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Impact of Temperature Variation on the Coefficient of Thermal Expansion of Noriterock from South African Platinum Mines in Confined Conditions

G. O. Oniyide
Department of Mining Engineering, Federal University of Technology, Akure, Ondo State, Nigeria
Corresponding Author: G. O. Oniyide

ABSTRACT: *This paper presents the results of the study on the impact of temperature variation on the coefficient of thermal expansion of noritefrom the South African platinum mines. The thermal expansion coefficients were measured at varying temperature and the constant pressure of 10 MPa. These mines are witnessing increasing temperatures with higher depth due to the high-temperature gradient. The experiment on the rock samples was done using a special set up comprising a variac, oven, digital thermometer, digital video extensometer, etc. under varying temperatures (20 to 140°C). The results of the laboratory tests show that the coefficient of linear thermal expansion increases with increasing temperature for all the samples. The tests also show that temperature has an influence on the failure of crack generation and extension, which caused expansion of rocks. It is an indication that as mining depth increases in platinum mines, there is a possibility of an increase in tensile failure, which is not only a product of increased in-situ stresses but temperature. The future design of deeper and hotter mines would also hugely benefit from the knowledge of rock's response to thermal stresses derived from laboratory tests.*

KEYWORDS: *Temperature testing, thermal expansion, platinum mines*

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I. INTRODUCTION

Increasing the depth of mining in underground mines brings about the challenges related to heat, in-situ stresses, and logistical issues. Heat associated problems have mainly focused on the side effect of heat on workers' health (heat-stroke), increasing production costs as a result of the higher cost of ventilation due to cooling and refrigeration. The effect of increasing temperature with increasing depth on the behavior of rock has not been given much consideration.

The platinum mines are in the Bushveld Igneous Complex (BIC), which is located in the northern part of South Africa. The BIC is the world's largest layered intrusion. It is about seven to nine kilometers thick and is divided into eastern, western and northern limbs. Its upper critical zone hosts the world's largest deposit of platinum group elements (PGE), (Schouwstra and Kinloch, 2000). Geological exploration information revealed the possibility of the platinum mines going for ultra-deep mining in the future. Schouwstra and Kinloch (2000) stated that the Merensky Reef has been traced for 300 km around the entire outcrop of the eastern and western limbs of the BIC, and to depths of 5km and beyond.

Gold mines in South Africa are generally deeper than the platinum mines, however, the latter has higher temperature gradient, which makes the platinum mines to be much warmer as the depth of mining increases. Biffi et al (2007) made a comparison of the geo-thermal gradient of the Witwatersrand Basin complex known by its gold mining and the BIC and reported that a virgin rock temperature of 40°C will be reached at an approximate depth of 650 m in the BIC as compared to a depth of about 1800 m in the West Witwatersrand Basin complex. The study of the effect of temperature on the rock behaviour would be beneficial to both gold and platinum mines, however, the main focus of the research is on the platinum mines due to their higher temperature gradient. Donoghue (2004) stated that the virgin rock temperatures (VRT) and air temperatures increase with depth, due to the geothermal gradient and auto-compression ofthe air column. Figure 1 shows the comparison of the VRT, while Figure 2 shows the VRT for the mines in BIC.

Cawthorn (1999) proposed adapting the knowledge from deep mining on the gold-bearing Witwatersrand mines to platinum mines. He, however, noted that higher temperatures would be an additional factor that would influence the platinum mines as they go deeper. In consideration of possible problems that would result from high stresses and high temperatures in deep platinum mines in the future, investigation of the influence of thermal stress on the rock behaviour becomes necessary from a rock engineering perspective. This paper therefore evaluates the temperature on the thermal expansion of rocks from the Bushveld complex.

1.1 Thermal properties of rocks

Mares and Tvrdy (2011) stated that the flow of heat is from the Earth's interior to the surface. The sources of this heat are:
(a)the decay of radioactive elements (radiogenic heat)
(b) geothermal exothermic reactions by the compression of the overlying beds (gravitational heat)
(c) tectonic movement and absorption of seismic wave energy."

The above-stated sources are the sources of heat within the earth prior to interference by mining activities. Hartman *et al*. (2012) listed the contributors of heat in the underground mines as auto-compression, wall rock, underground water, mine machinery and lights, human metabolism, oxidation, blasting, rock movement, and pipelines. Payne and Mitra (2008) gave the percentage contributions of the sources as shown in Figure 1.

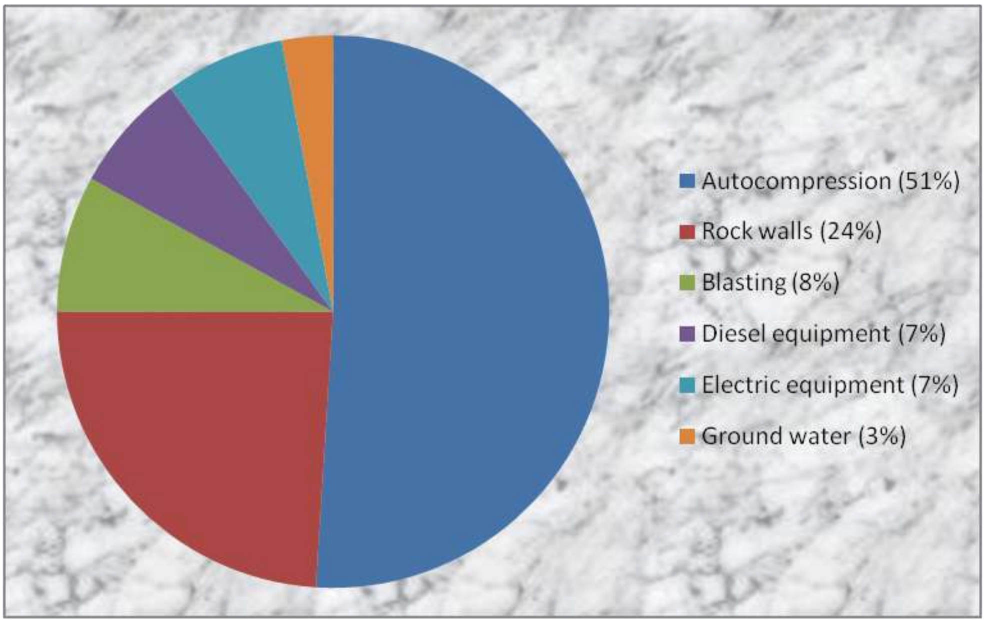

Figure 1: Percentage contributions of heat sources in underground mines (Payne and Mitra, 2008)

Different heat sources contribute to the heat load in the underground mines. The accumulated heat from these sources is reduced to underground working temperature (approximately 27°C) through ventilation for worker's comfort. The ventilation of the mine openings will lead to a cooling of the excavation skin, while the inner part of the rock remains hot. This results in temperature differential between the surface and the rock interior. The process of cooling of the warm rock occurs at different magnitudes at different depths due to varying virgin rock temperatures.

Clauser and Huenges (1995) explained that the interior heat of the earth is transmitted to its surface by conduction, radiation, and advection. Conduction refers to the transfer of heat energy directly from atom to atom along a temperature gradient. It can be in gas, liquid or solid state. The transfer of heat energy by the vertical movement of a mass of gas or liquid is called convection. Radiation, on the other hand, refers to the transfer of heat energy across the empty void of outer space. In an underground working environment, heat radiates from the walls of the rock into the excavated void, cooling of the openings occur through convection and advection, while the movement of heat energy from the rock interior to the cooled surface is through conduction.

Coefficient of thermal expansion is an important parameter that is used to evaluate the response of rock to variation in temperature. It can be linear or volumetric. The linear coefficient of thermal expansion, α, is the ratio of change in length to the original length per unit of temperature change, as expressed in Eq.(1).

$$\alpha = \frac{\Delta l}{\Delta T} \cdot \frac{1}{l} \quad (1)$$

Where,
Δl = change in length of the rock specimen
ΔT = change in temperature
l = original length of the rock specimen

Equation (2) gives the volumetric coefficient of thermal expansion, β, which is the ratio of change in volume to the original volume per unit of temperature change, as expressed in Eq.(2).

$$\beta = \frac{\Delta v}{\Delta T} \cdot \frac{1}{v} \quad (2)$$

Where,
Δv = change in volume of the rock specimen
ΔT = change in temperature
v = original volume of the rock specimen.
Huotari and Kukkonen (2004) stated the relationship between the linear and volumetric coefficient of thermal expansion as (Eq. (3)):

$$\beta = 3\alpha \quad (3)$$

According to Siegesmund*et al.* (2000), thermal expansion of rocks is influenced by properties such as mineral composition, texture, porosity, properties of the fluid in pores, micro-cracks, pressure, and temperature.

Wong and Brace (1979) studied the effect of confining pressure on the coefficient of thermal expansion of quartzite and limestone. They affirmed that the coefficient of thermal expansion decreases with increasing confinement as shown in Figure 2.24. This is due to higher confining pressures that impede crack formation and extension.

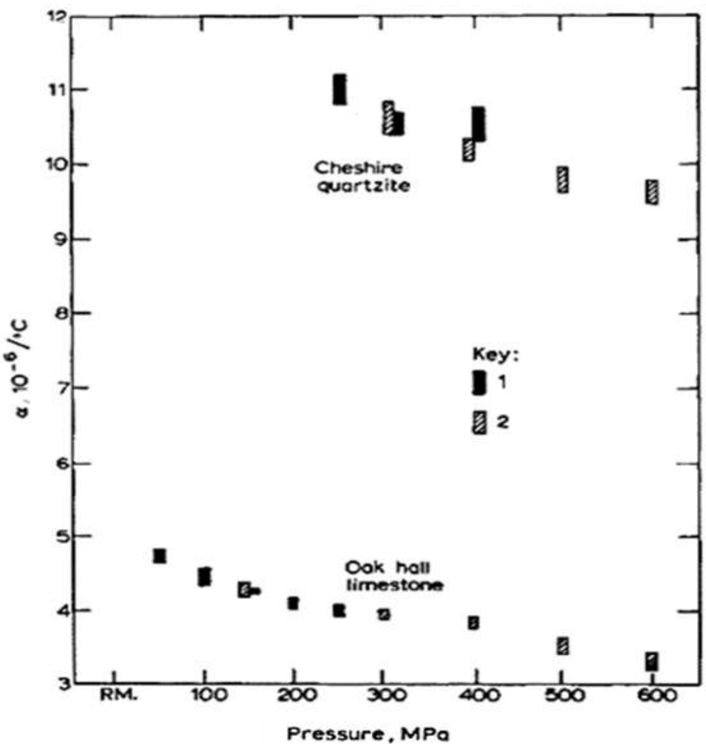

Figure 2: Influence of confining pressure on thermal expansion- when pressure was (1) decreased and (2) increased (Wong and Brace, 1979).

From Figure 2, it is observed that though higher confining pressure caused a reduction in the coefficient of thermal expansion, however, the effect is insignificant, except at higher pressure, above 600 MPa. For example, a pressure increase of 100 MPa only yields a 5% reduction in the coefficient of thermal expansion.

Cooper and Simmons (1977) explained that changes in temperature result in two types of cracks: (a) thermal cycling cracks generated due to inhomogeneous strain by the mismatch of thermal expansion boundaries, (b) thermal gradient cracks produced due to inhomogeneous strain resulting from differential temperature. Table 1 shows the effect of temperature on the coefficient of linear thermal expansion, α, of some rocks. It is obvious from the table that the values of α increase when tested at higher temperature range, that is 35-60°C, except for porfyric granodiorite. Table 2shows the volumetric and linear thermal expansion coefficient of some rocks. Looking at the values of α in Tables 1 and 2, it is observed that the α may vary within the rock types in the igneous, sedimentary or metamorphic rocks. Huotari and Kukkonen (2004) explained that such variation may be attributed to changes in texture, constituent minerals, mineral proportions, pore space, grain sizes, the orientation of minerals and fractures.

Table 1: Thermal expansion of some rocks with increasing temperature (Kjørholt, 1992)

The average coefficient of linear thermal expansion, α (10^{-6} per°C)				
Rocks	***Rock type***	***10-35°C***	***35-60°C***	***10-60°C***
Tonalite gneiss	*Metamorphic*	*6.6*	*9.7*	*8.1*
Mica gneiss	*Metamorphic*	*8.2*	*10.9*	*9.5*
Tonalite	*Igneous*	*6.6*	*8.8*	*7.7*
Porfyric granite	*Igneous*	*7.3*	*10.4*	*8.8*
Porfyric granodiorite	*Igneous*	*9.3*	*8.1*	*8.7*

Table 2: Volumetric and linear thermal expansion coefficient of some rocks (Robertson, 1988)

Rocks	***Rock type***	***Volumetric thermal expansion coefficient β (10^{-5} per °C)***	***Linear thermal expansion coefficient α (10^{-6} per °C)***
Granite, Rhyolite	*Igneous*	*2.4*	*8.0*
Diorite, andesite	*Igneous*	*2.1*	*7.0*
Gabbro, basalt	*Igneous*	*1.6*	*5.3*
Sandstone	*Sedimentary*	*3.0*	*10*
Limestone	*Sedimentary*	*2.4*	*8.0*
Marble	*Metamorphic*	*2.1*	*7.0*
Slate	*Metamorphic*	*2.7*	*9.0*
Quartzite	*Metamorphic*	*3.3*	*11*

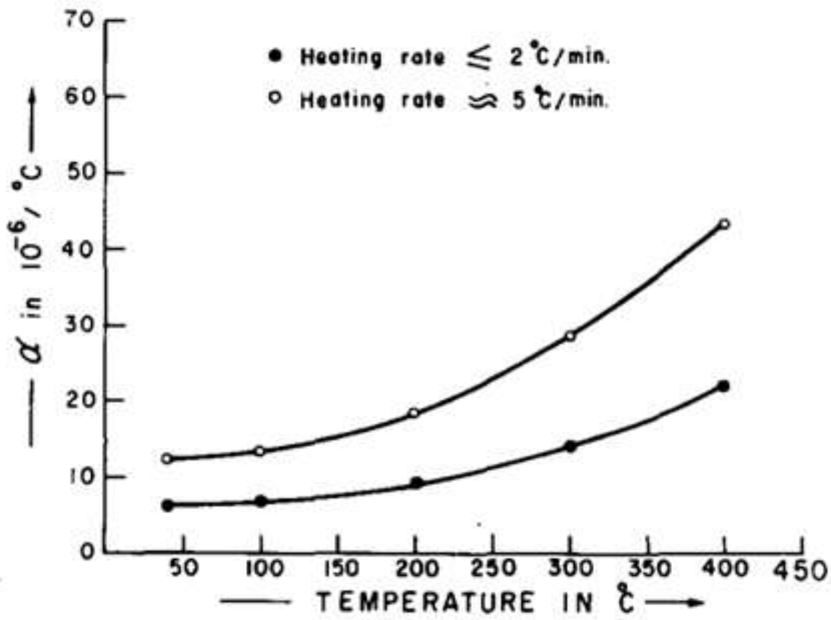

Figure 3: Effect of temperature and heating rate on the coefficient of thermal expansion of granite (Ramana and Sarma, 1980).

Figure 3 shows that α increases with increasing temperature. It also shows that heating rate has a significant influence on the expansion of rocks. According to Richter and Simmons (1974), thermal expansion of rock is affected by heating rate and the presence of micro-cracks in the sample. They suggested that heating rates not greater than 2°C/min is required for precise measurement of thermal expansion to eliminate cracking due to stress produced by a thermal gradient.

2. Measurement of the coefficient of thermal expansion

According to Battaglia*et al*. (1993), thermal expansion of rocks can be measured through static or dynamic testing methods. In a static procedure, the specimen is heated up to the temperature of interest and kept constant for a certain time until thermal equilibrium is achieved. The variation of length that takes place during the passage from one temperature to the other is subsequently recorded. In a dynamic procedure, the temperature is varied continuously and the variation of length is simultaneously measured.

Some of the methods of thermal expansion measurement, as given by Wong and Brace (1979), are dilatometer, interferometric, optical comparator, and X-ray diffractometric methods. Several investigators (Battaglia*et al*., 1993; Huotari and Kukkonen, 2004; Richter and Simmons, 1974) used dilatometers to study linear or volume change of rocks in experiments for determination of coefficient of thermal expansion. Huotari and Kukkonen (2004) explained that the measuring system of a dilatometer consisted of a furnace, thermocouple, sample holder and a linear variable displacement transducer (LVDT).

In this research, the heating rate of 2°C/min was used for the determination of the linear coefficient of thermal expansion.

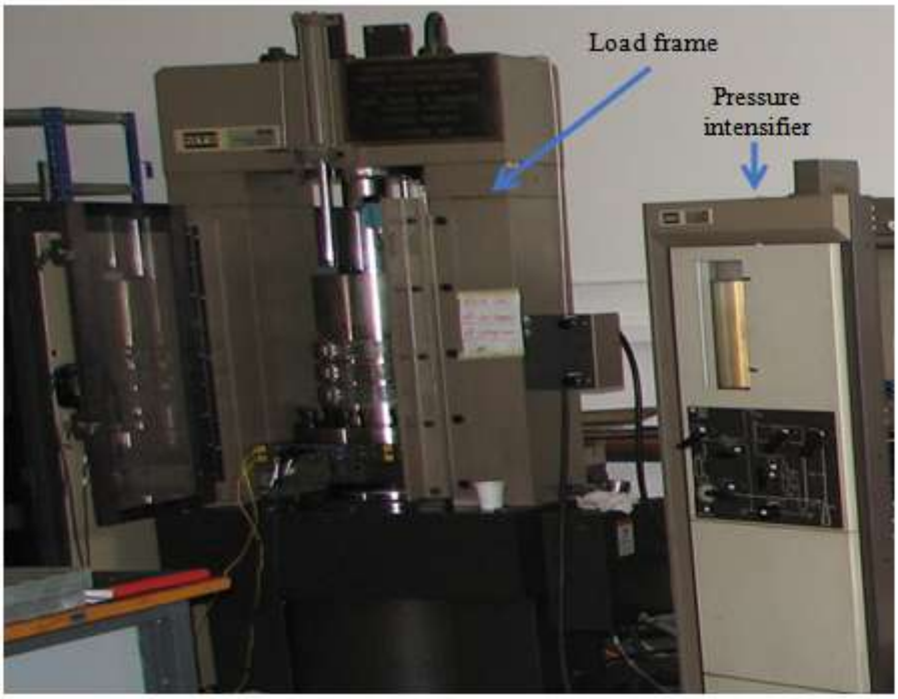

Figure 4: Servo-controlled testing machine and pressure intensifier

The triaxial cell assembly (Figure 4) is used to simulate in-situ rock conditions, in terms of stresses and temperature on rock specimen in order to investigate the effects of changes to these factors. The features of the MTS 793 triaxial cell includes; hydraulic lifts for easy and quick raising and lowering of the cell, in-vessel spherical seats for proper specimen alignment, confining cell with a capacity of 140 MPa, heating element and temperature control package for simulation of in-situ temperature from -10°C to +200°C. The range of temperature used for this research was between ambient (approximately 20°C) and 140°C. The extensometers are limited to operate at a maximum operating temperature of 150°C (MTS, 2001). The pressure vessel, when lowered onto the base plate forms a sealed pressure chamber for the specimen and extensometer assembly. Ten cap screws hold the pressure vessel to the base plate. The extensometer cables connect to the feed-through in the base plate (Figure 5).

Figure 5: Parts of MTS servo-controlled triaxial cell

Two types of extensometers were used. The axial extensometer measures strain over clearly defined gauge length. The axial extensometer used is MTS 632.90F (Figure 2.31), that has an axial gauge length of 50 mm. Its extension range is between 0.1 mm/mm and -0.05 mm/mm. Jacket effect was minimized through the use of heat-shrink Teflon jackets. The second extensometer is of the circumferential type used for measuring the overall circumferential strain (Figure 6). It has a capacity of extending by 15%. Both the axial and the circumferential extensometers are attached to the specimen before the pressure vessel is lowered as shown in Figure 6.

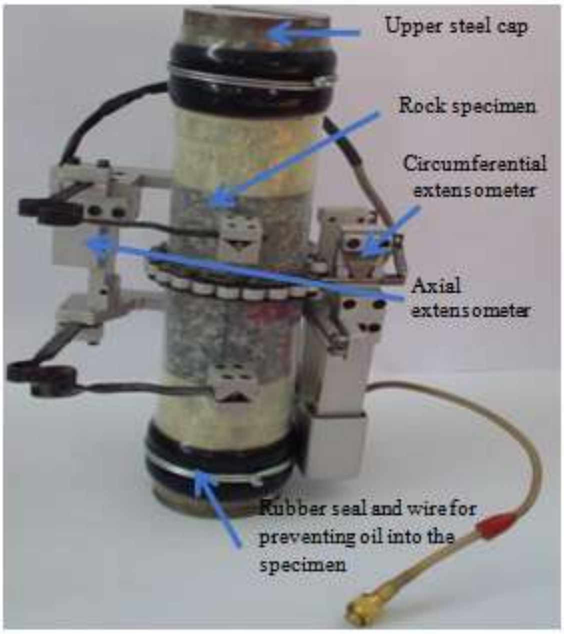

Figure 6: Axial and circumferential extensometers attached to Norite specimen – ready for testing.

3. Results and Discussion of the linear coefficient of thermal expansion test

Figure 7 shows the plots of axial thermal strain measured in a confined condition (10 MPa confining pressure), using MTS machine, as a function of temperature for norite.

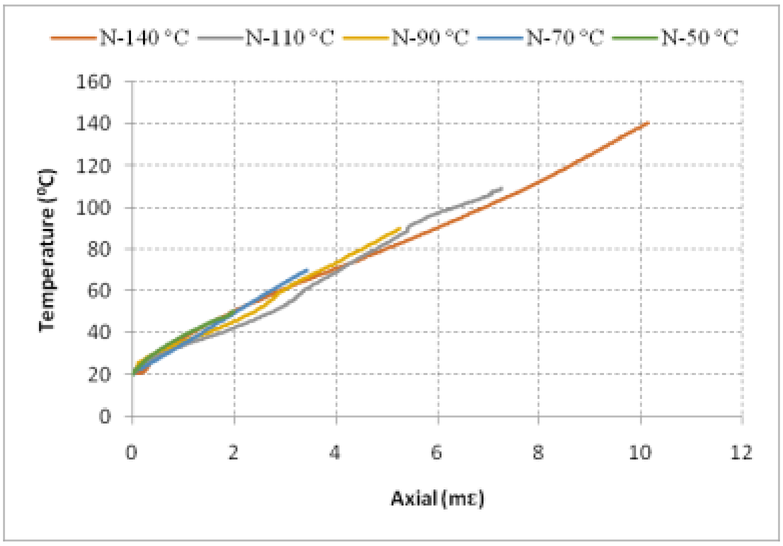

Figure 7: Plot of temperature versus axial stain for norite under 10 MPa confinement

Figure 7 shows a linear relationship between temperature and extension of the rock specimen. Five norite specimens were heated from ambient temperature (~20°C) to 50°C, 70°C, 90°C, 110°C, and 140°C as seen in Figure 7. Both axial and radial expansions of the rocks were noticed with increasing temperature. Only the axial strain is presented in Figure 7 since it is the required parameter for the calculation of the coefficient of linear thermal expansion (CLTE). The peak values of the axial thermal strain, when the desired temperature is reached, are used as input for the calculation of CLTE.
The CLTE of the samples at different temperatures is calculated using Eq. (1).
Below is a typical example of the CLTE calculation for the tested rock type.

Thermal strain at 110°C = -0.00078200 (-ve sign means expansion)
Initial temperature = 20.2°C
Final temperature = 110.1°C
Change in temperature = (110.1-20.2)°C = 87.9°C
Therefore,

$$\alpha_l = \frac{|-0.0007820|}{87.9} = 8.9\ x\ 10^{-6}$$

Figure 8 shows the plot of CLTE versus temperature for norite samples tested.

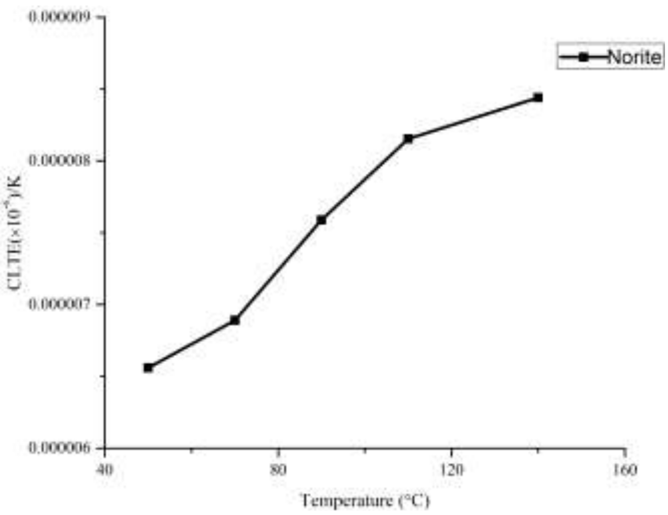

Figure 8: Plot of CLTE versus temperature for all rock types

Figure 8 clearly shows that there is a linear relationship between temperature and CLTE. The values of CLTE are input parameters into numerical modelling. For all the specimens tested, as seen in Figure (8), the range of CLTE values is very narrow, particularly at 90° and 110°C. This is not surprising since rocks are igneous. It was seen from the reviewed literature that variation of CLTE could be possible within the same rock type, however, there could be exceptions as well. The notable difference in the values of CLTE for different rocks at 50°, 70°, and 140°C could be attributed to the variation of the mineral constituents of rocks.

II. CONCLUSION

The study investigates the impact of variation in temperature on the coefficient of thermal expansion of the norite rock obtained from the platinum mines in South Africa. The results of the study show that the temperature varies linearly with both axial strain and the coefficient of thermal expansion, indicating that the temperature influences the deformation properties of the rock and hence influence the stability of the mine and the behaviour of the rock.

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