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TEMPERATURE CHANGE AND THE TOTAL STRESS ANOMALY IN PASTE BACKFILL

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ABSTRACT: This paper presents preliminary results from a laboratory backfill model test in order to explain the effect of temperature change during the cement hydration on the total stress within cemented paste backfill. It is conducted via temperature control test in the absence of the cement. This investigation is an attempt to resolve an anomalous behavior reported in recent full scale monitoring reports, where the total vertical stress at the stope base shows a progressive increase after backfilling is terminated. The result in this paper shows that the total vertical stress is not affected by the level of the temperature but rather by the temperature gradient. The empirical relationship between the temperature gradient and the change in the total vertical stress is proposed. The total stress anomaly found in the full scale monitoring of paste backfill could be explained by the finding.

Keywords: Backfill, Temperature, Arching, Total Stress, Anomaly

1. INTRODUCTION

Paste backfill is a type of material used to fill-up underground mined-out voids (stopes), which improves underground general stability condition. The material has a paste-like consistency made from a mixture of tailings, water, and cement binder to increase the strength of the paste. Figure 1 shows the paste backfill is being tested for its rheology property. The paste backfill or also called cemented paste backfill provides significant advantage in mining production as compared to the other type of backfills (e.g. hydraulic fill), which can be a self-supporting material. The adjacent ore bodies can be mined without the need of leaving some parts to act as underground pillars. Hence, the ore production can be maximized. The cemented paste backfill has been popularly used in the underground mining operations for the last two decades. Figure 2 shows a backfilling sequence in cemented paste backfilling.

During the backfilling, a barricade is constructed to plug the drawpoint. The barricade provides a temporary barrier to prevent the backfill to flow out of the stope until the backfill gains enough strength as a self-supporting material and be able to withstand pressure from blasting activity of the adjacent stope. As a temporary structure, the barricade has to be cost effective and acceptable in strength. When the barricade fails, a hefty amount of rehabilitation cost has to be spent and more importantly the safety of the underground workers is at serious risk.

In order to design an efficient barricade wall, the engineers must have a good understanding of the possible mechanisms within the paste backfill during and after backfilling, especially on the horizontal stress exerted by the paste backfill near the barricade. The conservative design practice uses the total vertical stress at the base (bottom) of the stope to estimate the maximum horizontal stress acting on the barricade wall. This assumption is reasonable since the total horizontal stress is equal to the total vertical stress during the backfilling (i.e., when paste is still in liquid phase) and the highest total vertical stress within the paste is located at the deepest location (i.e., at base).

Fig.1 Paste backfill

According to the overburdened stress theory [1], the total vertical stress (σ_v) is equal to:

$$\sigma_v = \gamma z \qquad (1)$$

where, γ is the bulk unit weight of the backfill (kN/m^3) and z is the depth of backfill (m).

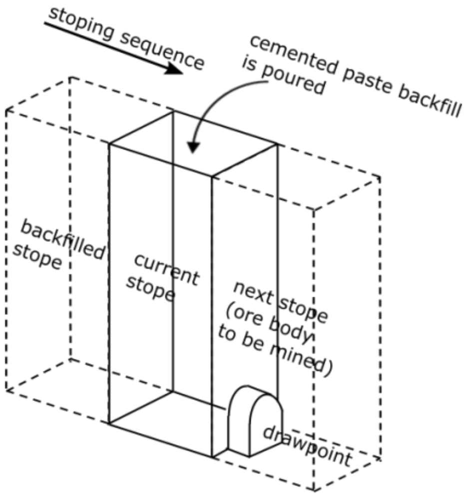

Fig.2 Cemented Paste Backfilling

The equation 1 is valid for a semi-confined area (such as stope) provided that the paste has not been consolidated. During the unconsolidated state, the paste is in liquid phase and the total stress at the base of the stope is then equal to the geostatic stress. After the backfilling is terminated the depth is constant and the geostatic stress is also constant. The plot of geostatic stress with elapsed time can be illustrated by a thick solid line in Figure 3. The consolidation appears after the termination of backfilling at which the effective stress starts to generate within the paste. During the consolidation, the interfacial friction between the paste and the stope side walls increases as the effective stress increases. The interfacial friction transfers some of forces in the paste to the side walls (called arching) and therefore, the total vertical stress at base is reduced. The time to consolidate depends of the material properties and the length of drainage path [2]. By considering the arching, the plot of the total vertical stress versus time deviates from the geostatic line as illustrated by the dash lines in Figure 3.

The general observation in Figure 3 is summarized from several full scale monitoring reports [3-10]. However, stress anomalies are found in some reports [3-8], where the total vertical stress increases during the rest period as illustrated by dash dot lines in Figure 3. This is obviously not expected since there is no paste is poured during the rest period. One of the hypotheses is attributed to the temperature increase during the cement hydration. This paper shows some preliminary results to test the hypothesis.

2. EXPERIMENT

2.1 Paste Material

The paste is produced from a mixture of water and silica flour as a replacement of tailings. In order to isolate the strength gain factor, the cement is excluded in the paste and the temperature increase is applied via temperature controller. Therefore, the paste backfill in this experiment is uncemented. The silica flour is sourced from SILVERBOND, Johor, Malaysia. It is an inert material with SiO_2 contents of 99.38% and the specific gravity of 2.65.

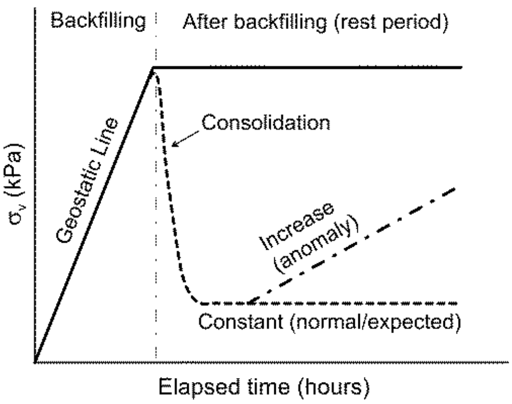

Fig. 3 General plots of total vertical stress at the base of the stope versus elapsed time based on full monitoring reports [3-10].

The particle size distribution (psd) of the silica flour is shown in Figure 4. Two additional points are superimposed to indicate general categories of materials to be used for paste fill and hydraulic fill [12]. The empty square symbol indicates that the paste material should have at least 15% of particles finer than 20 μm in order to retain the water to achieve reliable paste flow. It is shown that silica flour has more than 15% (i.e. 38%) of particles finer than 20 μm, thus it falls within the category. On the other hand, a solid square symbol indicates the category for hydraulic fills material, where it requires a maximum 10% of particles finer than 10 μm in order achieve adequate permeability. The silica flour has more than 10% (14.2%) of particles finer than 10 μm and therefore it does not fall in hydraulic fills category.

The paste is mixed using 10L portable flour mixer with a solid content of 72% and the unit weight of the paste is 17.5 kN/m^3. The solid content is defined as the mass of the dry silica flour over the total mass of paste. In mine operations, the solid content is determined by the type of the reticulation system. The higher solid content, the higher energy is needed to transport the paste backfill through the reticulation pipes and vice versa. In some cases, gravity system without pump is sufficient. The range of paste backfill solid content used in some mining paste backfill operation is between 71-82% [2-11].

2.2 Apparatus

A laboratory backfill model is built to simulate stope backfilling. The apparatus has four main parts, namely: a narrow wall, sensors, temperature control system, and data acquisition system. The complete apparatus is depicted in Figure 5.

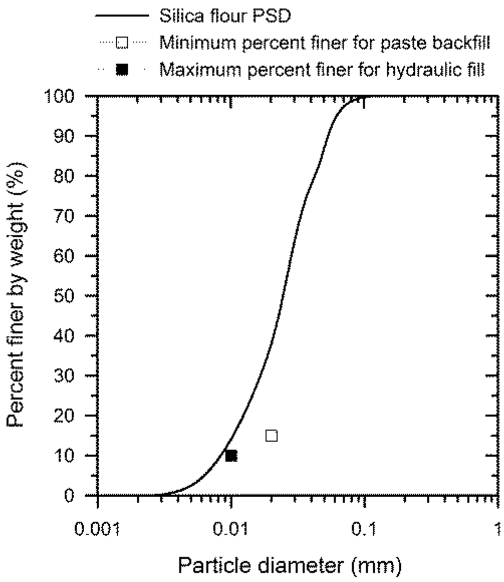

Fig. 4 Particle size distribution

The narrow wall consists of a rectangular aluminum box, two columns and the platform. The box is made of 1 cm thick aluminum measures 15 cm inner length (L), 5 cm inner width (W) and 80 cm inner height (H). The box has a base plate but has no plate at the top. The two columns are made of threaded steel rods fixed vertically on the platform. The rods support the box by fixing its sides via four nuts. The platform is made of thick steel with four legs. In order to ensure the horizontalness, the legs can be adjusted with a spirit level as a reference.

There are two types of sensor used: a load cell and a thermocouple. The load cell is used to measure the weight of the paste transferred to the base of the narrow wall. It is placed right under the base plate. The horizontalness of the load cell can be adjusted. The thermocouple used is type J, inserted into the paste from the above opening of the narrow wall. The temperature control system consists of heating elements and a microprocessor based temperature process control CN7263 manufactured by Omega Engineering. The heating elements are attached to the box using special aluminum holders and connected to the AC 240 volts power line via temperature controller. The target temperature can be set using “on-off” mode upon receiving signal from the thermocouple. The heating elements will be turned on if the temperature received is lower than the target temperature and vice versa.

The measurements from the sensors are sent to the computer via data acquisition system. The sensors calibration and trial testing are carried out prior to actual test to ensure the test accuracy.

It is important to emphasize that there is no fixed connection between the base plate and the narrow side wall. The base plate and the narrow side wall work independently. This is designed to separate the measurement of force that is transferred to the base of the box and the force that is transferred to the narrow side wall. Therefore, the base plate is not fixed to the narrow side wall. The base plate is simply seats on the load cell and separated by a 3 mm gap from the narrow side wall. In order to prevent flow of paste between the gap, it is closed and secured with latex membrane.

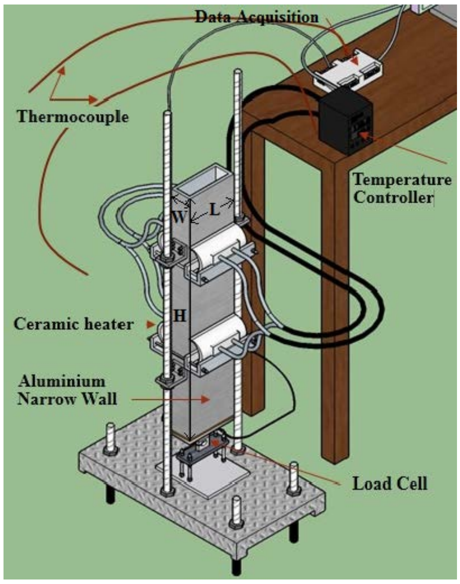

Fig. 5 The laboratory backfill model

2.3 Backfilling

The paste is filled (poured) into the box using funnel until about 70 cm in height. The thermocouple is inserted into the backfill from the top opening of the narrow wall. The opening of the narrow wall is then covered with plastic cling wrap to minimize the evaporation from the paste during monitoring. The room temperature during the filling is about 22 °C. At this time, the heating elements are turned off to minimize the risk from electric shock. After the filling is completed, the heating elements are turned on and the temperature control is set to the target temperature of 30 °C.

3. RESULTS

Figure 6a shows the full observation of vertical stress denotes as σ_v (kPa) and temperature of the paste, T (°C) against the elapsed time. The elapsed time starts from the filling until 78 hours after. The vertical stress, σ_v (kPa) is computed as:

$$\sigma_v = \frac{F}{A} \tag{2}$$

where, F is the downward force measured by the load cell (kN) and A is the base area of the narrow wall (0.0075 m^2). The temperature from the thermocouple is directly registered by the data acquisition in °C, therefore there is no additional computation is needed.

Figure 6a is decomposed into Figure 6b-6e that enlarges and highlights specific events in Figure 6a. Figure 6b-6e shows the total vertical stress versus elapsed time during the filling, consolidation, constant temperature after consolidation, and temperature ramp-up, respectively.

The filling event is highlighted in Figure 6b. The increase in the total vertical stress is as expected until it is terminated at about 40 seconds. The total vertical stress increases from 0 (empty) until about 12 kPa (full).

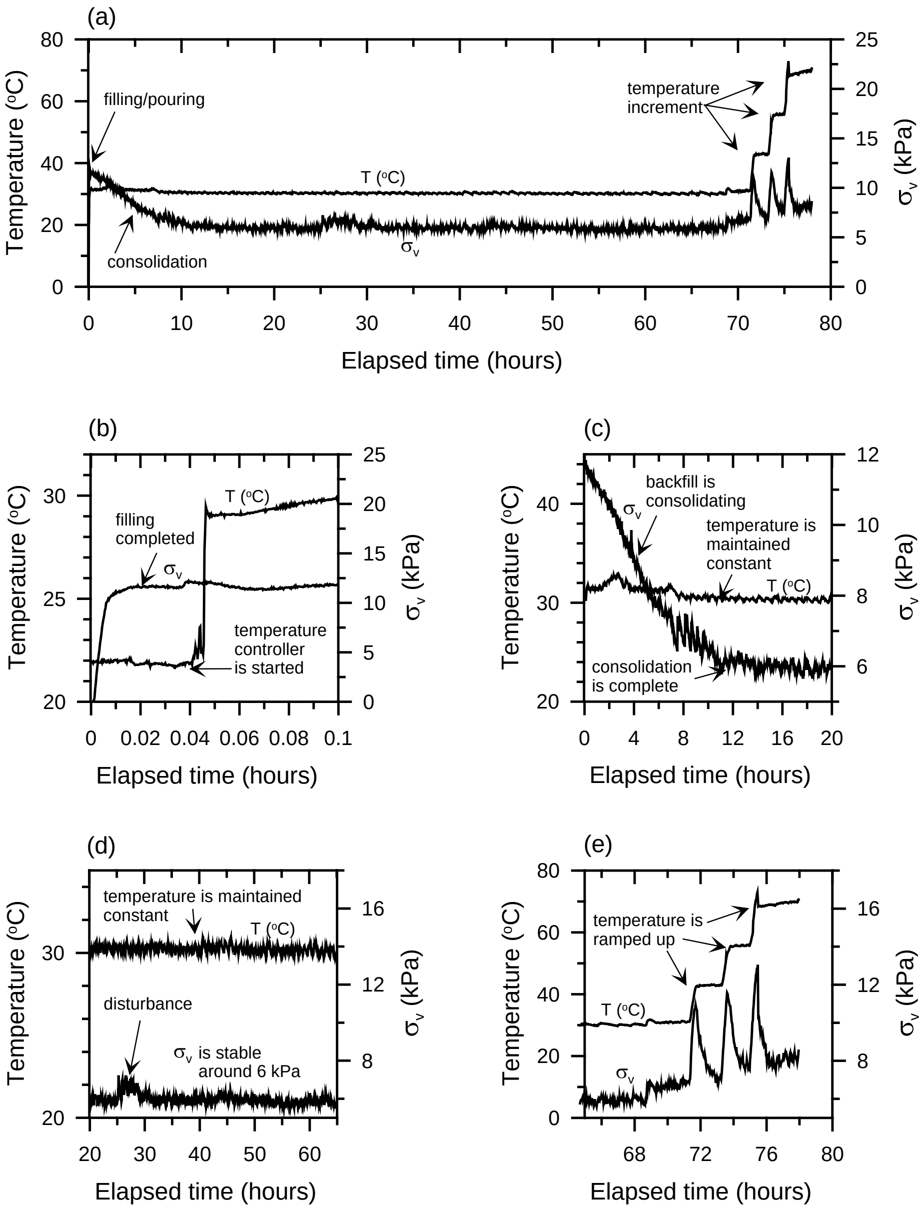

Fig. 6 Backfill monitoring: (a) full observation, (b) filling, (c) consolidation, (d) constant temperature after consolidation, and (e) temperature ramp-up.

The 12 kPa is equivalent to about 70 cm in height of paste according to equation 1. The vertical stress is kept constant until 0.1 hours. During the filling, the temperature is about 22 °C, which indicates the room temperature (not temperature of the paste) since the thermocouple has not been inserted into the paste.

About 2.4 minutes after the filling, the thermocouple is inserted into the paste, the heating elements and the temperature control is set to a target temperature of 30 °C. The temperature increases from 22 °C to about 30 °C in about 20 seconds and maintained. There is no effect in increasing temperature on the vertical stress during this filling period is apparent, except a small spike in the total vertical stress at the time the temperature controller starts to ramp up.

Figure 6c depicts the consolidation phase that starts from 6 minutes after the filling and completes at around 12 minutes. The temperature is maintained constant throughout this period. The total vertical stress at base reduces sharply and diminishes when approaching the completion of the consolidation. The consolidation in this process is attributed to the dissipation of pore water to the upper part of the paste and the paste is compressed. The consolidation increases the effective stress within the paste and the friction along the side walls are mobilized that leads to the development of arching. The arching transfers some of the stress within the paste to the side wall and onto the platform. The remaining stress is carried by the base plate. The arching causes the total vertical stress to reduce from 12 kPa to about 6 kPa (50% reduction) in 6 minutes. This consolidation phenomenon has also been found in the full scale monitoring [3-10].

Figure 6d shows that there is no change in the total vertical stress after the consolidation is completed. During this period the temperature is maintained constant. The total vertical stress is constant around 6 kPa. A small disturbance of about 1 kPa is shown as a spike in the total vertical stress, which is located between 26 to 28 hours elapsed time (occurs at daytime). The total vertical stress goes back to 6 kPa after 28 hours.

Figure 6e shows the effect of increasing the temperature (gradient) to the total vertical stress at base. The temperature is ramped-up (increase) and soak (maintained constant) in three step levels. The first step, the temperature is ramped-up from 30 to 42 °C and soaked for about 1.5 hours. During ramp-up, the temperature increases linearly with time in 30 minutes. The calculated temperature rate of increase ($\delta T/\delta t$) is 0.4 °C/hours. Due to this temperature increase, the total vertical stress increases by 4 kPa. It is thought that the increase of the total vertical stress is due to the expansion of the paste. The volumetric strain caused by the expansion is partly resisted by the side wall through friction; hence the arching is reduced and consequently, the additional stress to the base is generated. At the soaking period, the data shows interesting results where the vertical stress decreases and diminishes to its value before the ramped-up. The second step, the temperature is ramped-up from 42 to 55 °C at the same rate as the first step. The total vertical stress increases by 4 kPa. At the soaking period, the same phenomenon happens where the total vertical stress decreases and diminishes to the original value. The last step, the temperature is ramped-up from 55 to 72 °C with the same rate as the first and the second step. It increases the total vertical stress by 5.5 kPa. During the soaking period, it is noticed from Figure 6e that the temperature slightly drops down to 68 °C after reaching 72 °C, the temperature controller tries to maintain the temperature by heating the narrow wall and the temperature ramps-up again until 70 °C at which the monitoring is terminated. Despite slight drop in the temperature during soaking period, the same phenomenon as seen at the first and the second step reappear.

The relationship between the temperature and the vertical stress is shown in Figure 7. It shows a non-linear increase of vertical stress during the temperature increase. The patterns for the three steps are similar and the empirical formulation of the relationship can be established. In contrast with ramping-up process, soaking process shows vertical drop in the total vertical stress, which brings back the total vertical stress to its consolidated state. This implies that the change in the total vertical stress with respect to its consolidated state equals to zero ($\Delta\sigma_v=0$) if there is no change in temperature ($\Delta T=0$).

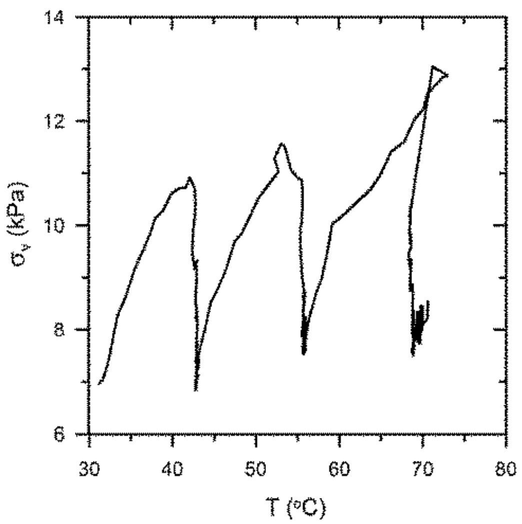

Fig.7 σ_v versus T

Figure 8 shows the relationship between the change in vertical stress ($\Delta\sigma_v$) and the change in temperature (ΔT) for the three steps during the temperature ramp-up period. Attempts have been made to curve fit the experimental data points. The continuous line in Figure 8 represents the best curve fitting to represent the empirical relationship between the change in vertical stress ($\Delta\sigma_v$) and the change in temperature (ΔT). The following form of equation is proposed:

$$\Delta\sigma_v = A\times\left(1-e^{B\times\Delta T}\right) \quad (3)$$

where, A and B are constants. For the curve fitting in Figure 8, the value of A and B are 5 and 0.15, respectively.

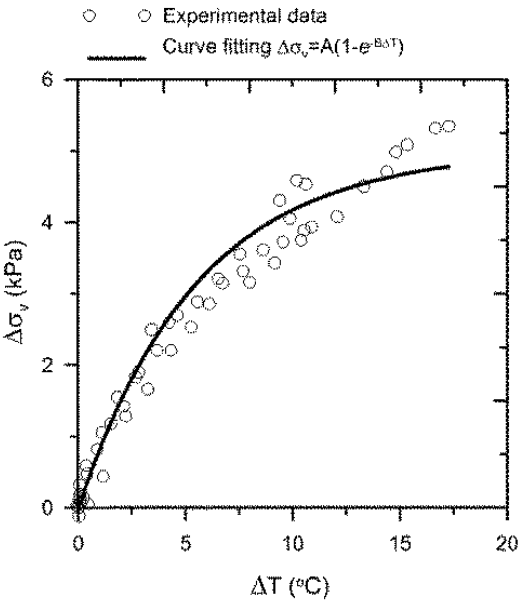

Fig.8 $\Delta\sigma_v$ versus ΔT

4. CONCLUSIONS

An experiment has been conducted to monitor the effect of the temperature change (gradient) on the total vertical stress within paste backfill via laboratory model. The following conclusions have been made: 1) the total vertical stress is not affected by the level of the temperature, 2) the increase in temperature causes the increase in the total vertical stress at the base of the stope, 3) the empirical relationship between the change in temperature and the change in the total vertical stress fits the exponential function, and 4) the total stress anomaly found in the full scale monitoring of paste backfill could be explained as the change in temperature within the backfill.

5. ACKNOWLEDGEMENTS

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