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Thermal Expansion Investigations of Oilwell Cements Using a Novel Apparatus.

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ABSTRACT

In the coming future, renewable energies will become an essential source to fulfill the increasing global demand for energy. Geothermal energy is a form of renewable energy and is being widely adopted around the world where suitable temperature exists in subsurface layers. Therefore, for the extraction of geothermal energy, wells have to be drilled and assurance should be made that well integrity is not compromised. In that respect, cementation plays an important role as the cement in the geothermal well is continuously exposed to thermal cyclic loading. These loads might affect the behavior and properties of cement and therefore can jeopardize the well integrity. For that reason, knowing the geometrical changes that cement might have due to the thermal loadings should be properly investigated. This paper will be presenting experimental results on linear thermal expansion of the different classes of cement that are exposed to high temperatures which will help in understanding the behavior of the cement in the geothermal environment. The paper will present the setup that has been designed and the results obtained on several cement recipes as well as few reference materials. Our results provide extremely reliable results for future well integrity simulations.

1. INTRODUCTION

The increasing energy demands have led to the search for new and renewable energies that can accomplish the needs of the present world. One of the options in terms of renewable energy, which also helps to the reduction of the greenhouse effect is geothermal energy. Geothermal comes from the Greek word gê means Earth and Thêrm refers to Energy, therefore, the energy collected from the geothermal comes from the subsurface layers of the Earth (Kagel et al., 2005, Abid et al., 2022). The advantages of using geothermal energy lie in a large number of untapped resources, the wide range of applications, and its availability in many parts of the world at some depths (Lund, 2000) where high temperatures can be obtained. As the cement in the geothermal well is exposed to high temperatures and cyclic thermal loading, hence, it is important to understand the thermal behavior of the cement, especially thermal expansion, which can help to assure the integrity of the well.

Thermal expansion has been the focus of many studies and can be defined as the change in the dimensional properties, such as length, volume, or area of a material, due to temperature variations (Bajpai, 2018). Thermal expansion occurs due to the increase in the kinetic energy present in the atoms of the material, leading to their movement, excitation, and separation (Liu et al., 2017). The effects of thermal expansion in the casing can be noticed due to stresses that might reach beyond the yield strength in compression, leading to a plastic strain in the casing which can collapse it (Kaldal and Thorbjornsson, 2016). Meanwhile, the cement sheath can also be affected due to thermal stresses that affect both the zonal isolation and the mechanical integrity of the well due to cracking and loss of adherence (Bu et al., 2017). Therefore, the conditions generated by the high temperatures make thermal expansion an important factor to take into consideration for geothermal processes.

This paper will focus on the determination of the linear thermal expansion of materials such as metal, rock, and cement with the novel apparatus.

Linear thermal expansion, which is based on the change in the length of the material can be expressed in a mathematical term represented 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 of length, original length, coefficient of linear thermal expansion, final temperature and initial temperature, respectively.

The coefficient of linear thermal expansion, α, refers to what extent a rod of any material, with initial length of 1 meter will become longer if the temperature is risen of 1 ℃ (Pluta & Hryniewicz, 2012). The unit of the thermal coefficient is 10^{-6}/℃ (E-06/ ℃), however, it can be converted to different units. The unit conversion factors are shown in the following Table 1.

Table 1: Conversion factors for the CLTE (ASM International, 2002).

From	To	Multiply by
10^{-6}/K	10^{-6}/ºF	0.55556
10^{-6}/ºF	10^{-6}/ºK	1.8
ppm/ºC	10^{-6}/ºK	1
10^{-6}/ºC	10^{-6}/ºK	1
(μm/m)/ºF	10^{-6}/ºK	1.8
(μm/m)/ºC	10^{-6}/ºK	1
10^{-6}/R	10^{-6}/ºK	1.8

From equation 1, the two physical parameters needed to determine the linear thermal expansion of a material are temperature and displacement and both can be measured using different set-ups and techniques (ASM International, 2002). These set-ups and techniques help to measure the change in length as well as the change in temperature conditions so the CLTE (coefficient of linear thermal expansion) can be calculated. A brief summary of the different techniques used to measure the CLTE is given in the following sections.

2. DIFFERENT CLTE MEASURING TECHNIQUES

2.1 Dilatometry

This technique is widely used in the measurement of linear thermal expansion. The common procedure consists of heating a material that is placed in a furnace and then measuring the displacement of the material through the sensor by means of push rods (ASM International, 2002). The apparatus used with this technique is called a dilatometer and the arrangement can vary as shown in the following figure:

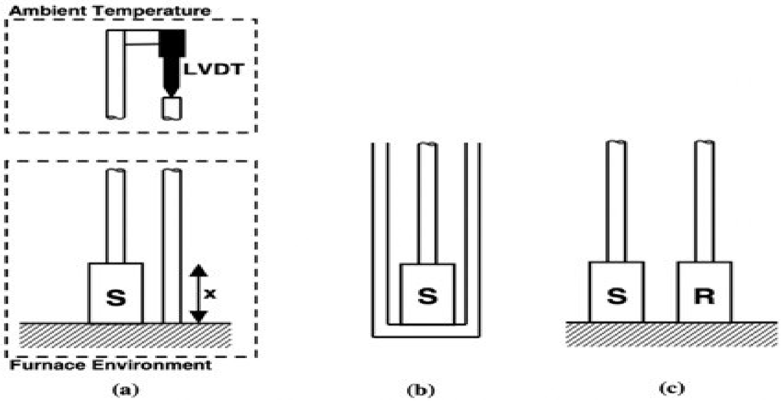

Figure 1: Dilatometers for thermal expansion measurements of different materials, S. (a) double push rod, (b) tube and a push rod, (c) differential with reference material, R. (James et al., 2001).

The push roads can be from different materials, such as aluminum, graphite, or vitreous silica and the selection of the material is dependent upon the temperature in which the test is to be conducted. The standard that deals with the dilatometry with different push rods is given in ASTM E228-95 and ASTM D696. Despite being the most used technique, one of the cons of this method is its accuracy which is less than that of interferometry.

2.2 Interferometry

This is an optical interference technique in which the displacement of the material is measured through the wavelengths of light that travel parallel to the displacement direction (James et al, 2001). These techniques can be Fizeau, Fabry-Pérot, or some other laser-based polarizing interferometers (Touloukian et al., 1975; Hahn, 1988 and Ruffino, 1994). The precision of this technique is better than the one obtained by using dilatometry, nonetheless, the equipment tends to be more expensive, and the temperature range is usually under 700 ºC. ASTM has a standard for optical interferometry which is the ASTM E28-99.

2.3 Thermomechanical analysis

With this technique, measurements are performed by using a thermomechanical analyzer which consists of a probe and a specimen holder. The probe is the one that transmits the changes in the length to a transducer that converts the movement of the probe into an electrical signal (ASM International, 2002). Depending on the apparatus some other instruments besides the probe and the sample holder can be part of it. For example, some of them have furnaces and sensors for temperature while others, such as the one described by Hitachi High-tech (2022), have thermocouples and force generators. Meanwhile, the apparatus described by ISO in the 11359 standards has also a cooling device and a gas supply. The temperature range usually goes from -120 to 600 ºC and besides the ISO 11359 standard, ASTM has its own reference for thermomechanical analysis in ASTM E831. These techniques have been used to measure the coefficient of linear thermal expansion as reviewed by James et al (2001).

This paper will focus on the setup of the novel apparatus that uses an optical shadowing technique to measure the CLTE of the oil well cement, metals, and rock. The calibration of the equipment was done with aluminum and the results were compared with the literature values.

3. EXPERIMENTAL SETUP

3.1 Experimental apparatus

A set-up was assembled at the OU Well Integrity Laboratory with the main objective of measuring the change in length when exposed to different temperatures and then calculating the CLTE of the given material. The new setup was designed with the scope of testing cylindrical samples that later can be used for other geomechanically investigations in particularly UCS and triaxial testing. However, the setup is much simpler than a conventional triaxial cell and allows for large number of tests, which are highly valuable for materials with high inhomogeneity such as cements or rocks. The parts used for the setup of the novel thermal expansion apparatus are as follows.

- Micrometer
- Micrometer laser beams
- Heat controller
- Aluminum block
- Thermometers (for the sample and for the aluminum block)
- Cylindrical sample

In the center of the setup lies the aluminum block through which a 25 mm hole has been drilled (that holds the sample). The cube is fixed in the center of a laser micrometer that measures the initial and final length when the temperature of the cube is increased. The length of the sample that can be used in this experiment should be in the range of 53 to 67 mm. The material is originally placed in the cylindrical-shaped hole of the aluminum block and heated continuously during the duration of the experiment. The measurement of the length is done by the laser beams using optical shadowing and the values are displayed by the micrometer controller. The measurement is continuous during all the tests so the length of the material can be determined while the temperature is increased and ends when it remains constant. The temperature is risen and controlled by the heater controller, which allows the test to be done in a range from 0 to 400 ºF but higher temperatures are possible.

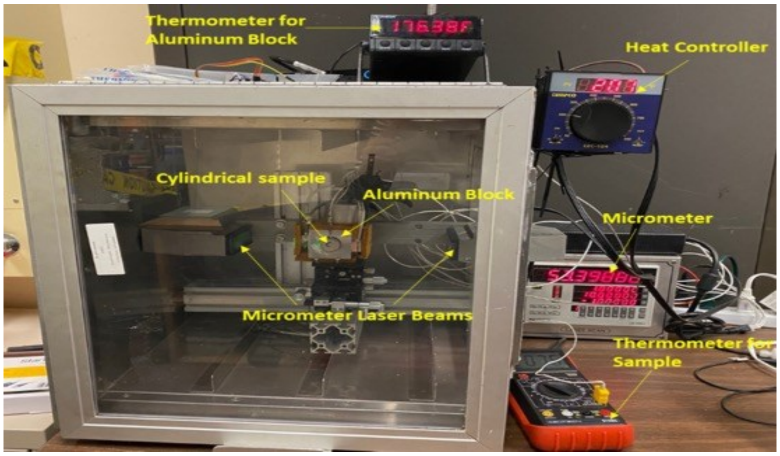

Figure 2: Novel apparatus built at the laboratory.

3.2 Procedure – Calibration test

In order to be sure that the tests are done properly, the apparatus must be calibrated. The calibration consists of the measurement of a material with a known CLTE, which can be found in different publications, and comparing it with the obtained results from the apparatus.

The process consists of placing the sample into the aluminum block, where the micrometer reads its initial length at room temperature and atmospheric pressure. The temperature, given by the heater controller, is recorded and then the setup is heated up through the controller to the desired temperature. The material remains under high-temperature conditions for one hour and change in length is recorded continuously. The final length is the maximum length recorded from the specimen under constant high-temperature exposure.

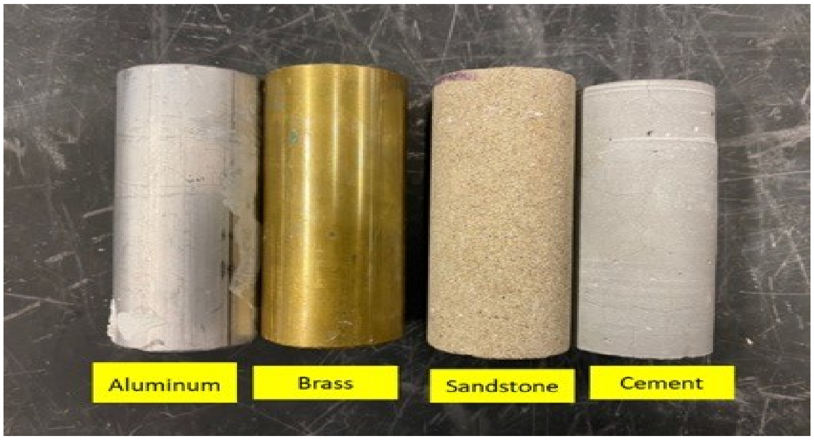

Figure 3: Materials used for CLTE measurements.

For one hour when the constant temperature is provided, the length of the material is recorded. Depending on the material to be tested (like good thermal conductivity materials) some recordings can be usually made 45 minutes after the beginning of the test, and it serves as a comparison with the length collected at the end of the hour in order to determine if the expansion has remained constant. These readings help in the measurement, especially in cement samples because of their heterogeneity. The main idea of these constant recordings is to obtain effective thermal expansion, including the time during the hour of measurement in which the material has reached its final length under high-temperature exposures. After the measurement of the final length and confirming that the value has remained constant, equation 1 can be used for the calculation of CLTE. Before the start of testing, a calibration test was performed with an aluminum sample. The apparatus is said to be calibrated when the results of the CLTE of the material are similar to that of the literature. The results are shown in figure 4 and table 2.

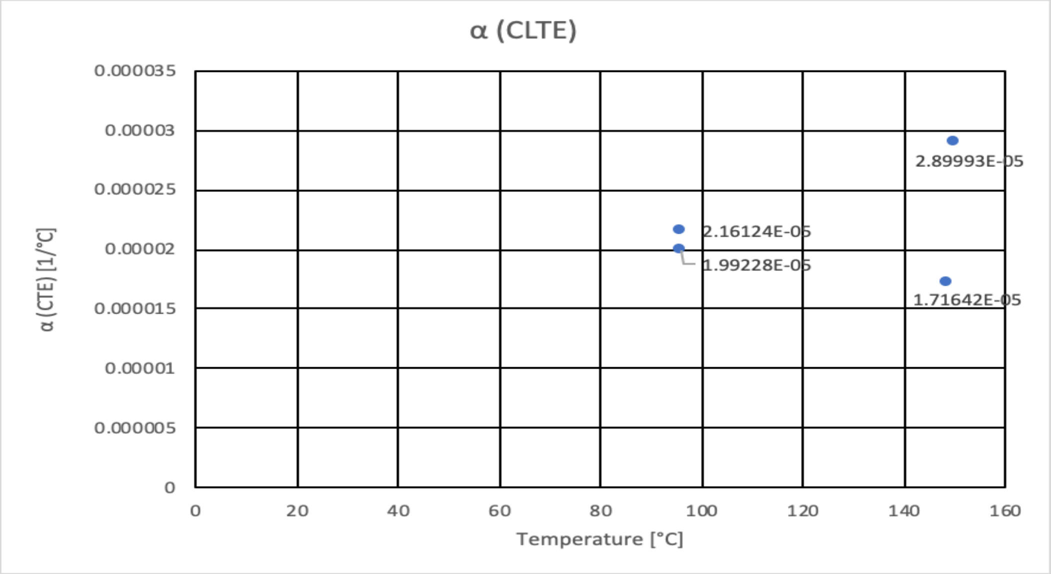

Figure 4: CLTE of aluminum for calibration purposes.

Table 2: Calibration of the apparatus using aluminum as a reference.

Temperature (℃)	α (CLTE) [1/℃]
148	1.71642E-05
150	2.89993E-05
96	1.99228E-05
96	2.16124E-05

The CLTE of aluminum given in some literature such as The Engineering Toolbox (2003) is in the range of 21-24E-06 [1/℃] typically at 25 °C (77 °F), whereas in the Metals Handbook Desk Edition (1998) by ASM and Davis, the CLTE value for aluminum (99.996%) is presented as 23.6E-06 in a temperature range of 20 – 100 °C. It can be seen from Table 2 that the value obtained from the thermal expansion setup is almost the same range of values given in the literature. Therefore, it can be said that the apparatus was calibrated and was ready to measure the CLTE of different materials.

4. CLTE RESULTS OF DIFFERENT MATERIALS

The CLTE measurement was done on two metals (brass and aluminum), a rock which was sandstone, and a cement sample. For the cement testing of thermal expansion, it must be noted that it depends on different factors such as mixture gradients that include aggregate types or volume fractions, age, admixtures, and relative humidity (Mindess and Young, 1981; Fu and Chung, 1999). Other factors to take into consideration when measuring the CLTE of different cement samples are cycles of cooling/heating, temperature ranges, and specimen shapes (Mindess and Young, 1981; Helmuth, 1961).

4.1 Brass

The CLTE result of the brass is shown in figure 5. The results ranged from 12 to 17.4E-06 [1/℃]. It was observed that the thermal expansion coefficient of brass depends on the temperature and the value of the CLTE obtained was close to the values presented in the different literature such as The Engineering Toolbox (2003) which gives the value in the range of 18 to 19E-06 [1/℃] for temperatures at 25 °C (77 °F). For yellow brass purposes the value given in the Metals Handbook Desk Edition (1998) by ASM and Davis is 20.3E-06 [1/℃], whereas Dunn (2018) provides CLTE values of 18E-06 [1/℃] and a range of coefficient of thermal expansion values that go from 18 to 21E-06 [1/℃] for leaded and aluminum brasses in a range temperature of room temperature and 100 – 390 ℃.

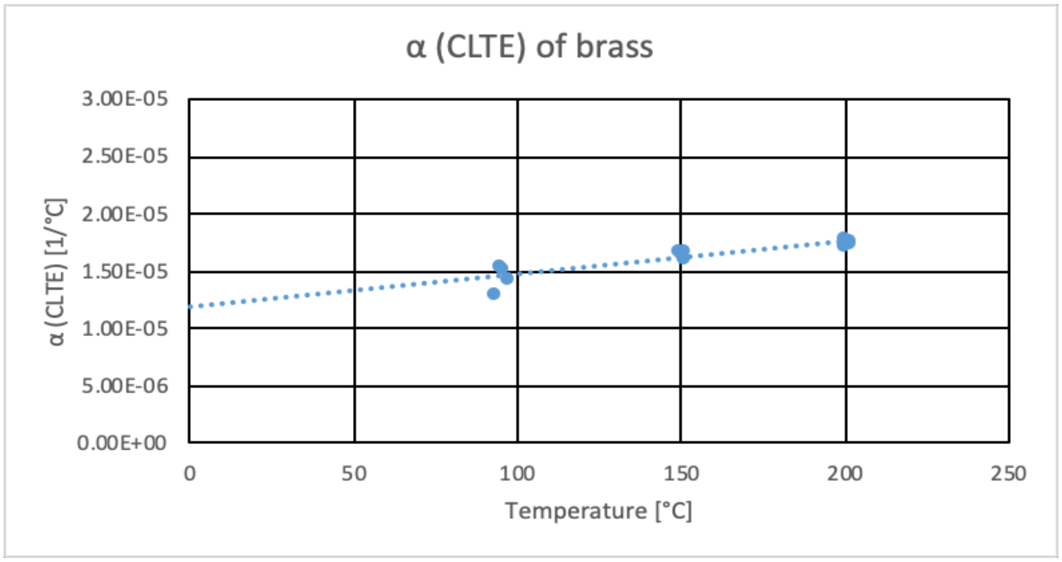

Figure 5: CLTE of brass measured with the apparatus.

4.2 Aluminum

Although Aluminum was initially used to calibrate the apparatus, we later performed more tests in order to check the variation of the Aluminum CLTE with temperature. The aluminum shows a CLTE in a range of 21 to 23E-06 [1/℃] as shown in figure 6, and it was within the range of the value obtained by thermal expansion studies conducted by Yogaswara and Elijabbar (2018) using a diffraction method. The values obtained by them were from 22.972 to 23.438E-06 [1/℃]. They used the value of 23E-06 [1/℃] as a reference which corresponds to values presented in different literature such as by The Engineering Toolbox (2003) (21 to 24E-06 [1/℃]) for temperature 25 ℃ (77 ℉). As shown in the calibration section, the Metals Handbook Desk Edition (1998) by ASM and Davis shows a CLTE value of 23.6E-06 for aluminum (99.996%) in a temperature range of 20 – 100 °C, whereas Dunn (2018) provides CLTE values of 25E-06 [1/℃] and a range of coefficient of thermal expansion values that go from 21 to 25E-06 [1/℃] for aluminum in a range temperature of room temperature and 100 – 390 ℃, both references within the range of the results obtained in this research.

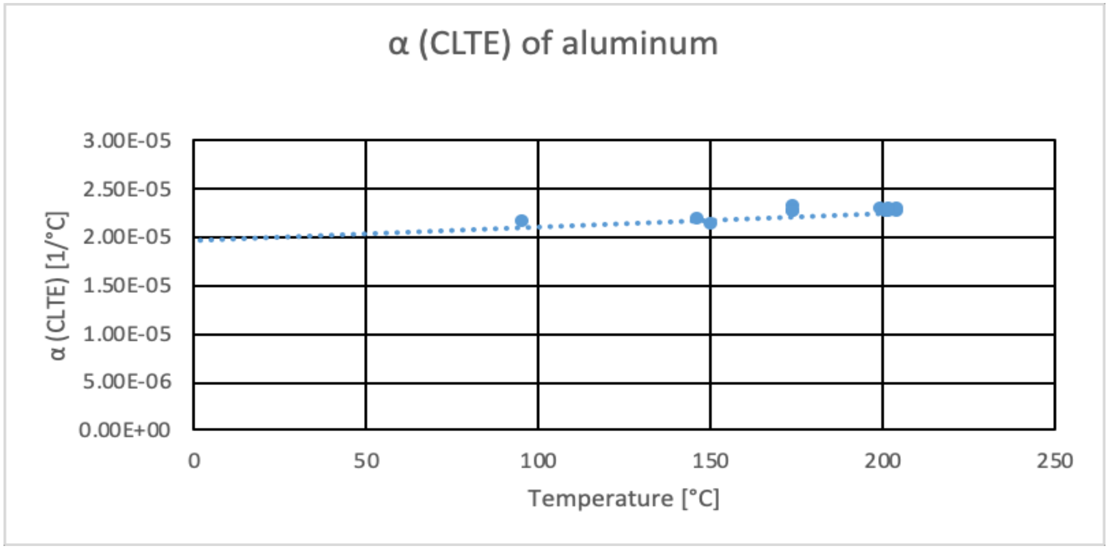

Figure 6: CLTE of the aluminum measured with the novel apparatus.

4.3 Sandstone

For sandstone, some literature such as The Engineering Toolbox (2003) gives a value of 1.16E-05 [1/℃] for temperatures at 25 ℃ (77 ℉) whereas a study conducted by Feng et al (2020) presented a CLTE value of 1.84E-05 [1/℃] in a temperature range of room temperature to 600 ℃. Nonetheless, it is important to remember that values may vary depending on different factors present in the rocks, such as anisotropy, size of the grains, and degree of bonding (Feng et al., 2020). The values obtained with the apparatus are shown in figure 7. It can be seen from the following figure that constant CLTE values were obtained when the temperature was within the range of 150 to 200°C and are closer to the values from the literature.

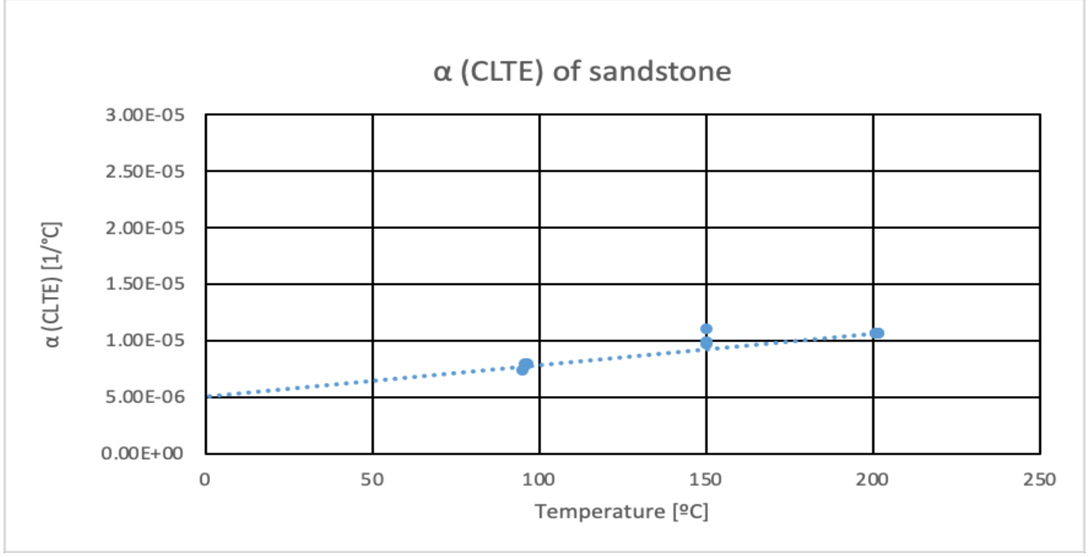

Figure 7: CLTE of sandstone measured with the apparatus.

4.4 Cement

The mixture prepared in the laboratory for the cement test was Class H cement with 10% sand. The CLTE was measured and is shown in figure 8. It can be seen that for the Class H cement plus 10% sand, depending on the temperature the CLTE goes up to 8.6E-06 [1/ºC]. The value is within the range of the value of 8.8E-06 [1/ºC] obtained by Loiseau (2014) in a cement/silica mixture in which he used 40 % silica by weight of cement class G. This mixture is the most common system used for high-temperature-cement applications according to Loiseau (2014). Besides that, Loiseau (2014) also measured the CLTE of neat class G as a reference and obtained the value of 9.10E-06 [1/ºC], which is still close to the values observed in this research with Class H cement plus 10% sand.

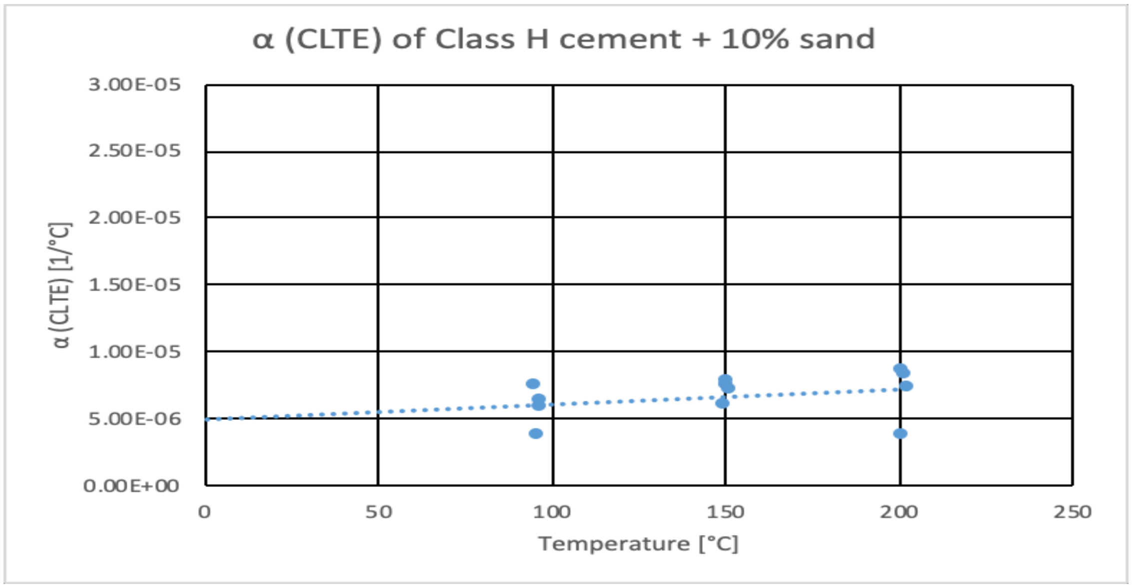

Figure 8: CLTE of Class H cement plus 10% of sand, measured with the apparatus.

5. DISCUSSIONS

Although, our preliminary tests are limited, we can easily show that the cement and rock samples are showing large variations between testing. The reason of these variations in case of cement can be attributed to the fact that the cement hydration may still be ongoing during heating cycles and thus could result in variations of the CLTE. Furthermore, both rock and cement are porous materials, with air trapped within their pore space, which may result in these variations. This can be seen when the R2 are calculated for all samples as shown in figure 9, cement showing the lowest R2 possible value. We assumed that all CLTE will vary linear with and thus all trendlines are linear. Xie et al 2016, have presented a study steel showing that metals are expected to show a linear relationship between CLTE and temperature. Unexpectedly, the sandstone shows a good R2 results when compare among all results. We are currently continuing to perform additional measurements on various Aluminum and Brass samples as well as at various temperatures, and it is to believe that the R2 values will get improving. Interesting is the CLTE for sandstone and cement seems closer and both are similar at lower temperatures (which are backward forecasted only but not measured). Also, it should be noted that most common reporting of CLTE is at 25°C. This is one reason why our measured values are showing slightly higher values than reported.

Also, since our method is testing the samples in steps, we expect that material inhomogeneity will induce a hysteresis behavior that is currently under investigations. To compensate for this, we are preparing two different testing procedures:

- Step up and down method (where the samples are heated in small steps and the expansion is measured after temperature stabilization)
- Cyclic methods (where the samples are heated to the desired temperature, then cooled down to room temperature, then heated again to the next temperature level)

While the second method was used for this paper, we noticed that two much thermal cycles may overload some samples. These investigations are currently ongoing.

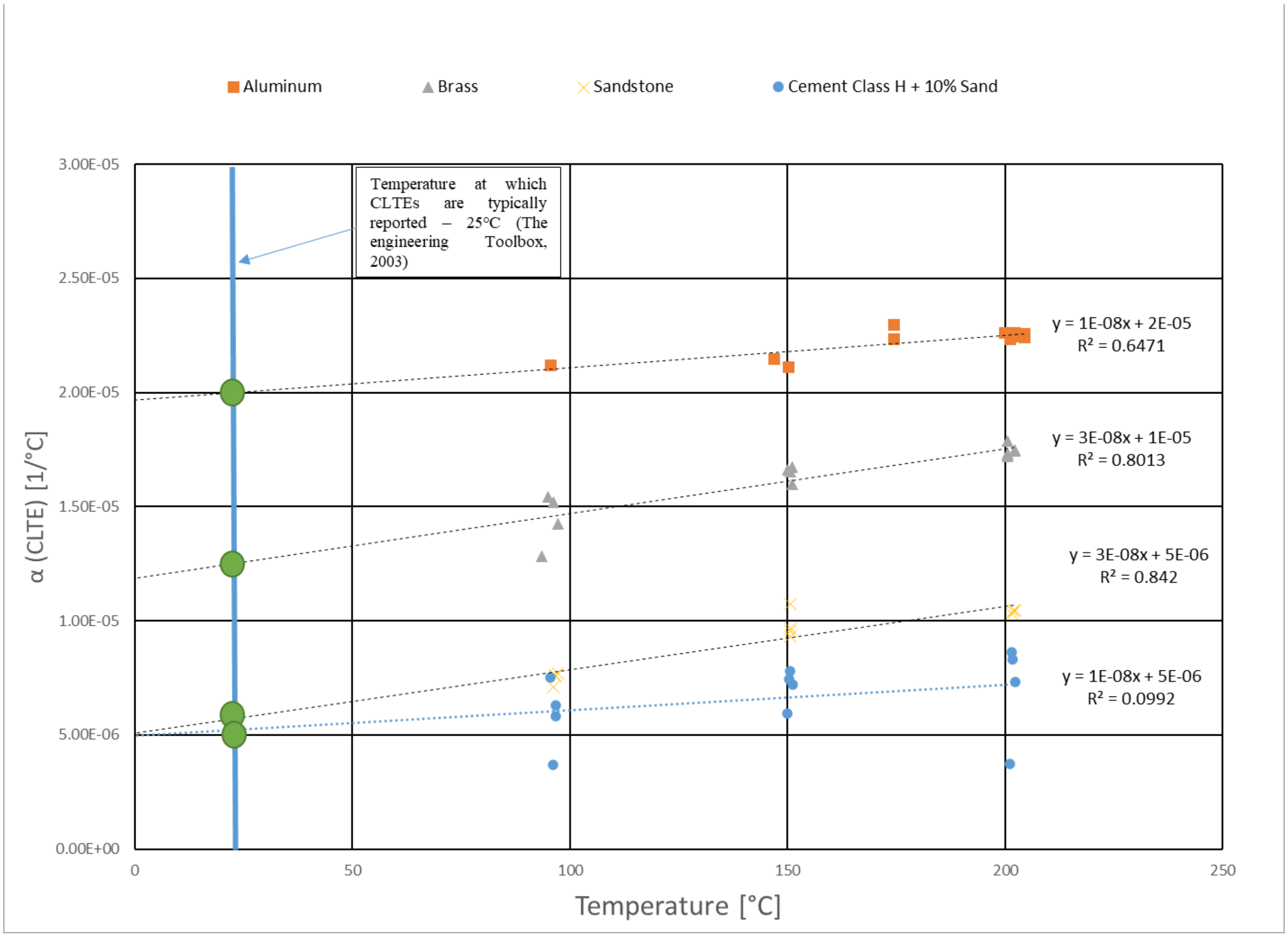

Figure 9: R2 calculated for all samples and the typically reported CLTE temperature.

6. CONCLUSIONS

The coefficient of linear thermal expansion is an important property that needs to be measured to assure the integrity of the geothermal well. Therefore, the measurement of this thermal property must be performed and taken into consideration, especially since it can affect both the casing and the cement sheath. Current data seems to be very scarce for downhole materials that could highlight the geothermal well integrity.

The novel apparatus in this study uses laser shadowing for the measurement of CLTE and it is designed to measure cylindrical samples at a relative low cost and fast testing time. The apparatus showed excellent with good repeatability results for metals, rock, and cement samples as the results obtained from this apparatus were in line with the values found in the literature.

In the case of cement and rock, some factors affect the results of CLTE, but this apparatus still proved its accuracy in the determination of thermal expansion property.

We are currently testing a wide range of wellbore cements and rocks in order to update the OU cement repository database with accurate thermal expansion data sets.

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