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Thermal Expansion Coefficient Measurements with a Unique Equipment for Wellbore Integrity and Geothermal Purposes

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Abstract

In oil and gas operations, cement plays a vital role in terms of well integrity, as suggested by different studies. Despite mechanical properties have been widely studied to better comprehend the behavior of cement, thermal properties have not been thoroughly investigated. The thermal loads generated by the elevated temperatures present may affect the properties and the behavior of the cement, putting at risk the integrity of the well.

Thermal expansion, which is a thermal property present in the cement under these conditions, could affect the cement's bonding with both the formation and casing, as well as generating micro-annuli in the cement matrix. Moreover, this poster shows a unique equipment, capable of accurately measuring the linear thermal expansion in different oilwell cements, as well as other materials.

The results help to identify the coefficient of linear thermal expansion of the different cement mixtures, helping to preserve the integrity of the oil and gas wells.

Introduction

In oil and gas operations, as well as in geothermal, well integrity has become a concern of the utmost importance. Well integrity can be defined as a well's ability to produce or inject fluids in a controlled manner while also preventing any undesired fluids migration outside the well system (Teodoriu et. al, 2021; as cited from Torbergsen et al., 2012).

There are different causes that may lead to a loss of the well integirty. Some of them are related to the lack of knowledge of downhole conditions in which temperature changes in casing fluids induce expansion and contraction in the casing, leading to stresses on the cement-casing interface. In addition, inappropriate well construction practices, improper design verification and validation on the downhole specimen, or incorrect selection of cement type and casing material can cause problems with well integrity (Teodoriu et. al, 2021; as cited from Phi et al., 2019; Bachu and Bennion, 2009; Lavrov et al., 2016 and Zhang and Bachu, 2011). Therefore, the best chance of reducing well integrity challenges is during the well construction phase (Teodoriu et. al, 2021; as cited from Iyer et al., 2020).

In this aspect, cement as well as casing play a fundamental role in the integrity of the wells. For cement, many studies have been conducted on the mechanical, rheological, chemical, and transfer (porosity and permeability) properties of well cement. However, research on thermal properties is limited, which is one of the most important parameters when it comes to high-temperature wellbore conditions, especially in geothermal wells. Though many thermal properties such as thermal conductivity, heat capacity, effusivity, and diffusivity should be studied, the most critical is thermal expansion, as it can affect the integrity of the cement and the casing.

Thermal expansion can be defined as the variation in the dimensions of any material when exposed to temperature changes. This variation can be presented either linearly, aerially or volumetrically (Bajapai, 2018). The effects of thermal expansion in the casing can induce new stresses that might exceed the yield strength with respect to compression, developing a plastic strain that may end up in the casing collapse (Kaldal and Thorbjornsson, 2016).

On the cement sheath, thermal expansion may cause micro annuli, cracks, and debonding from the casing due to the induced thermal stresses (Bu et al., 2017).

This paper focuses on linear thermal expansion, which refers to the change in length of any material and is mathematically represented in Equation 1.

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

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

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

The coefficient of linear thermal expansion (CLTE) can be defined as the increase in length per unit rise in temperature (Cverna and ASM, 2002), and it is dependent on two physical properties: the length and the temperature. Different methods such as dilatometry, thermomechanical analysis or interferometry have been used to measure these properties and later calculate the CLTE.

In this investigation, a novel apparatus was developed at The Well Integrity Laboratory at The University of Oklahoma with the objective of calculating the CLTE of different materials. The apparatus works on the principle of optical shadowing, which allows the measurement of both the length and temperature properties needed for CLTE calculations.

Novel Equipment for CLTE measurements

The novel equipment developed at the Well Integrity Laboratory at OU, allows the measurement of the CLTE of different cylindrical-shaped materials, as shown in Figure 1. The advantage of using cylindrical-shaped samples is that the expansion is more linear and measurable in cylinders rather than in cubical samples. Moreover, other cement properties can be easily determined through cylindrical samples.

Figure 1 – Samples used for CLTE measurements.

The equipment, shown in Figure 2, comprises of the following components:

- Micrometer
- Heat controller
- Aluminum block
- Thermometers
- Sample (cylindrical-shaped)
- Data acquisition system

As described in previous publications (Velazco et al., 2023; Velazco et al., 2024), all the elements work simultaneously, allowing the measurement of the two physical properties (temperature and length) required to determine the CLTE.

The micrometer allows the measurement and length display of the sample, which is placed in the aluminum block, where it is heated via resistors and is controlled by the heat controller. This apparatus can achieve a temperature of up to 315 ºC (600 ºF).

In this study, the samples were exposed to temperatures in the range between 95 – 200 ºC (200 – 400 ºF). The thermometer also records the temperature in the sample, which corroborates an effective heat transfer.

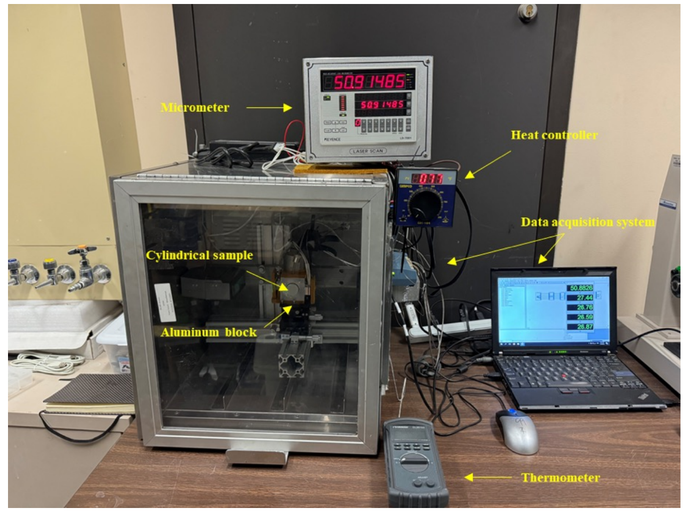

Figure 2 – Novel apparatus designed for CLTE measurements at The Well Integrity Laboratory.

The data acquisition system, which uses the DASYLab software, also allows the recording of the length and temperature of the sample and system. Moreover, while the heat controller and thermometer display the temperature of the sample, the data acquisition system collects four different temperatures in four different spots along the aluminum block, via four thermocouples. The reason for having four different thermocouples measuring the temperature in different spots, is to corroborate that the sample is uniformly heated to the desired temperature. Figure 3 shows the distribution of these temperatures along the aluminum block, while also measuring the length of the cyclindrical sample versus time.

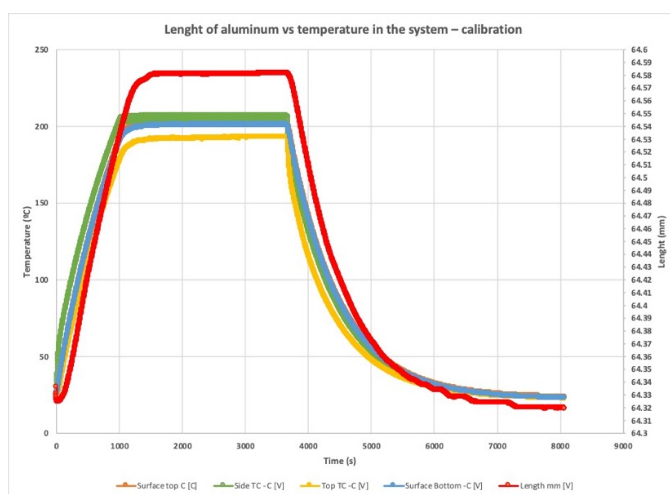

Figure 3 – Temperatures along the aluminum block, with their distribution, and length of the sample recorded by the data acquisition system versus time.

Figure 3 shows a calibration test performed at ~200 ºC (400 ºF), and it can be seen that the temperature was uniformly distributed along the length of the sample.

The description of the temperatures measured with the data acquisition system, and displayed in the plots from Figure 3, is as follows:

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

The temperature reaches a steady-state point within one hour, which is the time of the experiment. The red plot displayed in Figure 3 represents the length of the sample, which expands upon heating and, once the system is cooled down, goes back to the initial conditions.

Methodology

The workflow of the methodology followed to calculate the coefficient of linear thermal expansion (CLTE) of different materials is shown in Figure 4. To effectively calculate the CLTE, the system has to be calibrated. Once the system is calibrated, the sample has to be placed in the aluminum block, and the micrometer reads the initial length of the sample at room temperature and atmospheric pressure conditions. Then, the temperature desired for the experiment is set by the heat controller. As mentioned above, the temperature range during this study was between 95 – 200 ºC (200 – 400 ºF). The sample is heated for one hour while the change in length is constantly monitored. After one hour, the final length and temperature are recorded. The CLTE is then calculated by using Equation 2. The initial temperature and length are measured at the beginning of the test. Meanwhile, the final temperature, corresponding to the high temperature set with the heat controller, is the temperature at which the sample has achieved its maximum elongation, which is also taken as the final length of the sample.

Additional explanation of the procedure followed while testing can be found in our previous study (Velazco et. al, 2023).

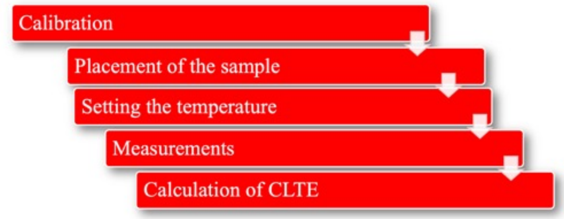

Figure 4 – Workflow of methodology used for CLTE calculation using the novel apparatus.

The following sections will provide the results obtained when calibrating the system, and the results of CLTE for the materials tested.

Calibration

The calibration of the system was performed by using a metallic material, which has a well-known coefficient of linear thermal expansion, present in different literature. The homogeneity of metals helps avoid any hysteresis behavior and allows the system to be fully calibrated. In this investigation, the equipment was calibrated using aluminum as a reference material, as is also shown in previous publications (Velazco, 2023; Velazco, 2024).

Aluminum

Aluminum was one of the materials used to calibrate the apparatus. This material has a coefficient of linear thermal expansion (CLTE) of 2.36E–05 [1/ºC], according to the American Society for Metals (ASM) and Davis (1998). The Engineering Toolbox (2023) provides aluminum CLTE values in the range of 2.1 to 2.4E–05 [1/ºC]. The results obtained while calibrating the equipment are shown in Figure 5.

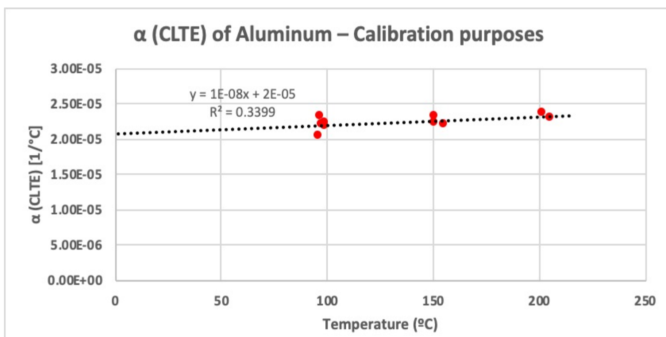

Figure 5 – CLTE values of Aluminum for calibration purposes.

The CLTE values obtained while calibrating the system are in the range of 2.1 to 2.37E–05 [1/ºC], which are aligned with the values present in the literature.

Results

After calibrating the system, CLTE measurements were performed for different materials, including metals, rock and cement composites. The metals used in this investigation were

Brass and Carbon Steel. The cement composites used were Class G + 10% MB and Class G + 5% Sand that were cured for one year. For the CLTE measurement of the rock, Granite was chosen as it is one of the rocks that is mostly present in the geothermal wells. For the CLTE measurement of the rock, Granite was chosen as it is one of the rocks that is mostly present in the geothermal wells. CLTE measurements on rocks are essential due to the thermal stresses that are generated by the thermal expansion. (Thirumalai, 1970). The results are described as follows.

Brass

Brass, which is also found in a previous study (Velazco et al., 2023) shows CLTE values in the range of 1.5 to 1.8E–05 [1/ºC]. The CLTE values provided by The Engineering Toolbox (2023) are from 1.8 to 1.9E–05 [1/ºC]. Dunn (2016) provides CLTE values of 1.8E–05 [1/ºC].

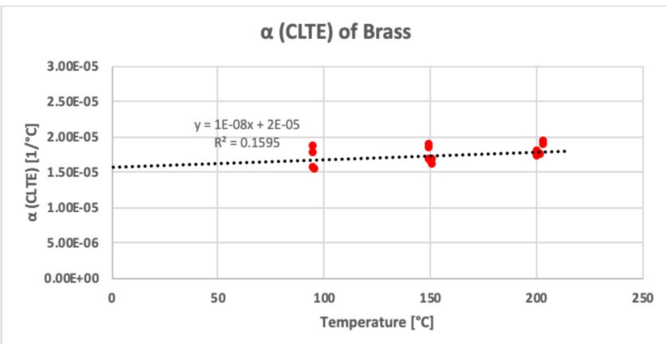

Figure 6 – CLTE values of Brass.

It can be seen that the CLTE values obtained with this apparatus, and displayed in Figure 6, are in accordance with the values found in the literature.

Carbon Steel

Carbon steel was also measured with the novel equipment to calculate its CLTE, as it is a material that is commonly used in the casing. Figure 7 shows the CLTE values obtained that range from 1 to 1.3E–05 [1/ºC].

Depending on the type of carbon steel, Industrial Metal Supply Co. (2022) provides CLTE values between the range of 1.08 to 1.25E–05 [1/ºC]. Shane et al. (2015), as cited from Kahraman (2007), provide CLTE values of 1.17E–05 [1/ºC] for A36 carbon steel, which is the carbon steel presented in this study. Hence, the value of CLTE obtained in this study aligns with the value present in the literature.

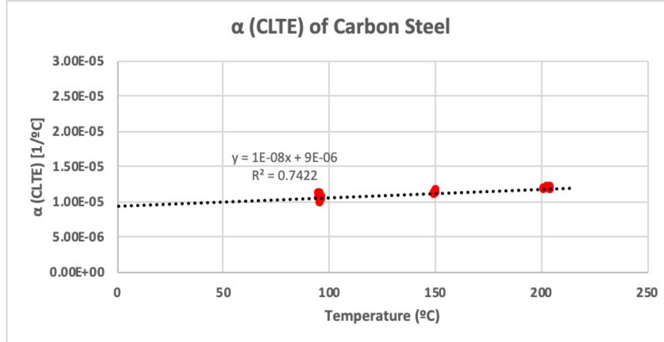

Figure 7 – CLTE values of Carbon Steel.

Granite

Figure 8 shows the result of the CLTE measurement of the Granite. It must be noted that some parameters, such as anisotropy, degree of bonding, or size of grains, were not considered during the experiment.

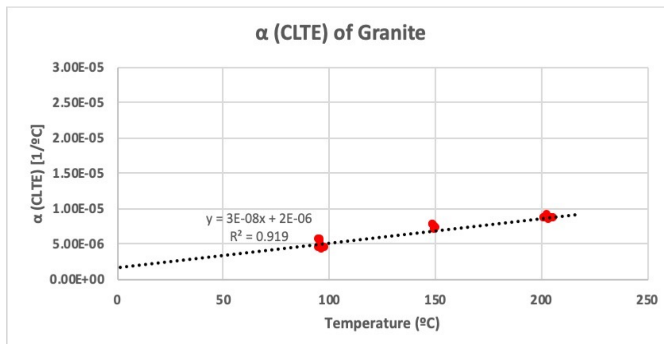

Figure 8 – CLTE values of Granite.

Figure 8 shows that the CLTE for Granite follows a linear trend, in which the coefficient values increase with temperature. CLTE values were from 5E–0 6[1/ºC] to 1E–05 [1/ºC].

A review study on the CLTE value of Granite was conducted by Dwivedi et al. (2008), in which they provided the range of Indian Granite to be 1.3E–05[1/ºC], 1.4E–05 [1/ºC] and 7E–0 6[1/ºC] to 1.4E–05 [1/ºC]. Whereas the CLTE value of Stripa granites presented by Myer (1981) ranged from 8.75E–0 6[1/ºC] to 1.6E–05 [1/ºC]. It is worth mentioning that the testing conditions of these experiments with respect to pressure and temperature were the same as those used in this study. It can be seen that the values reported in the literature correspond to the CLTE value presented in this study.

Class G + 10% MB

The cement mixture used for this investigation consisted of Class G + 10% MB. The measured CLTE values are shown in Figure 9, and it can be seen that the value of CLTE ranges between 5E–0 6[1/ºC] to 1E–05 [1/ºC]. These values were then compared with CLTE values present in the literature for cement composites. Loiseau (2014) provided CLTE values of 8.8E–06 [1/ºC] for a cement/silica mixture. In this mixture, he used 40% silica by weight of cement Class G. The author suggested that this mixture can be used for high-temperature-cement applications since the silica helps to prevent cement's retrogression at HPHT conditions. At first instance, some values obtained while measuring this mixture are close to values in literature. However, the curing conditions and additives used in this study differ from the investigation conducted by Loiseau (2014) because of which some differences in the CLTE value from the literature were observed.

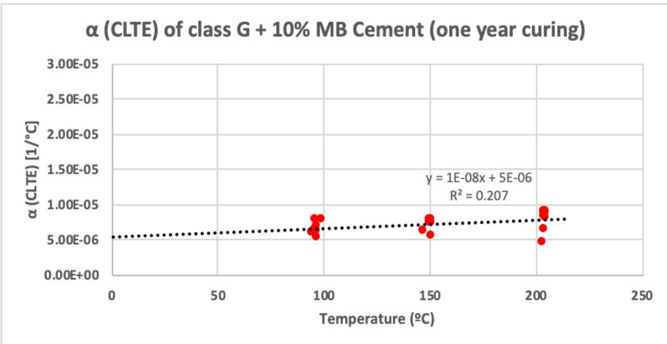

Figure 9 – CLTE values of Class G + 10% MB.

Class G + 5% Sand

CLTE values for the Class G + 5% Sand are illustrated in Figure 10.

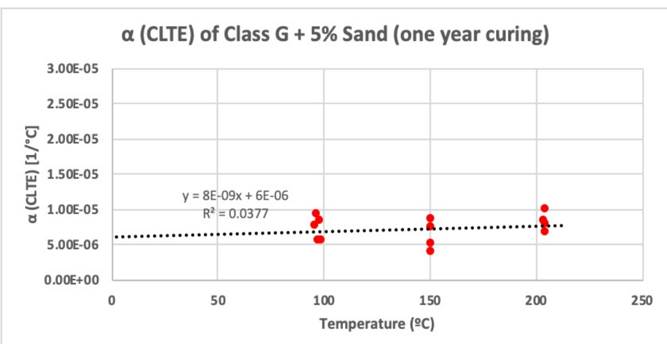

Figure 10 – CLTE values of Class G + 5% Sand.

From above, it can be noticed that the CLTE values obtained were in a range between 5E–06 [1/ºC] and 1E–05 [1/ºC]. Similar to the Class G + 10% MB, some of the values obtained for this mixture aligned with the values provided by Loiseau (2014).

Discussions

CLTE values obtained for metallic elements, such as Brass or Carbon Steel, showed good consistency and were in accordance with the values present in different literature. Xie et al. (2018) showed how some metallic elements are expected to have a linear relationship between CLTE and temperature, which can also be observed by the results presented in this study.

The CLTE of the Granite followed a linear trend with the temperature. However, this experiment did not consider Granite's grain size, anisotropy, and degree of bonding. Nonetheless, the values obtained were similar to values presented in other studies for the same temperature and pressure conditions.

The two cement composites, cured under the same conditions, showed similar CLTE values, ranging from 5E–06 [1/ºC] to 1E–05 [1/ºC]. However, a slight difference in the CLTE value from this study and the one present in the literature was noted, which can be due to different curing conditions and additives used in this research. It is also important to remember that the cement composites are not homogeneous; therefore, the CLTE values may vary.

Moreover, the values of CLTE of the cement samples and the rock were smaller than the values observed from the metals. This could be associated with the homogeneity of the metallic elements and the heterogeneity present in the cement and the rock.

Conclusions

Thermal expansion is one of the essential parameters of casing and cement, and it should be determined to ensure the integrity of the well, whether it is for oil or gas operations or a geothermal project. The coefficient of linear thermal expansion gives a good understanding of casing, rock, and cement expansion. In that respect, a novel apparatus was designed in the OU Well Integrity Lab to measure the CLTE values of different materials.

The results of CLTE values of Brass and Carbon Steel obtained from this equipment were in accordance with the values present in the literature, which shows the accuracy of the novel apparatus. The values ranged from 1.5 to 1.8E–05 [1/ºC] and from 1 to 1.3E–05 [1/ºC] for Brass and Carbon Steel, respectively. For the rock, the CLTE values of Granite were similar to the values reported in the different studies under similar conditions. These values ranged from 5E–0 6[1/ºC] to 1E–05 [1/ºC], which followed a linear trend with respect to the temperature. Furthermore, for the two cement composites, which were Class G + 10% MB and Class G +5% Sand, the CLTE values ranged between 5E–06 [1/ºC] and 1E–05 [1/ºC]. It was found that curing conditions and additives may affect the CLTE. Moreover, the metals showed the highest values of CLTE, whereas Granite and cement samples had smaller CLTE values.

More investigations with this novel apparatus are currently ongoing at the Well Integrity Laboratory, with the objective of long-term testing of metallic and non-metallic materials, rocks and different cement composites. The OU cement repository is also being updated to provide more results on the different experiments performed at the laboratory as well as generate more accurate thermal expansion datasets.

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