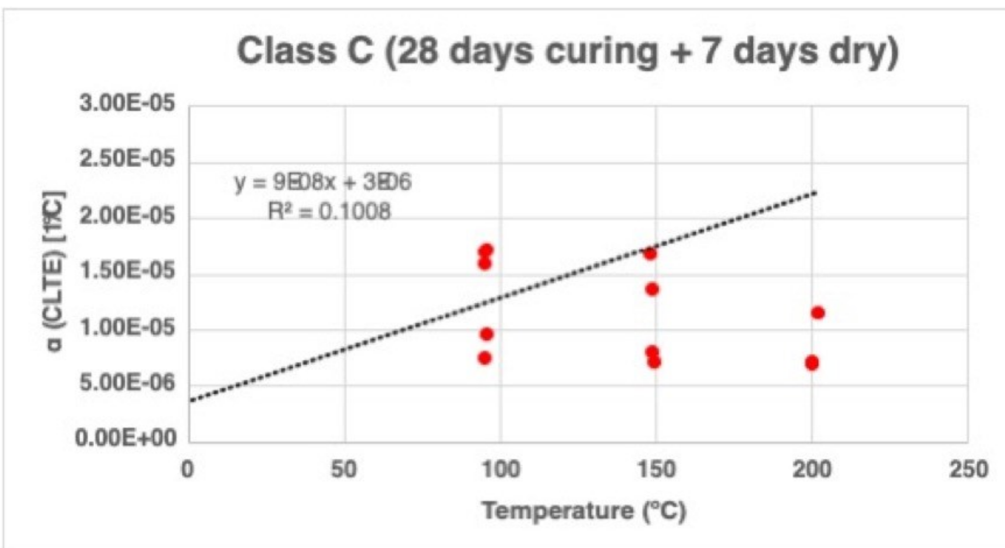

Figure 7: CLTE values for Class C samples

3.3 Class H

Class H cement showed two prominent ranges of CLTE values when exposed to high temperatures. CLTE values in the range of 1.2E-05 [1/℃] to 1.6E-05 [1/℃] were present when the samples were exposed to 100, 150 and 200 ℃ (200, 300 and 400 ℉), as shown in Figure 8. In addition, some values ranged from 6E-06 [1/℃] to 9E-06 [1/℃].

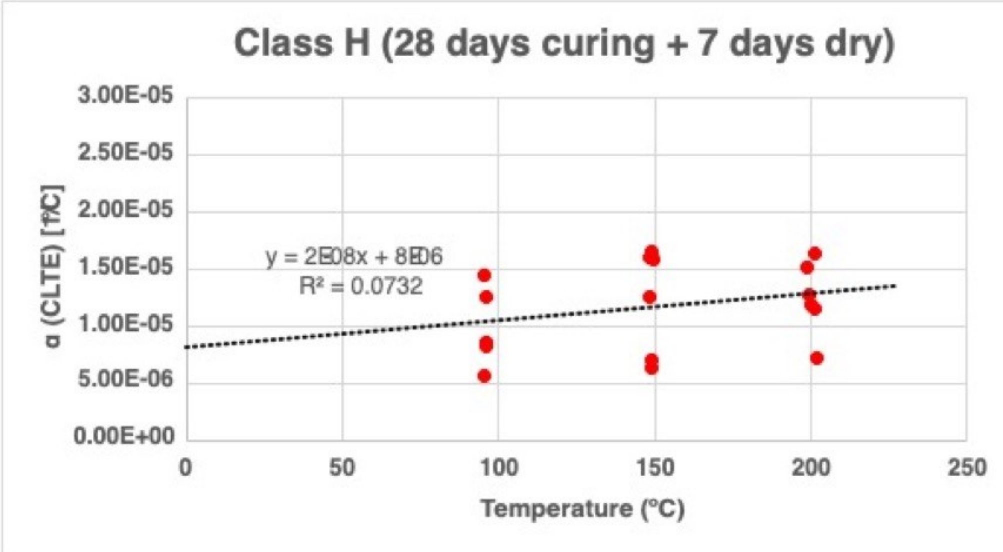

Figure 8: CLTE values for Class H

3.4 Class G + 40% Silica

Class G + 40% Silica was also tested since it is a common mixture used in high-temperature high-pressure (HPHT) cement applications. Silica helps prevent the cement's retrogression at HPHT conditions by producing additional compressive strength through pozzolanic reactions (Loiseau, 2014). The CLTE values obtained in this test vary for each high temperature in which the samples were exposed, as shown in Figure 9. CLTE values of 2E-05 [1/ºC] to 2.5E-05 [1/ºC] were more prominent at a temperature of 100°C (200 ºF), whereas CLTE values around 1E-05 [1/ºC] to 1.5E-05 [1/ºC] were measured when the samples were exposed to 150°C and 200°C (300 ºF and 400 ºF). The CLTE values differ from the values provided by Loiseau (2014) of 8.8E -06 [1/ºC]. Further discussions about the difference between the results from this study and the study performed by Loiseau will be made in the next section.

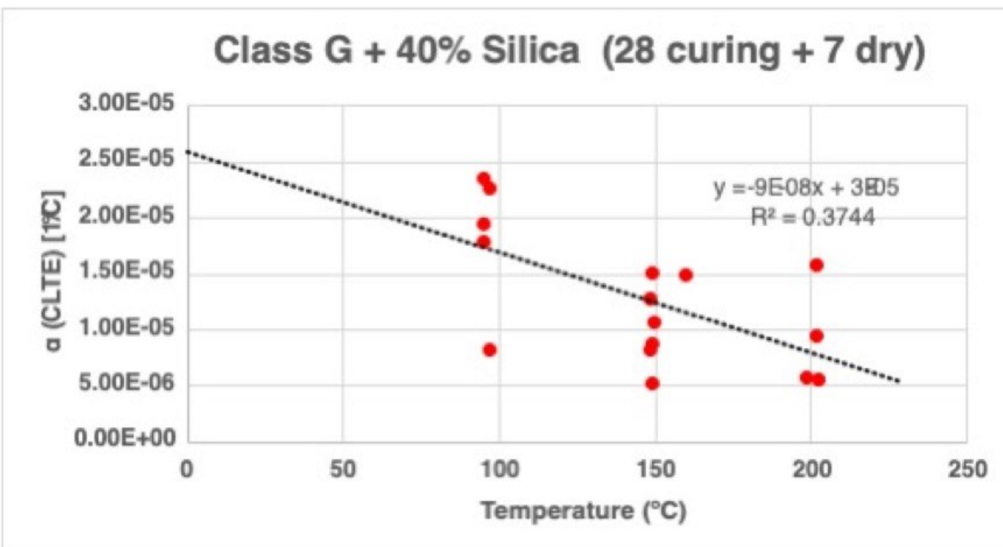

Figure 9: CLTE values for Class G + 40% silica samples

4. DISCUSSIONS

Some important things can be observed from the results obtained in this research. First, the variance in CLTE of the same cement samples is visible despite having the same composition, curing time, and conditions. This phenomenon could be attributed to the air trapped in the cement's porous media and the hydration that occurs during the heating process. It is also important to mention that oilwell cements are not homogeneous materials; hence, the CLTE values may vary the way they did during this study. In contrast, homogeneous materials, such as Brass and Aluminum, which were used for the calibration, showed consistent results.

Another important factor to take into consideration would be the curing time of the cement samples. Despite all the samples being cured in water for 28 days and dried for 7 days at room temperature and pressure, different CLTE were present not just comparing the results between different mixtures but also individually. Moreover, it is concluded by Abid et al. (2023) that the thermal properties of the cement evolve with time and become consistent after a certain number of curing days that might differ from sample to sample depending on their composition. Therefore, testing of the cement samples cured for longer periods is ongoing to better understand the impact of curing in cement composites and its impact on thermal expansion. Nonetheless, it was observed that the highest values of CLTE were obtained from Class G + 40% at an exposure temperature of 100 ℃ (200 ℉). These values would reach up to 2.5E-05[1/℃]. Class C and Class G samples at the same exposure temperature also showed the highest CLTE values, between 1.5E-05 [1/℃] and 2E-05[1/℃]. The lowest range in values of CLTE was provided by Class H, in which the maximum values of CLTE were up to 1.6E-05 [1/℃]. Additionally, Class G at 200 ℃ (400 ℉) showed the lowest CLTE between the four different recipes with values of 1E-05 [1/℃].

For the cement Class G +40% Silica, the CLTE values differed from the results of 8.8E -06 [1/℃] provided by Loiseau (2014). The reason behind this could be related to the difference in the curing time of the cement and the temperature used in the curing for the two different experiments. As mentioned, this study performed experiments in oilwell cements with curing time of 28 days + 7 drying the samples, whereas Loiseau study cured the samples for one week at a pressure of 20.7 MPa and temperature of 137. ℃.

5. CONCLUSIONS

Linear thermal expansion is a property that, along with other thermal and mechanical properties of oilwell cements, plays a vital role in the integrity of the wells. Therefore, four different well cements were prepared and tested for thermal expansion at three different temperatures in this study.

The result obtained by apparatus developed in the Well Integrity Laboratory at OU showed reliable results as the CLTE values obtained from the homogenous materials like Brass and Aluminum were close to the ones presented in the literature. However, the values of the CLTE obtained for the cement sample showed inconsistency because of their homogeneity and the curing time. Therefore, it can be said that curing time is an essential factor when measuring the thermal expansion of the well cement. Hence, the OU cement repository will be updated with more tests for oilwell cement for different compositions and longer curing periods.

Furthermore, we noticed that CLTE can also be used to characterize the cement type, and thus, proper selection of cement type and recipe can affect the overall wellbore heat transfer. Class G particularly seems to shrink during the heat-up process.

6. ACKNOWLEDGMENTS

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