Contribution for Stress State Monitoring in a Backfilled Gallery with Seismic Waves

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Abstract — **In the last decades, paste fill employ has increased rapidly; however, understanding its mechanical properties need further investigations in order to sustain its support role. The aim of this master thesis is to discover an effective way to estimate the vertical in situ stress in a backfilled mined stope, as well as predict its displacements by using seismic waves.**
A 1:100 scale model, replicating a backfilled stope from Neves Corvo mine, was manufactured for laboratory use. Sulphurous reject from its concentration plant was conceded for paste production in laboratory, where the final mixture containing 5% cement was made. The model was subjected to vertical loads, with the use of an uniaxial press, to study the wave velocity behavior on successively increased vertical stresses. The wave velocity measurements relied on three vertically mounted pairs of piezoelectric sensors; two pairs for P wave and one pair for S wave readings, submerse on the paste.
Collected data suggest a linear trend between seismic wave velocity, stress state and displacement, where P wave velocity present a higher sensitivity for the pressure range applied. A creep tendency was observed for the paste, being necessary the inclusion of trial time for the estimation of the vertical stress with the data set collected; however, further investigation in this area is needed in order to better understand paste fill behavior over time.
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***Index Terms* — Paste Fill Stress; Internal Displacement; Mining Monitoring Methods; Seismic waves; In-Situ Stresses; Creep**

I. Introduction

The essence of mining is to extract valuable minerals from the earth's crust. Nevertheless, this promotes the creation of underground mine voids. During the past decades, a new technique has been developed to fill these voids with non-valuable products of mining operation. The use of Cemented Paste Backfill (CPB), a mixture of de-watered tailings, water and cement binder, not only reduces the amount of surface storage volume of the mine tails, but also increases ore recovery.

Some mining methods imply primary – secondary stopping sequences in order to maximize ore body recovery and consequently exploration rates. Once the primary stopes are extracted, CPB is piped from the surface for direct delivery to these stopes; acting as artificial pillars and providing stable adjacent walls to secondary stope excavation. The use of CPB enables application of more selective and stable mining methods, where ground support is not only made by the classic equipment but also with mine tailings generated by mining operations, Belem et al., (2000).

In the early past, the use of monitorization techniques in backfill has been developed in order to understand the applied stresses in early and posterior stages, Hassani et al., (2001). Collecting and interpreting real time data of internal pressures in CPB may result in a safer and more efficient design of backfill strategies.

Ultrasonic techniques is a non-destructive test and easy to apply, both in site and laboratory. This technique have been widely used to characterize cementitious material properties, such as CPB. Laboratory ultrasonic wave measurements have been applied to characterize the uniaxial compressive strength of paste backfill. A good agreement was observed between measured and estimated results, Ercikdi et al., (2013). This study showed the possibility to study more properties of CPB with a new technique. Ultrasonic pulse velocity (UPV) measurements have been used to estimate the confining pressures of rocks, although there are no studies on the utilization of this technique for internal stress estimation on CPB.

II. Experimental procedure

A. Sample

The CPB mixture made in the course of this experiment, simulate the mine backfill plant process after de-watering the tailings (cake). The paste was made by adding Portland cement to the cake, both provided by Neves-Corvo mine, and water. The solid content of paste mixture was set to 91% solids, with 5% cement.

The required amount of tailings, water and binder were mixed and homogenized during seven minutes to accomplish the desired consistence. Then a sample of CPB was measured in order to attest its density, which was 2300Kg/m^3.

B. Equipment

The objective of this paper is to measure the vertical seismic velocities through submerse piezoelectric sensors on the laboratory-scale of a backfilled stope. Figure 1 shows the setup used to obtain S and P wave signals in the backfill model.

A pulse generator (BK PRECISION® 4011A) sends a square pulse to the S or P transducer with frequencies set to 50-150Hz. A mechanical wave is sent through the sample to a receiver, which is vertically aligned to it. Therefore, the pulses are sent to the oscilloscope (R&S®HMO1002). The trigger is set through a connection between the pulse generator and the oscilloscope in order to measure the time arrival between sensors.

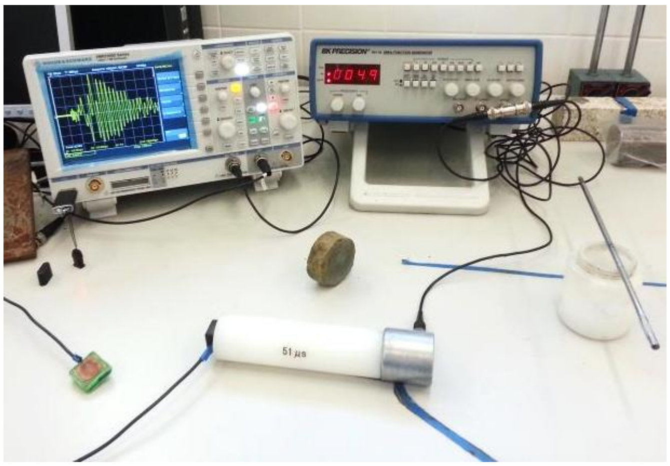

Figure 1 – Ultrasonic Velocity Test (UPV)

C. Laboratory-Scale of a Backfilled Stope

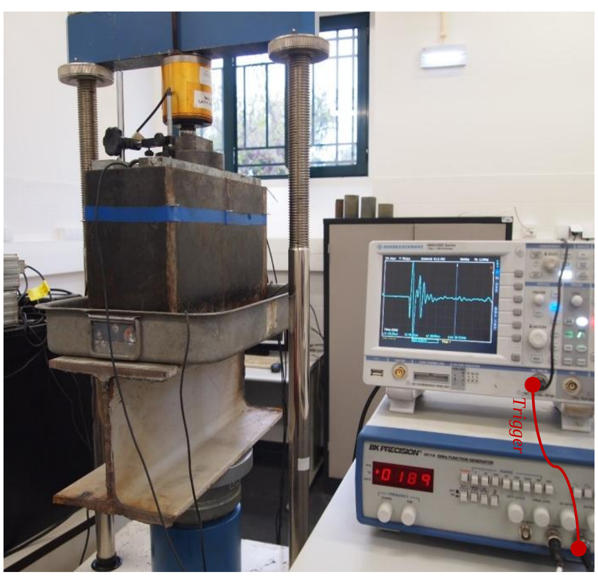

Figure 2 - Experimental Setup: 1) Laboratory-Scale model; 2) Load Cell; 3) Oscilloscope; 4) Pulse Generator; 5) Water collector; 6) Load distribution system

The simulated physic model represents an underground Bench & Fill stope, with the $12 \times 20\ m$ cross section standard used at SOMINCOR, at a $1:100$ scale. For the laboratory model, a 40 m long Bench was simulated so, according the defined scale, the final dimensions are 40×12×20 cm, Figure 2 position ①.

To nullify lateral displacements the model was steel made. With 5 mm width iron plates for its walls and bottom and a 10 mm width plate for its lid. This lid had smaller dimension than the actual model so it was able to slide in to its interior as a result of the axial loads applied by the press, Figure 2 position⑦.

Due to the small contact area of load cell in the lid, Figure 2 position②, a different method of distributing force through a wider area had to be devised. For this purpose, two steel beams were used in order to provide an acceptable distribution of downward force over the entire lid, Figure 2 position⑥.

The bottom part of the model was perforated with $3\ mm$ diameter orifices, $13mm$ apart, creating a mesh pattern with a total of 33 orifices. The purpose of these small holes is to vertically drain the water content of the paste fill, as it occurs in an underground environment, into a collector, Figure 2 position ⑤.

D. Preparation of the Experimental Setup

The presented model included two pairs of P sensors and one pair of S sensors, vertically separated by 8 cm and 3 cm respectively. The sensors, manufactured during the dissertation period, were composed with a piezo element (Piceramic®) attached to a copper electrode by an epoxy thin layer and with an outer plastic coupling. The bottom sensors were fixed to an acrylic piece in order to ensure immobility during the experiment. Their respective electrical wiring went through the bottom drainage orifices meaning that new connections had to be made between each trial of the experiment.

The top sensors were attached to a plastic mesh, sized to the horizontal section of the model, which was able to accompany the vertical displacement presented by the paste fill during

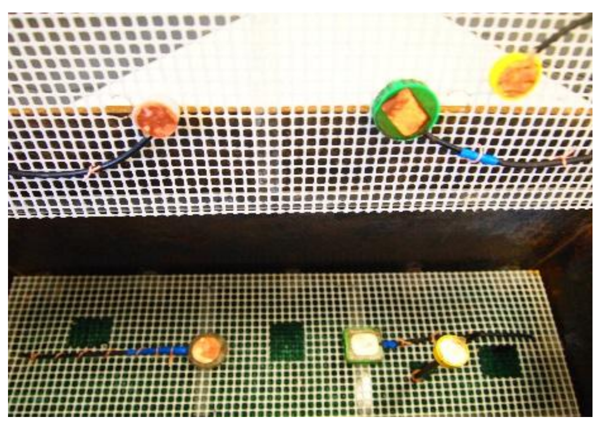

Figure 3 – Top and bottom sensor assembly

trials, Figure 3.

The plastic mesh ensured horizontal displacements, observed during preliminary experiments, would not misalign the top sensors relatively to the bottom ones for the necessary measurements needed.

It was necessary the sensors maintain their original positions during the first 42 hours of cement hydration, since the objective was to measure only the behaviour of the internal tensions after CPB attained certain stiffness. With this in mind, during this period the plastic mesh was tethered to the sides of the model, insuring its immobility. When cement hydration was considered complete, the tethers were cut down, allowing top sensors to move along with CPB displacements.

The CPB was introduced manually using a piping device, in order to reproduce its backfill deposition in an underground gallery, Figure 4.

Figure 4 - Paste deposition in the model through a piping device

This procedure was done in two stages. The first stage consisted on pouring down the paste fill until it covered the bottom sensors. The model was constantly vibrated in order to expel any air bubbles that may have formed during the deposition process. The model was then filled to the level of the top sensors. Vibration was again applied at this stage in order to minimize air bubble formation. At this point, the plastic mesh containing the top sensors was secured into place and the model is filled to the top.

During the experiment, it became necessary to place an additional extension to the LVDTs to enable them to reach the top sensors in order to measure their displacement. It was also necessary to introduce the LVDT's in a tube, closed at its bottom by a piece of leather; this step was necessary to avoid contact between the LVDT's extension and the cemented paste fill, ensuring its vertical mobility.

With the model filled to the top, it was necessary to wait for the cemented paste fill to gain some stiffness so as to be able to support the model's lid. With this one in place, the LVDT´s were introduced through the attached tubes until they reached the top sensors level and were fixed to the sides of the model, Figure 5. Knowing the vertical displacement of the top sensors, as pressure was applied by the loading press, it becomes possible to measure seismic wave velocities and compare them with the stress state of the paste fill.

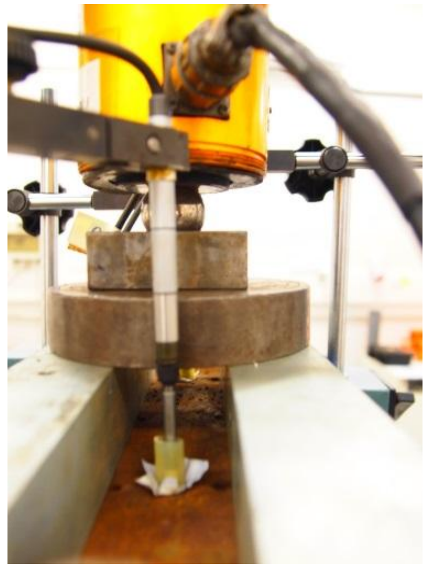

Figure 5 – Detailed view of LVDT and load distribution system

E. Ultrasonic Velocity Test

TABLE 1
LOAD SEQUENCE BY CURE TIME

Cure Time (h)	Load applied (kN)	Vertical Stress (kPa)
42	0,5	14,35
47	2	43,20
50	3	62,43
70	5	100,89
97	9	177,82
115	11	216,28
139	13	254,74
147	15	293,20

At predetermined curing periods, vertical pressures were applied into the top of model, Table 1.

For the UPV testing, longitudinal P-wave velocities were measured using an ultrasonic pulse velocity test (UPV). In the measurements, arrival time of ultrasonic pulses were registered with an accuracy of $0{,}1\ \mu s$. The waveform was stacked five times to eliminate noise and preserve the true signal. A filter was used to "clean up" the signal with the purpose of make clear arrival time readings. This determination was obtained by the peak-wave.

After the measurements, wave velocity was calculated from the measured travel time (t_i) and the distance between transducers, also variable in time, equation 1.

$$V_P(t) = \frac{L - \delta_i}{t_i}, \quad [m/s] \qquad (1)$$

The travel distance was calculated by the initial distance (L) minus the displacement registed in the LVDT per time step (δ_i). For the diagonal sensors, the travel distance was calculated by the Pythagorean Theorem.

After disassembling each experiment, a calibration was made to verify delays in the propagation time. It was observed an increase of the delay between experiments, which led to a correction of the propagation time equation (2).

$$t_i = t_r - \left(\frac{t_d^i - t_d^f}{t_t}\right) \times t_e \qquad (2)$$

where t_r is the registered propagation time (μs) ; t_d^i and t_d^f are initial and final time delay(μs), respectively; t_t is the total time of the experiment (h) and t_e is the cure time (h).

III. Results & Discussion

The results presented in this section concern the variations of the wave velocities, displacement and stress during a stress applied test. Data was originated by 136 measurements, using 2 paired sets of vertically and diagonally aligned sensors, Figure 6 and Figure 7, respectively.

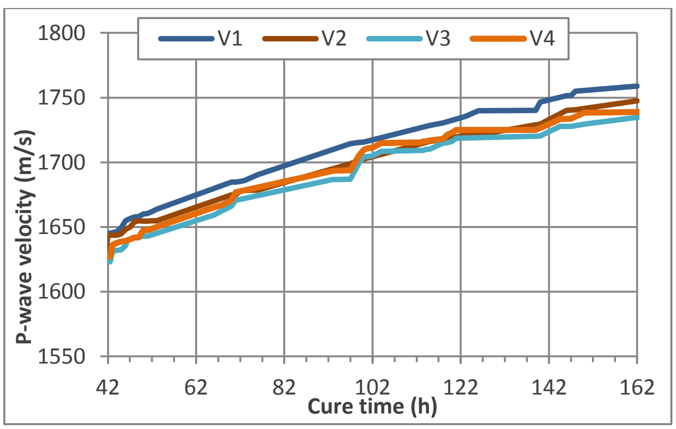

Figure 4 – P wave velocity for vertically aligned sensors

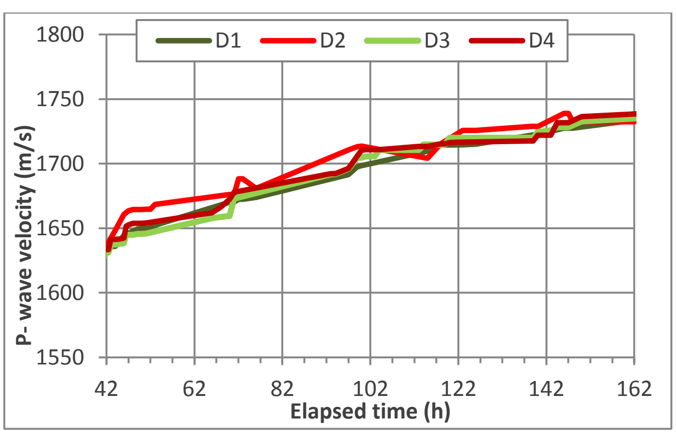

Figure 5 – P wave velocity for diagonally aligned sensors

CPB has initially a fluid behaviour with no shear strength. As it cures, its shear strength increases due to the presence of cement hydrates. After 42 hours, it was established that CPB had enough stiffness to start the test procedure.

Initially, UPV measurements for the P-wave velocity determination were $1644 \pm 10\ m/s$ and $1633 \pm 10\ m/s$, for the stage with no deformation and in the first and second trials, respectively. Galaa et al. (2015) observed the same velocities for a cure time of 42 hours. A wave velocity increase was observed for each pressure applied. This demonstrated a time dependency between the UPV measurements and the applied forces.

S-wave velocities are displayed in Figure 8; they were detected after 42 hours and 29 hours for the first and second trial, respectively. S-wave variations obtained between the two experiences were probably due to a higher concentration of quartz and pyrite in the first trial, made clear by mineralogic analysis of both CPB mixtures

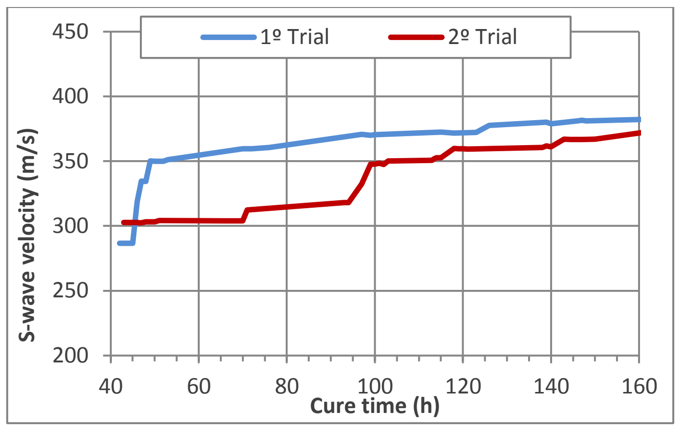

Figure 6 – S wave velocity measured

CPB displacements during loading have shown a good agreement between trials, Figure 9:

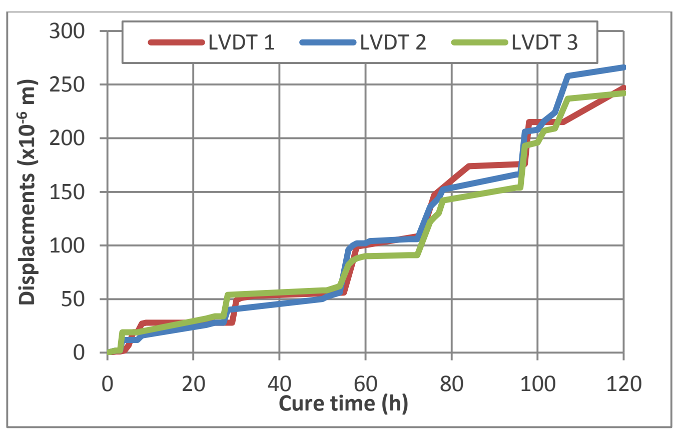

Figure 7 - Displacements measurements

A. Deformation versus time

Table 2 presents the values obtained for each load maximum P and S wave velocity measurements, as well as time and deformation records. A comparison between deformation and time was made in order to evaluate the time dependency of CPB for each load increment. For this it was necessary to create a chart between displacements and time so as to observe the material fluency for each pressure increase. The slope of the regression line applied for each measurements, $\Delta\delta/\Delta t$, was observed on the Table 2. For the first five loads there was a constant deformation per time of $0{,}48 \pm 0{,}04\ \mu m/h$; then a sudden increase reached $2{,}45\,\mu m/h$, followed by a new decrease tendency.

The same biphasic behaviour was also noted on the UPV measurements for different displacements.

B. Displacement versus UPV measurements

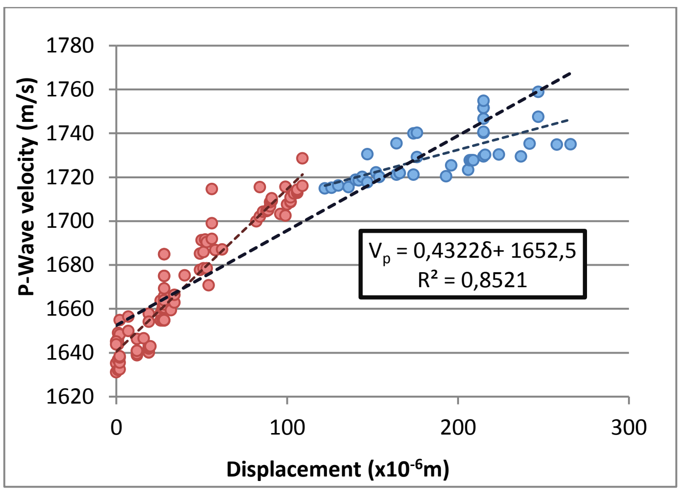

Figure 10 – P-wave velocity versus displacement for situations two regimes and for the global trend line

Figure 10 shows different P wave velocities in accordance with backfill internal displacement. For low displacements, and consequently, low pressures, most microfissures and pore spaces are not closed, leading to a higher surface area between grains and a higher variation of the P wave velocity. After a certain displacement the material turns more compacted and therefore velocities present less variation.

According to Asef & Najibi (2013), a two segment curve is obtained when a rock is submitted to various confining pressures. As stress-strain curve is proportional, is expected the same trend in velocity-pressure and velocity-displacements.

In the model presented by Wang et al. (2005) the UPV for low pressures manifested an exponential trend curve before a critical pressure was achieved. After surpassing the critical point, velocity-pressure curves acquired a linear elastic trend. It's possible, for the range of pressures applied, the presence of the first regime, although the lack of data does not allow this approximation.

In order to study the global trend of the recorded data, linear and logarithmic regression curves were made, Equations (3) and (4), respectively:

$$v_P = 1652{,}6e^{0{,}0003\delta} \qquad R^2 = 0{,}8483 \qquad (3)$$

$$v_P = 0{,}4322\,\delta + 1652{,}5 \qquad R^2 = 0{,}8521 \qquad (4)$$

These equations take, as best fit regression curves, a linear function with a correlation factor of 85,21%. In a laboratory scale, is important to point out that the best correlation factor does not necessarily predict, in long term, the behaviour of the parameters in study; for this reason further evaluations need to be taken.

The assessment of the root function for the exponential and linear-regression was 1652,6 m/s and 1652,5 m/s, respectively; this values are within the margin error of the observed velocities for null pressure applied, 1638,72± 16,4 m/s. The results suggest the linear model is the most suitable for the data set.

TABLE 2

VERTICAL AND HORIZONTAL PRESSURE WITH THE MAXIMUM UPV VELOCITIES MEASURE FOR EACH LOAD CYCLE; AS ALSO THE DEFORMATION RATE DETERMINED PER CYCLE

σ_h (kPa)	σ_v (kPa)	UPV (m/s)		$\Delta\delta/\Delta t$
		P Wave	S Wave	
0,33	14,35	1647,05	231,22	0,54
2,71	43,2	1652,69	259,08	0,48
4,88	62,43	1677,78	265,76	0,48
9,43	100,89	1704,24	287,53	0,48
16,59	177,82	1722,72	297,97	0,48
26,89	216,28	1732,62	307,73	1,42
35,14	254,74	1742,62	310,86	2,45
40,94	293,2	1748,84	314,31	1,15

C. Comparison between Vertical Stress and UPV Measurements

The trend line feature on Excel was used to adjust the maximum P and S wave velocity values recorded for each load with the vertical stress on the plane of the sensors, Figure 11-A e B, respectively. The data set utilize for the study is presented on the Table 2.

A linear trend is observed for the variation of the UPV measurements with the vertical pressure. For the P wave velocity is observed a good correlation, with a value of 93,63%. Standard errors for the regression parameters were $\pm 0{,}0461$ for the slope fit and $\pm 6{,}8608$ for the interception, indicating good adjustment. For a 95% confidence interval it was estimated a P-wave velocity increase of $0{,}2755$ to $0{,}4672\ m/s$ for each 1kPa vertically applied.

The regression line made to compare S-wave with vertical stress for each trial was not within the margin error for the slope so a global trend couldn't be made. The discrepancies observed were probably related to the minerology of the paste backfill, where the quartz and pyrite concentration lead to higher S wave velocity.

D. Comparison between Horizontal Stress and UPV Measurements

Figure 7 describes UPV measurement obtained through diagonally sensors; these measurements showed a good agreement with vertical aligned measurements (Figure 6); indicating the presence of a homogenous and isotropic body. Consequently, Hooke's law can be used to determine the horizontal stress of CPB. The values of the elastic constant were determined by Carvalho (2014) for the same CPB mixture with the exception of the binder content that was 1% lower (E=0,16 GPa and v=0.12). The transverse strain was determined with the ratio of the vertical displacement of the sensors plane with the initial distance.

The estimated horizontal stresses values are described on the Table 2. S and P-wave velocity were plotted in order to verify the linear relation between those variables with the estimated horizontal stress.

A good correlation between the two parameters was observed. Under field conditions, the occurrence of rock mass/CPB interaction leads to a non linear variation of the vertical and horizontal stress in CPB. For this reason it is necessary to account for the arch effect, although this approximation can't be made using Hooke's Law equation.

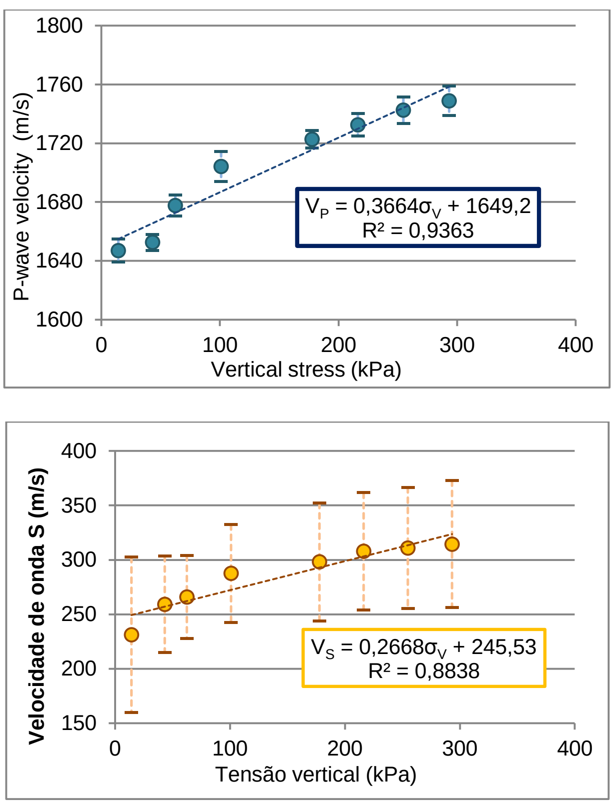

Figure 11 - Vertical stress (σ_v) versus a) P-Wave velocity and b) S-Wave velocity

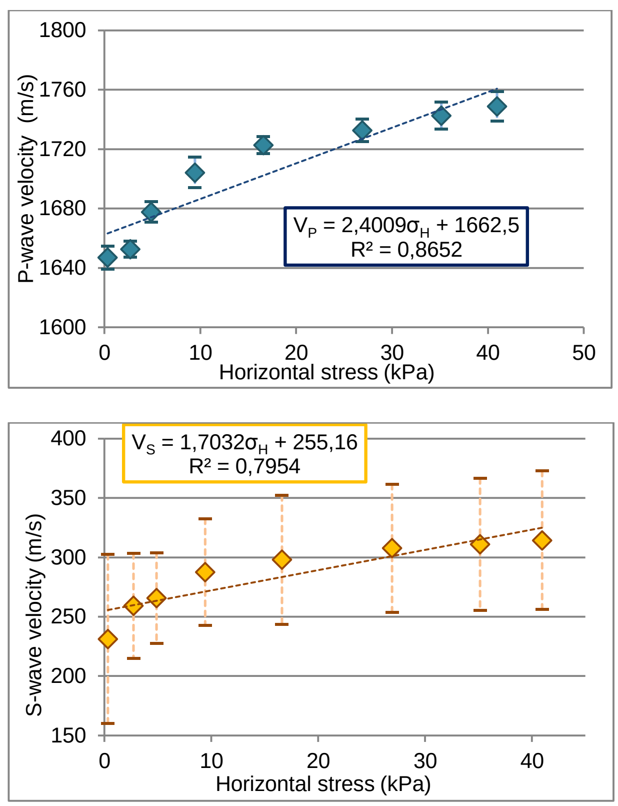

Figure 12 – Horizontal stress (σ_h) versus a) P-Wave velocity and b) S-Wave velocity

E. Multiple Regression

Displacement by time trends in CPB showed the possibility of a creep deformation (sometimes called cold flow) tendency, typical of the viscoelastic materials.

For early-age CPB by Hassani et al., (2001). Belem et al., (2000), concluded that the stresses in a backfilled gallery varied during hydration time. All the material exhibited a viscoelastic behavior, although its influence can be disregarded due to a reduced dependence (Roylance, 2001). In order to study the time dependence for the estimation of the vertical stress in CPB, a multiple linear regression was used.

Assuming data normality and homoscedasticity, the results for the variation of the UPV, displacements and time measured for each increment of load were:

$$\sigma = 1{,}09 v_P + 0{,}66\delta - 1759{,}43 \qquad R^2 = 0{,}9697 \quad (5)$$

$$\sigma = 0{,}77 v_P + 0{,}53\delta - 0{,}56t - 1246{,}44 \quad R^2 = 0{,}9711 \quad (6)$$

Where the vertical pressure, σ is in kPa; displacement δ in µm and time of the experience in (h) where the $t = 0h$ correspond to $t_t = 42h$.

Comparison between equation 5 and 6 showed that time should be accounted due to the higher correlation. In this way, was considered equation 6 as the most representative for the parameters under study.

IV. Conclusion

In mining exploration, knowledge of *in situ* stress state contributes directly to miners safety and to maintain the structural integrity of galleries, Ackim (2011). A new monitorization method was developed to estimate the vertical stress in a backfilled gallery.

The model was built to simulate field conditions, concerning stress conditions, strain and drainage, although assuming an absence of lateral displacements. The laboratory procedure and model assembly enabled repetitive recordings, so as a correct experimental practice was achieved. It was observed a two stage relationship displacements and time, with a turning point stress of 216 kPa applied. Firstly an uniform regimen with a velocity of 0,48 µm/h was estimated; this rate was equivalent to 4,2 mm per year. For the second regimen, a more accelerated behaviour was observed. It was observed the same biphasic behaviour in the displacement per UPV.

A linear trend was evident for P-wave velocity versus displacement, where an increase of a displacement unit reflected in a 0,4322 m/s rise on P-wave velocity.

The main goal of the article is to correlate the UPV measurements with stress state. In order to accomplish this it was estimated the horizontal stress with the Hooke Law, assuming an homogeneous and isotropic body. P and S wave demonstrated a good correlation factor (86,36% and 79,54%, respectively) with horizontal stress. It is important to highlight that, in most cases, CPB demonstrates an arching effect, which implies higher horizontal forces. Hooke Law doesn't consider this common phenomenon and more research needs to be done in this area.

It was observed a linear trend for vertical stress relation with P and S-wave velocity. It was determined that P-wave was more sensitive to stress applied, showing a correlation factor of 93,63% for P-wave and 88,38% for S-wave and a variation of 72% higher per unit of stress applied.

A multiple regression was used in order to evaluate a global trend of the P-wave velocity and displacement for vertical loads applied. It was observed a correlation increase of 0,14% with the inclusion of time.

For conclusion, seismic wave velocity, using Neves Corvo CPB with 5% cement mixture, can be used to study the deformation and stress state of a backfilled gallery.

Acknowledgment

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