American Journal of Engineering Research (AJER)
e-ISSN: 2320-0847 p-ISSN : 2320-0936
Volume-8, Issue-5, pp-250-257
www.ajer.org
Research Paper Open Access

Influence of Temperature and Loading on Sonic Velocity of Bushveld Rocks

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

ABSTRACT: *This paper presents the analyses of a study on the influence of temperature and loading on the sonic velocity of rocks from the Bushveld Igneous Complex (BIC), South Africa. The BIC has higher virgin rock temperature (VRT) than the gold mines 'Witwatersrand Basin Complex'. The platinum mines in future can also advance ultra-deep levels as the gold mines are now since the Merensky Reef has been reported to extend beyond 5 km, then the virgin rock temperature at a depth of 5 km will be approximately 140ºC. As mines go deeper, underground excavations are subjected to increase internal stresses and temperature. Hence, there is a need for the investigation on the behaviour of rock with respect to temperature and stress variation.*

KEYWORDS*: Temperature, Loading, Sonic Velocity, Bushveld Rocks*

Date of Submission: 07-05-2019 Date of acceptance: 24-05-2019

I. INTRODUCTION

Ultrasonic measurement, which is a non-destructive method, has been used for various studies such as, determination of rock dynamic elastic constants (Soroush and Qutob, 2011), degree of rock weathering (Kahramanet al, 2007), blasting efficiencies in rock mass (Young et al. 1985) and rock mass characterization (Bery and Saad, 2012; Klose et al, 2007). Sound velocities of rocks are influenced by factors such as rock type, elastic properties, texture, density, porosity, anisotropy, confining pressure, grain size and shape, water content, temperature, weathering, alteration zones, microcracks, bedding planes, and joint properties (roughness, filling materials, water, dip and strike (Altindag, 2012; Kahramanet al, 2007).

The longitudinal/compressional (P-wave) and transverse/shear (S-wave) velocities are calculated from the transition time of a traveling elastic pulse measured along the axis of a cylindrical core specimen with parallel end faces. Aydin (2014) classified the techniques of generating sound waves and detecting their propagation through solids into two. The first technique involves the use of a single transducer, which he called the pulse-echo technique, while the second technique, called pitch-catch technique, uses a pair of transducers (transmitter and receiver). In this research, the pitch-catch technique was used in examining the influence of temperature on P- and S-wave velocities of BIC rocks.

A typical layout of important ultrasonic testing components is shown in Figure 1 The components include a signal generator, an oscilloscope for visual analyses of the waveform, amplifier for signal enhancement, a data acquisition unit and two transducers (Aydin, 2014).

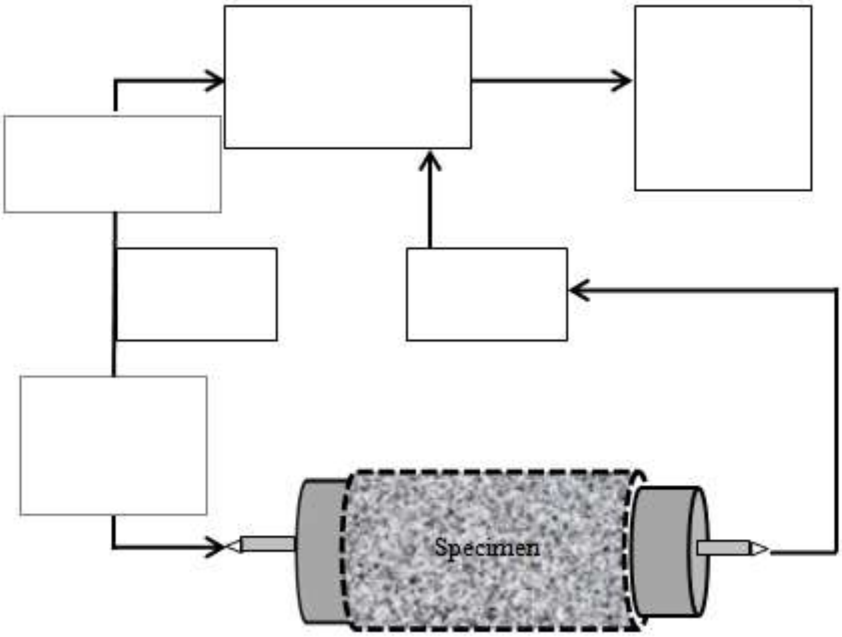

Figure 1: Layout of essential components of an ultrasonic apparatus (adapted from Aydin, 2014).

In order to achieve good test results, Aydin (2014) suggested the following:

(1) The test specimen's surface should be smooth, flat, parallel and should be measured at several points with a precision of ±0.01 mm.

(2) A thin layer of coupling material, such as Vaseline, oil, should be used to ensure efficient and uniform energy transfer from/to transducers.

(3) Transducers should be positioned and aligned to produce an acoustic axis (center beam), that is, normal to both faces.

(4) When the transducers are manually coupled, the travel times should be measured at least three times applying different pressures.

2.8.1 Calculation of P- and S-wave velocities

The P-wave velocity (V_p) and S-wave velocity (V_s) are determined from (ISRM, 2014)

$$V_p = L/t_p \quad (2.18)$$

and

$$V_s = L/t_s \quad (2.19)$$

Where L is the travel path length, tp, and t_s are travel times for P- and S-waves, respectively.

Setyowiyoto and Samsuri(2009) demonstrated that increasing temperature caused a reduction in the values of both P and S velocities. They reported that the P and S velocities of carbonate rock decreased from 3910 m/s to 3480 m/s and from 1965 m/s to 1780 m/s respectively when temperature increased from 28.47° to 57.10°C. Figure 2.40 shows the elastic wave velocities (Vp and Vs) as a function of temperature for three pore fluid conditions (without pore fluid, with Argon gas-filled, and with water-filled). In all of the three conditions, the elastic wave velocities decreased linearly with increasing temperature.

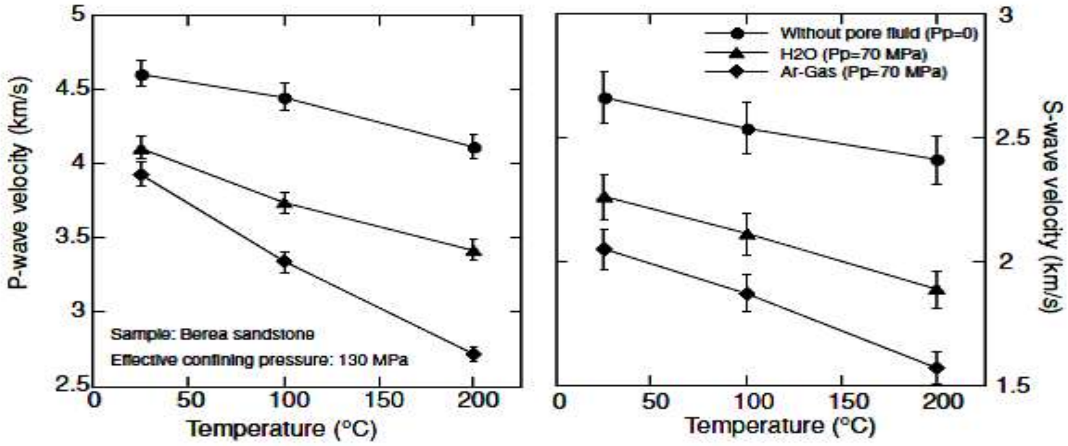

Figure 2: Influence of temperature on P- and S-wave velocities (Kitamura et al, 2006)

Confining pressure generally increases the wave velocities (Figure 3). He and Schmitt (2006) plotted the experimentally measured and Gassmann's equation calculated P- and S-wave velocities on a dry and water saturated sample. They explained that microcracks are not only playing an important role in controlling the pressure dependence of velocity, they also have a large effect on fluid substitution. Setyowiyoto and Samsuri (2009) also explained that an increase in pressure causes compaction, porosity reduction and increase in ultrasonic wave velocities.

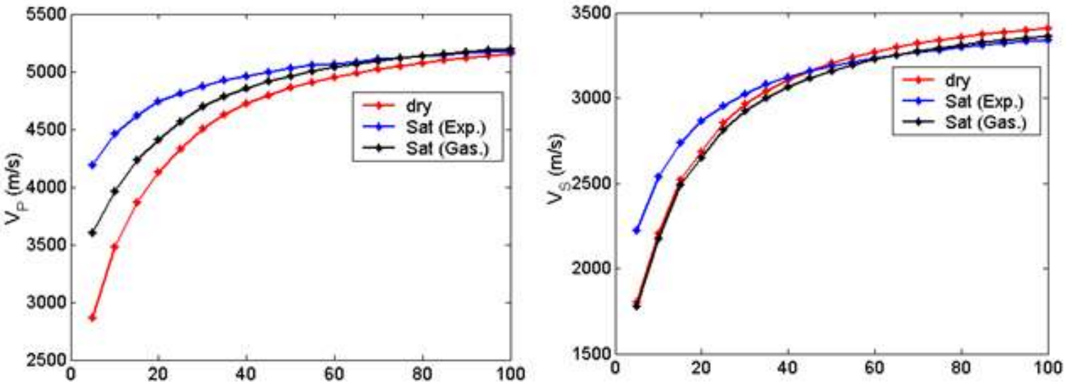

Figure 3: Influence of confining pressure on P- and S-wave velocities (He and Schmitt, 2006)

Figure 4 shows that velocity is strongly dependent on rock porosity. Setyowiyoto and Samsuri (2009) reported an inverse trend in the relationship between velocity and porosity. For example, when the porosity of some carbonate rocks increased from 5% to 20% acoustic velocity decreased from 4500 m/s to 2000 m/s.

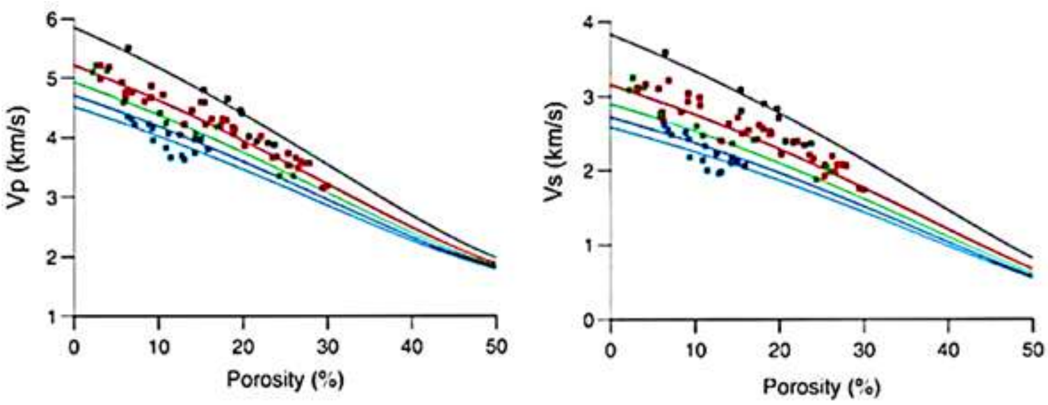

Figure 4 Influence of porosity on P- and S-wave velocities (Paoletti, 2012))

Fortin et al (2011) measured the axial and radial seismic velocities in a triaxial experiment on Etna basalt at confining pressure of 20 MPa. The plots of deviatoric stress versus axial strain and P- and S-wave velocities versus axial strain are provided in Figure 5. As Figure 5 shows, V_p-axial is higher than V_p-radial. V_p-radial as well as V_s-horizontal decrease with increasing axial loading. These observations were attributed to crack initiation and propagation.

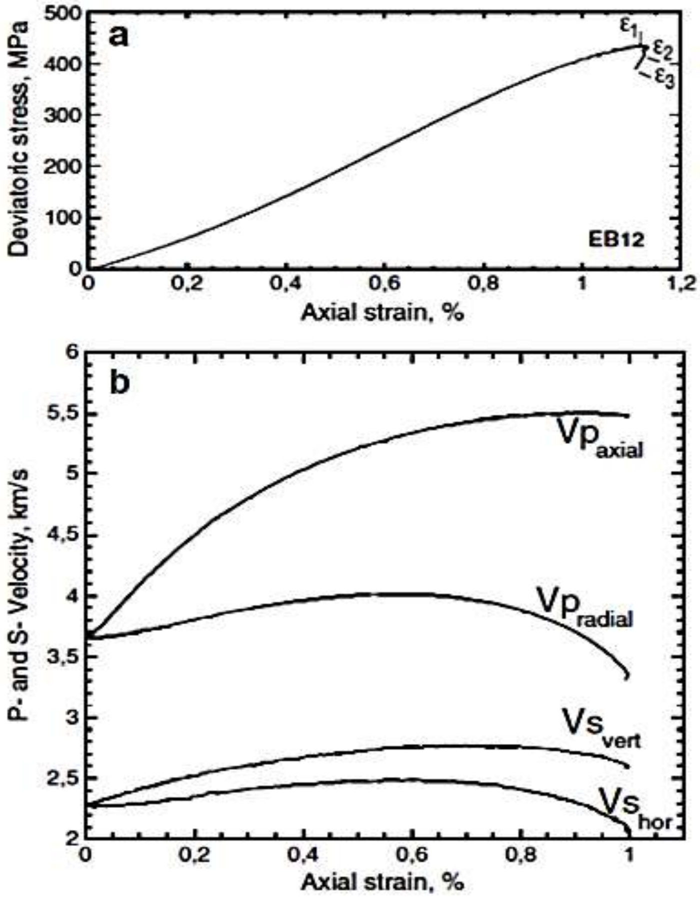

Figure 5: (a) Deviatoric stress versus axial strain (b) P- and S-wave velocities versus axial strain for Etna basalt. (Fortin et al, 2011).

II. MATERIALS AND METHOD

The rock samples tested were obtained from four different mines located in the northern and the western limb of the BIC. The mines and the samples obtained are summarized in Table 1.

Specimen preparation

The specimens were prepared according to the ISRM standard. The test specimens were prepared with a height to diameter ratio of 2.5. The ends of the specimen were cut and ground parallel to each other, and at a right angle to the longitudinal axis. The disparity between the perpendicular ends of the specimen to its longitudinal axis was not more than 0.05 in 50 mm.

Two types of non-destructive tests were carried out on nine BIC rock types to examine their response in terms of their P-wave velocity (V_p) and S-wave velocity (V_s). The first test is the temperature test, where the temperature is increased from approximately 20°C to 140°C. The second test is the compression test, in which the P- and S-wave velocities are determined with axial stresses of 10, 20 and 100 MPa on the specimens. The diameter of all the test specimens is 42 mm while the lengths vary. Both tests were done individually on the same specimen. In order to ensure efficient and uniform energy transfer from/to transducers, lubricating oil was applied to the ends of the specimens prior to placement in between the transducers.

Temperature-ultrasonic tests

The dimensions and mass of the specimens were measured and recorded (Table 1). The ultrasonic tests were firstly performed on the specimens prior to heating, to determine the P- and S-wave velocities in ambient condition. The experimental set-up is shown in Figure 6. After the ambient ultrasonic measurements, the specimens were kept for 2 hours in the oven at 145°C. It was not possible to position the transducers inside the oven and carry out the ultrasonic test for two reasons. Firstly, there was not enough space to allow coupling of transducers onto the specimens.

The second and more important reason is that cables of the transducers would have been affected by a high level of heat. Therefore, the specimens were taken out of the oven and immediately placed for ultrasonic measurement. Although, the oven is positioned close to the ultrasonic testing apparatus, (Figure 7), approximately 5°C is lost due to the movement of specimen and time interval required for measurements.

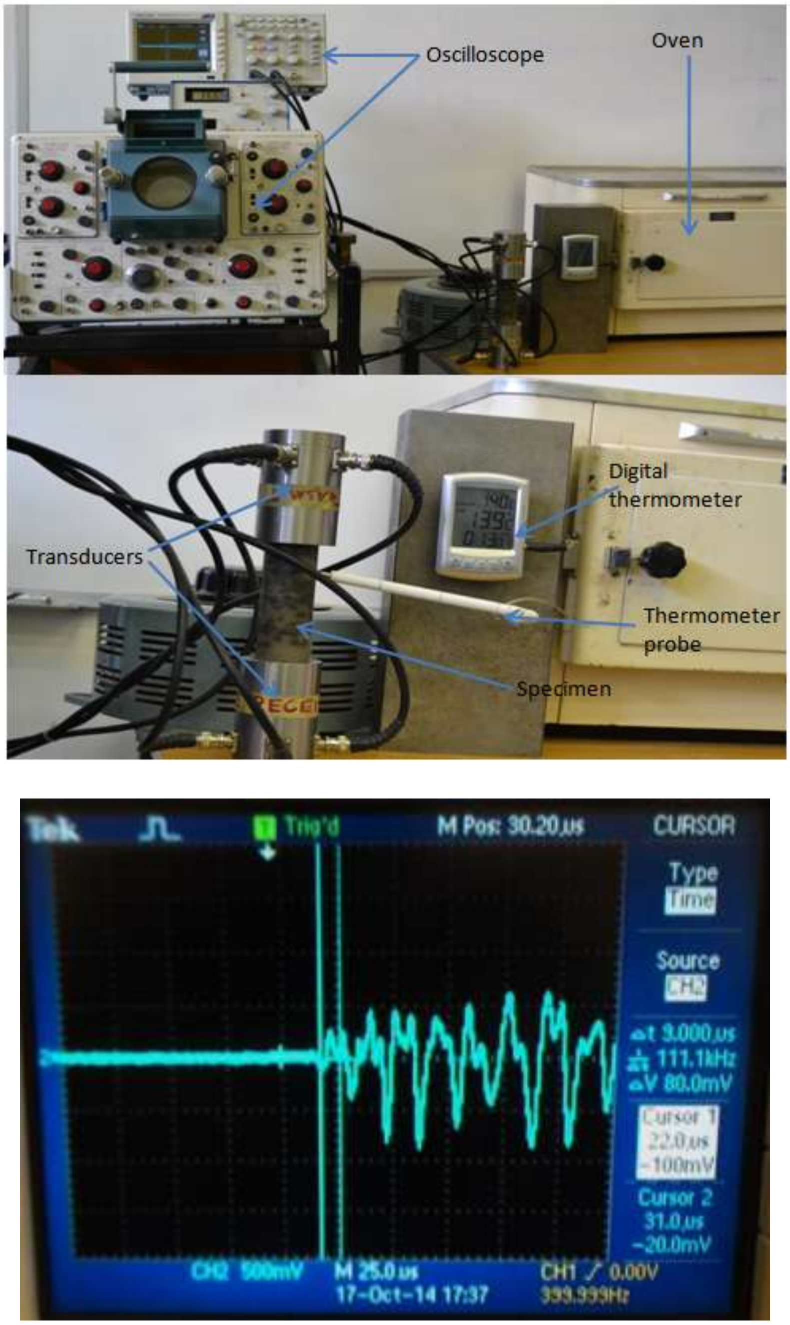

Figure 7: Sample screen shot of P-wave measurement at 140^{o}C for MA.

III. RESULTS AND DISCUSSION

The P- and S-wave velocities were calculated from the measured specimen lengths and travel times. Figure 7 shows a sample screen shot of P-wave measurement at 140°C for MA. The P- and S-wave travel times are provided in Table 1, while Figure 7 shows the plots of P- and S-wave velocities versus temperature.

Table 1: Specimen dimensions and velocities (temperature-ultrasonic tests)

Specimens	Diameter (mm)	Mass (g)	Length (mm)	P-wave		S-wave	
				V_{amb}(m/s)	$V_{140\,^oC}$ (m/s)	V_{amb} (m/s)	$V_{140\,^oC}$ (m/s)
CR	36.4	371.2	90.6	3020	2831	1294	1105
N	36.3	271.8	90.6	3356	3124	1485	1461
LN	36.0	265.1	90.6	3775	3624	1849	1536
GN	36.3	289.3	90.7	4535	4123	2212	1778
MA	36.2	265.9	95.5	4775	4341	1802	1647
G	36.4	256.1	95.0	3958	3800	2065	1863
GF	36.2	264.2	96.1	4004	3696	1961	1922
VTA	36.4	260.2	96.0	3556	3310	1745	1524
PX	36.2	294.9	90.5	3771	3352	1588	1534

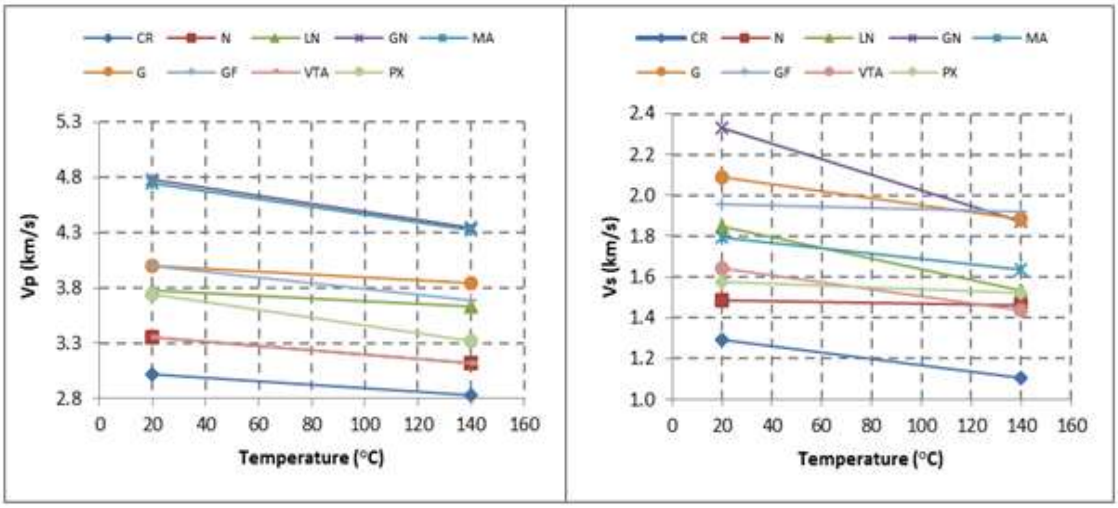

Figure 8: V_p and V_s versus temperature for temperature-ultrasonic tests

As observed in Table 1, the P- and S-wave velocities at ambient temperature are higher than at 140°C. This is attributed to the thermal expansion of the rocks. The expansion of rocks causes the further generation of micro-cracks, which results in the attenuation of waves. This attenuation delays the arrival of the ultrasonic signals. The increase in the wave travel time at 140°C translates to a reduction in the P- and S-wave velocities (Figure 8).

3.8.2 Compression-ultrasonic tests

The compression-ultrasonic tests were done by the use of ultrasonic test apparatus in the MTS servo-controlled testing machine (Figure 9). The specimens were axially stressed at 10, 20 and 100 MPa (which fall within 50 to 75% of the UCS of most rocks tested except for chromitite) to examine the effect of loading on the P- and S-wave velocities. The axial stresses applied to chromitite are limited to 10, 20 and 30 MPa due to lower UCS of chromitite. The tests were repeated three times and the average travel times are provided in Table 2.

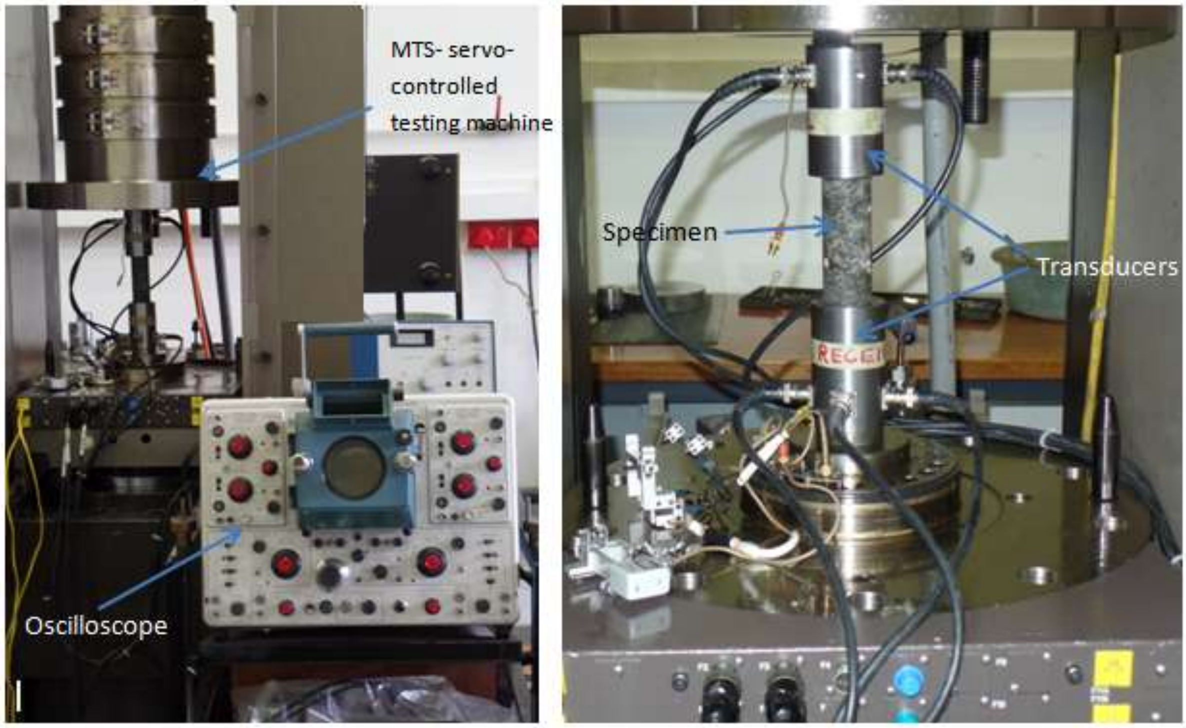

Figure 9: Experimental set-up compression-ultrasonic experiment.

As Table 2 shows, increasing axial stress results in the reduction of travel times. The plots of V_p and V_s versus axial stress for compression-ultrasonic tests are provided in Figure 4. It is obvious from these plots that V_p and V_s increase with increasing axial stress. This is caused by the compaction of the specimens along the direction of wave-velocity measurement due to the axial loading. As explained in the literature review section of this thesis, compaction lowers the arrival time and invariably increases wave velocities. It is noteworthy that the gradient of the graph (Figure 4) is higher between 10 and 20 MPa axial stress and reduces between 20 and 100 MPa. At lower axial stress, pre-existing microcracks and pores close up completely at the initial stages, as a result of the compaction and shortening of the specimen. The result is similar to the one obtained by Fortin et al (2011) although their test was under the triaxial condition with 20 MPa confining pressure.
Examining the results of the temperature-ultrasonic and compression-ultrasonic experiments, one can conclude that temperature and stress have a clear influence on P-, S-wave velocities. This would change the behaviour of rocks in the underground environment, particularly with increasing mining depth.

Table 2: P-and S-waves travel time for compression-ultrasonic tests

	P-wave						S-wave					
Specimens	**T_{p1} (µs)**	**V_{p1} (m/s)**	**T_{p2} (µs)**	**V_{p2} (m/s)**	**T_{p3} (µs)**	**Vp_3 (m/s)**	**T_{s1} (µs)**	**Vs_1 (m/s)**	**T_{s2} (µs)**	**V_{s2} (m/s)**	**T_{s3} (µs)**	**Vs_3 (m/s)**
CR	28	3236	27	3356	25	3624	65	1394	60	1510	55	1647
N	24	3775	23	3939	21	4314	50	1812	48	1888	43	2107
LN	20	4530	19	4768	17	5329	42	2157	40	2265	37	2449
GN	18	5039	17	5335	16	5669	38	2387	35	2591	34	2668
MA	19	5026	18	5306	17	5618	51	1873	45	2122	42	2274
G	20	4750	19	5000	17	5588	40	2375	36	2639	34	2794
GF	23	4178	21	4576	19	5058	46	2089	42	2288	38	2529
VTA	25	3840	24	4000	22	4364	51	1882	44	2182	40	2400
PX	23	3935	22	4114	20	4525	54	1676	48	1885	44	2057

Note: T_{p1}, T_{p2}, T_{p3} and T_{s1}, T_{s2}, T_{s3} are the P- and S-wave travel times for the applied stress of 10, 20 and 100 MPa, while V_{p1}, V_{p2}, V_{p3} and v_{s1}, V_{s2}, V_{s3} are the equivalent velocities.

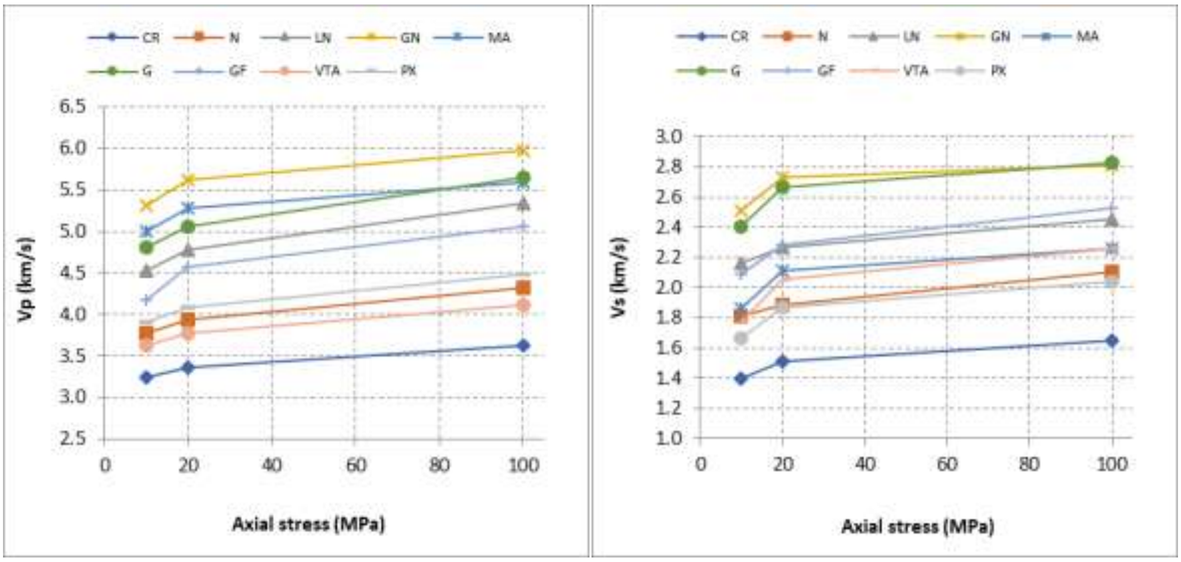

Figure 10: V_p and V_s versus axial stress for compression-ultrasonic tests

IV. CONCLUSION

The study investigates the influence of temperature and loading on Sonic Velocity of Bushveld Rocks. From the results of the study, the following conclusions can be drawn:

(1) The Sonic velocity varies inversely with temperature.

(2) The Sonic velocity increase with increase in axial stress.

Therefore, the temperature and compression loading have influence on the dynamic properties of the Bushveld Rocks.

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Oniyide G.O" Influence of Temperature and Loading on Sonic Velocity of Bushveld Rocks" American Journal of Engineering Research (AJER), vol.8, no.05, 2019, pp.250-257