Using effective stress theory to characterize the behaviour of backfill

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ABSTRACT **The importance of understanding the behaviour of cemented paste backfill (CPB) within the framework of the effective stress concept is highlighted in this paper. Only through understanding built on this concept can problems such as barricade loads, the rate of consolidation, and arching be fully understood. The critical importance of the development of stiffness during the hydration process and its impact on factors such as barricade loads is used to illustrate why conventional approaches that implicitly ignore the effective stress principle are incapable of capturing the essential components of CPB behaviour.**

KEYWORDS Cemented backfill, Effective stress, Barricade loads, Consolidation

INTRODUCTION

The primary reason for backfilling will vary from site to site, with the main advantages being one or a combination of the following: occupying the mining void, limiting the amount of wall convergence, use as a replacement roof, minimizing areas of high stress concentration or providing a self-supporting wall to the void created by extraction of adjacent stopes. Another factor that is very likely to increase in importance with time is the potential environmental benefit. Whatever the primary and secondary functions of a backfill, the use of backfill is likely to increase significantly with time and it is imperative that a comprehensive understanding of the material be developed so that material selection and backfill system design can be optimized.

MOVING FROM HYDRAULIC FILL TO DESIGNER FILLS

There is a range of fill types being used other than conventional hydraulic fill, but this paper pertains to one particular type of fill, namely cemented paste backfill (CPB). However, the framework for understanding CPB described here is generic enough to encompass all types of fill, including hydraulic backfill, whether cemented or not, as shown later in the paper.

Conventional hydraulic fill involves the removal of the finer fraction of the total tailings stream, leaving a fill that is relatively coarse and free draining. This is the primary fill type used in South Africa, where the mined voids are usually narrow, but laterally extensive. In this application, the shear strength of the fill is relatively unimportant and it is rather the resistance to closure (i.e. the stiffness or modulus of compressibility) that is of primary interest. As the filled stopes compress under essentially confined, one-dimensional (also known as K_0) conditions, the stiffness increases with displacement. Well-graded hydaulic fills have been shown to generate the highest settled density and this, combined with the exponential confined compression behaviour of soil (Fourie, Gürtunca, de Swardt, & Wendland, 1993), generates the most resistance to closure.

In applications in Australia and Canada, where many mines have high stopes, the shear strength of the backfill is extremely important. As successive stopes are mined, previously placed backfill is exposed. The exposed vertical or sub-vertical faces must have sufficient shear strength to remain stable under these conditions. Hydraulic fill is cohesionless and cement (or another binder) is added to provide the required strength. There are many examples where this approach has been used very effectively (e.g. Mt. Isa Mines in Queensland; Cowling, 1998). There are an increasing number of operations that are using CPB as part of their support strategy. As discussed by Potvin and Fourie (2005), in Australia these operations include Henty, Cannington, St. Ives, and Kanowna Belle. As mentioned above, it is the shear strength that is of prime consideration in these applications and many studies have focused on how strength is affected by binder content, slurry density, particle size distribution of tailings, and cement water chemistry, among other factors (Henderson Revell, Landriault, & Coxon, 2005). Concomitantly, there has been no (apparent) reason to consider how the stiffness of the fill is affected by these parameters. As argued in this paper, the stiffness of CPB and how it evolves are critical issues in understanding CPB and

represents a significant departure from current thinking on this topic. The rate of stiffness increase is intrinsically dependent on the process of consolidation and this paper also emphasizes the critical importance of this process.

PROBLEMS WITH THE USE OF CPB

The use of CPB has not been without difficulties. One of the primary concerns that continues to bedevil more widespread application of the technique is safety. There have been a number of failures of the barricades (or barriers) that retain the fill before an adequate strength is developed, although many of these failures have not been reported in the literature. Helinski, Fourie and Fahey (2006) reported that, during the period between December 2003 and December 2004, there were at least six barricade failures worldwide and we are aware of another five occurrences in the 12 months up to February 2007. Mercifully, fatalities have rarely resulted from these accidents, although the risk to workers remains uncertain, but potentially severe.

OBSERVATIONS FROM THE SOIL MECHANICS LITERATURE

In mining applications, the principles of classical soil mechanics have been used to understand the behaviour of mine tailings, facilitating designs based on sound fundamental principles. As will be shown in this paper, there are numerous principles embedded in the soil mechanics literature that can be used to improve our understanding of backfill behaviour, leading, we suggest, to safer and more economical designs and operating procedures. Just because backfill material contains a binder does not mean that fundamental soil mechanics principles are not available to understand such materials. This section of the paper highlights some aspects of soil mechanics literature that have a direct relevance to backfill performance and may help to construct a model for the quantification of backfill behaviour.

PRINCIPLE OF EFFECTIVE STRESS

The most important principle in soil mechanics is effective stress. In a saturated medium (e.g. a fill material in which the voids are water filled), the total imposed stress, such as the vertical overburden stress, σ_v that results from the weight of overlying fill material is apportioned between the stress in the water in the fill voids, u, and the inter-particle contact stress σ_v', commonly referred to as the effective stress. In its simplest form the relationship is thus:

$$\sigma_v = \sigma_v' + u$$

In a material that drains very slowly, the sudden imposition of a load increment is carried by an equivalent increase in the pressure in the water in the voids, not by the inter-particle forces. This is because the water is less compressible than the soil or backfill matrix and, thus, carries the load. This is true even in a saturated cemented fill, as the stiffness of the pore water will still be far greater than a typical fully hydrated cemented fill material. As the water pressure gradually dissipates, the load is transferred to the soil or backfill matrix, resulting in the development of higher inter-particle forces (effective stress). This is the process termed consolidation. The adjective 'effective' is used to indicate that it is this stress, and not the total stress, that dictates the strength and stiffness of non-cemented soils; furthermore, it is this effective stress that produces deformation of the soil 'skeleton.'

A consequence of the 'total stress' approach to backfill analysis has been the confusion of definitions and parameters. One example of this is the concept of lateral thrust, as embodied in the earth pressure coefficient parameter. In soil mechanics, this term is defined as the ratio between the horizontal and vertical *effective* stresses: $K_0 = \sigma_h'/\sigma_v'$. In some of the backfill literature, this parameter is defined in terms of the horizontal and vertical total stress (indicated as K_T in this paper). It is important to recognize that $K_0 \neq K_T$ and ignoring this fact can lead to erroneous estimates of barricade loads and the degree to which arching may develop in a stope.

As an example, the original Marston (1930) technique of estimating lateral stresses, σ_h, under conditions where some arching occurs above the point of interest is based on the equation:

$$\sigma_h = \frac{\gamma B}{2\mu'}\left(1 - e^{2K_a\mu' H/B}\right)$$

where γ is the fill bulk unit weight, B and H are the width and total height (respectively) of the stope, μ' is the coefficient of sliding friction at the fill/wall interface, and K_a is the active earth pressure coefficient. This latter parameter is a function of the friction angle and is typically approximately 0.3. The important thing to notice about the above equation is the absence of any reference to pore water pressure. It effectively assumes that the fill is fully drained and that full inter-particle friction is developed. The implications of this simplification are discussed later in the paper.

IMPORTANCE OF STIFFNESS AND HOW IT DEVELOPS WITH TIME

The suitability of backfill in a particular application is invariably evaluated in terms of its unconfined

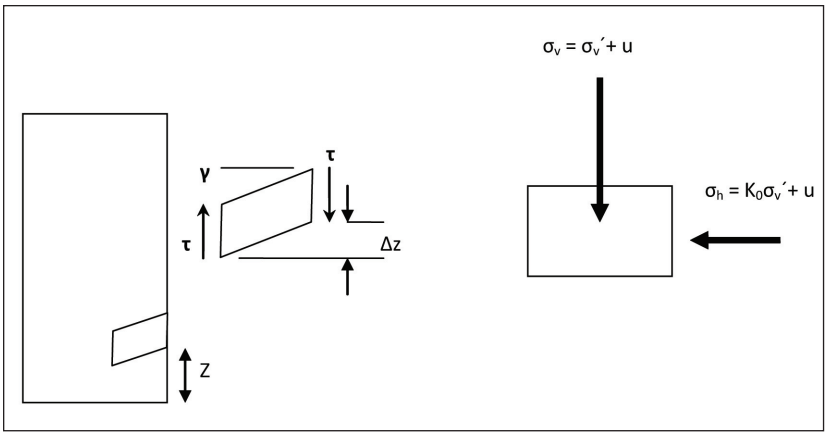

Fig. 1. Illustration of generation of shear strain at the backfill-wall interface and the effect on horizontal thrust.

compressive strength (UCS). The stiffness (or modulus of elasticity) is usually not a major consideration. The importance of the stiffness parameter in the behaviour of CPB is illustrated in Figure 1 by the simple column of backfill, which is assumed to be free draining at the base and to be confined by impermeable side walls. If the backfill is very impermeable and water does not drain out under gravity, due to the stiffness of the water phase, no settlement of the backfill surface occurs. If no settlement occurs, no shear stress is mobilized at the backfill/sidewall interface and the weight of the backfill is carried by the base of the cylinder containing the backfill. In other words, no arching occurs. At the other end of the spectrum (free draining hydraulic backfill), the fill begins to settle virtually as soon as it is placed and the distortion that occurs due to this settlement results in the mobilization of shear stresses at the fill/wall interface. The movement that occurs is initially resisted by the shear stiffness of the interface (or the material adjacent to the interface), so the stiffer the fill the more stress is generated (up to the limit of the available shear strength). The strength that can be mobilized at the interface will be a function of the friction that can be generated, which in turn is a function of the normal (i.e. horizontal) *effective* stress acting on any potential plane of slip, such as the interface. This again illustrates that, for any fill that is not free draining, it is the effective stress, and not the total stress, that is critical to quantifying the stress regime within a stope and, hence, how much arching (and thus stress relief on barricades) can actually occur.

YIELD VERSUS FAILURE

As mentioned earlier, consideration of backfill stability is invariably in terms of a measure of ultimate strength, i.e. a condition of failure. The concept of yield, which refers to a stress state that produces irrecoverable strains and precedes outright failure, is important to consider when trying to model backfill.

A significant component of the strength in a CPB is derived from the bonds of cementation. Any constitutive model must account for this cohesive strength, as well as how it may be mobilized and ultimately destroyed. A feature of CPB behaviour that is particularly pertinent to the performance of a filled stope, but is not well modelled by most existing constitutive models, is illustrated in Figure 2. This figure shows behaviour in confined compression of a cemented specimen (e.g. CPB) and the axes are the mean effective stress $p'=(\sigma_1'+2\sigma_3')/3$ on the horizontal axis, where σ_1' and σ_3' are the major and minor (often analogous to vertical and horizontal) principal effective stresses, and density is represented on the vertical axis. An increase in mean stress causes an increase in density. The dashed line on the figure is for an uncemented backfill and increases in mean effective stress result in a smooth increase in density. The solid line represents a cemented fill and the response to an increasing mean stress is a response that is initially much stiffer than the uncemented material, followed by a very rapid increase in density beyond a critical value of applied stress. This process occurs once a significant proportion of the bonds of cementation are broken, resulting in a 'collapse' of the internal structure of the fill. The shaded area on Figure 2 is often referred to as the 'stress permitted space' and the size of this space is a function of the cement bond strength.

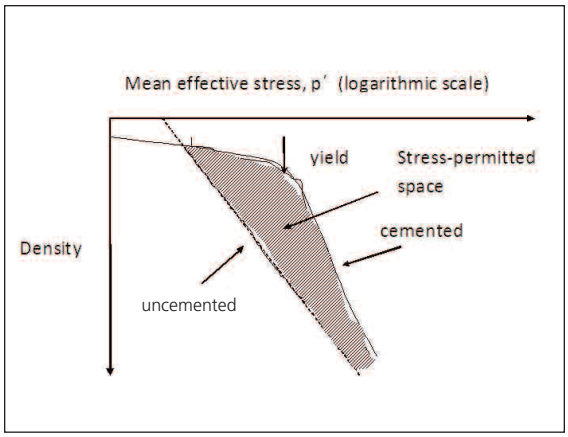

Fig. 2. Illustration of additional yield strength generated by bonds of cementation in a CPB.

COHESIVE AND FRICTIONAL COMPONENTS OF THE ULTIMATE STRENGTH

In a study of the behaviour of cemented sand, Cuccovillo and Coop (1997) showed that bond degradation results in a progressive transformation of the structured soil into a frictional material, giving rise to changes in the yield stress and shear stiffness that contrasted with the strain-hardening behaviour of the

same sand without cement. The frictional component of strength is only mobilized at higher values of strain, once the cement bonds have been broken sufficiently to allow inter-particle friction to develop.

There are conflicting views on how the addition of cement influences the angle of internal friction of a cemented backfill. The majority of studies indicate a slight increase, which some have attributed to the more jagged arrangement of particles in a sheared cemented backfill. However, some soil mechanics researchers, such as Coop and Atkinson (1993), found that the critical state (i.e. ultimate limit state) friction angle of cemented material was slightly lower (37° vs 40°) than the equivalent uncemented material—an observation they attributed to the cement coating on particles making them more slippery. However, concerns such as this are relatively unimportant in the context of overall backfill performance, where the need to accurately determine and characterize the cohesive strength that develops far outweighs the importance of a small change in the angle of internal friction.

There is a paucity of information on how the stress conditions during curing affect the measured UCS. Early studies by Mitchell and Wong (1982) began to address these issues, but do not appear to have been followed up to any significant extent. In their studies, they found curing under humid conditions resulted in a lower UCS, which is unsurprising given that the humid curing resulted in specimens with higher water content after curing. Even more interesting is to consider how changing conditions during curing can influence the measured UCS. Many studies have compared density with UCS; for example, Rankine, Rankine, Sivakugan, Karunasena, and Bloss (2001) showed increases in UCS with percentage solids, with large changes in strength occurring as the solids content was incrementally increased from 74% in increments of only 2%. An obvious question that arises is, "how much densification in fact occurs during the curing process within a backfilled stope?" From studies such as those described above, it is clearly an important factor.

Consoli, Rotta, and Prietto (2000) showed that the stress state acting during the cementing process plays a fundamental role in the post-curing mechanical behaviour of a cemented soil and Rotta, Consoli, Prietto, Coop, and Graham (2003) reported the very important observation that a decrease in the void ratio (an increase in density) during formation of the cement bonds causes an increase in the primary yield stress and an expansion of the primary yield surface of the cemented material. Blight and Spearing (1996) also showed a very clear benefit of stope wall closure during curing, even at a closure rate equivalent to 5% per day. The benefit accrues from the increased density that occurs and, as long as the material is stressed during the curing process, the results are beneficial. This phenomenon is of more than passing interest, as it suggests that the initial density at which a backfill is placed is less important than the density existing at the time the cement bonds are formed.

ILLUSTRATION OF THE IMPORTANCE OF CONSOLIDATION IN A CPB

Measuring stresses within a minefill mass is fraught with difficulties, such as obtaining load cells that provide a true measure of stress and are unaffected by the changing stiffness of a hydrating backfill. The interaction between consolidation and arching was therefore studied using a geotechnical centrifuge. The equipment used was the geotechnical centrifuge at the University of Western Australia. The benefit of using a geotechnical centrifuge is that total force can be measured at a boundary rather than attempting to install an inclusion (stress cell) into the mass. Figure 3 shows the experimental setup installed in a "strong box" on the centrifuge.

This test involved placing material containing cement into a cylinder to investigate the interaction between consolidation and arching. The problem with using a geotechnical centrifuge is that, while the increase in gravitational forces helps increase the stresses (and in turn pore pressures), the drainage path remains constant. As a result, enormous hydraulic gradients are established and pore pressures are dissipated very rapidly. Therefore,

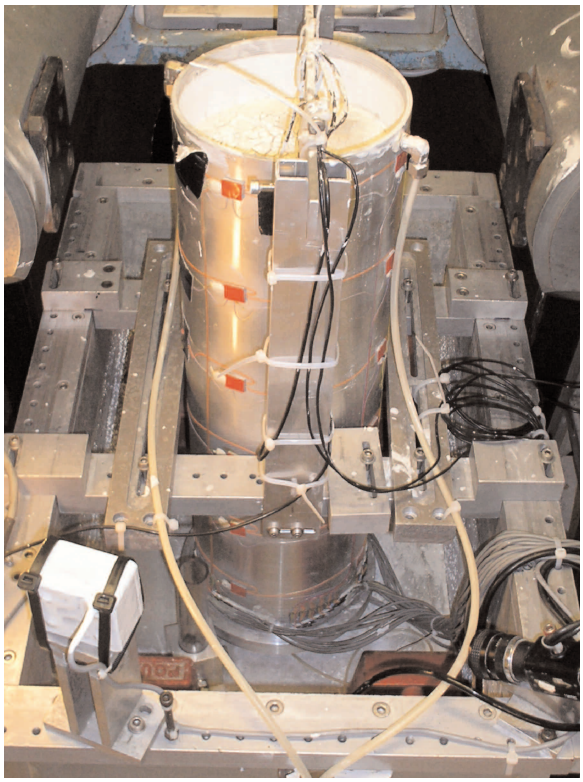

Fig. 3. Instrumented cylinder inside geotechnical centrifuge.

should a conventional mine tailings material be adopted for this work, the rate of consolidation would be very rapid even for the finest tailings material. In an effort to slow this consolidation rate, the material used was commercially available kaolin clay. Because the experiment was aimed at investigating the stress distribution in a cemented soil, 25% cement was added to the material. This ensured that the material would attain an unconfined compressive strength that was in the order of 300 kPa within 21 hours.

The cylinder had an internal diameter of 180 mm and was 600 mm high, with a threaded (rough) internal perimeter and a false base resting on loadcells 100 mm from the base of the cylinder. In addition, the wall of the cylinder was fitted with axial and hoop strain gauges. The hoop strain gauges were correlated with the total horizontal stress by filling the cylinder with water and spinning the centrifuge at various angular velocities; the axial strain was correlated against different axial forces by applying different weights to the top of the cylinder and spinning at different speeds. In addition, the pore water pressure was measured at the base as well as at different elevations throughout the material.

Testing was carried out under an average gravitational field of 100 x gravitational conditions. The test involved placing an initial layer 250 mm high and allowing this material to consolidate and cement for a period of 24 hours before placing a second layer (lift 2) 250 mm high above this layer. Strength testing indicated that after 21 hours of curing, the initial layer (lift 1) had achieved an unconfined compressive strength of approximately 300 kPa.

Figure 4 presents preliminary test results from this experiment. This plot only shows the response measured subsequent to the start of placement of the second lift, plotted against time. This second lift was placed 22 hr after the first layer and the period from 22.4 to 25.4 hr has been presented. Results do not include loads or pore pressures developed during the initial layer placement. Figure 4 shows that soon after placement (22.4 hr), the base load cells were registering an increase in load (2.6 kN) that corresponds to the total vertical load applied during placement of lift 2. This is an indication that there is no arching (even in the cemented layer). It can also be seen that the pore water pressure (right-hand axis) is at a maximum at this point. As the pore water pressure reduces (due to consolidation), there is an associated reduction in the load on the base and an increase in the load that is being transferred as axial load through the cylinder (measured by the axial strain gauge A6). This is an indication that even in the cemented soil, the behaviour is primarily dictated by consolidation.

During the placement of lift 2, the vertical stress that was applied to the surface of lift 1 was 105 kPa (this stress corresponds to the vertical load increment of 2.6 kN shown in Figure 4). It is interesting to note that the pore pressure measurement at the base of the sample (base of lift 1) showed an increase in pore pressure of 93 kPa upon placement of lift 2 (i.e. about 89% of the total vertical stress increment). Furthermore, the change in total horizontal stress that was measured at the H5 location was 94 kPa (the base of lift 1). These results suggest that when a vertical stress is applied to a saturated mass in an undrained fashion, there will be minimal arching, regardless of the degree of cementation. Furthermore, the increase in total horizontal stress at the base of this mass (which effectively represents the loading on a containment barricade) will be equal to this applied vertical stress. This experiment further demonstrates the point that in order to understand the loads that will be placed on barricade structures, one must first develop a comprehensive understanding of the consolidation behaviour.

QUANTIFYING BARRICADE STRESSES

Limit state techniques for estimating stresses, such as those suggested by Marston (1930) and Terzaghi (1943), can provide non-conservative results because, in addition to assumptions regarding effective stresses, there is also a fundamental problem with the assumed material behaviour. Limit state techniques such as these assume that cemented backfill is a rigid perfectly plastic material and that the peak strength is mobilized everywhere simultaneously. However, cemented soils demonstrate a behaviour that is anything but rigid or perfectly plastic and, depending on the geometry and effective stress, different degrees of the ultimate strength will be mobilized. To demonstrate this point, the rigid perfectly plastic material assumption has been superimposed on the stress-strain response of a typical CPB triaxial test in Figure 5. This figure shows that the assumption of perfect plasticity is in no way representative of the

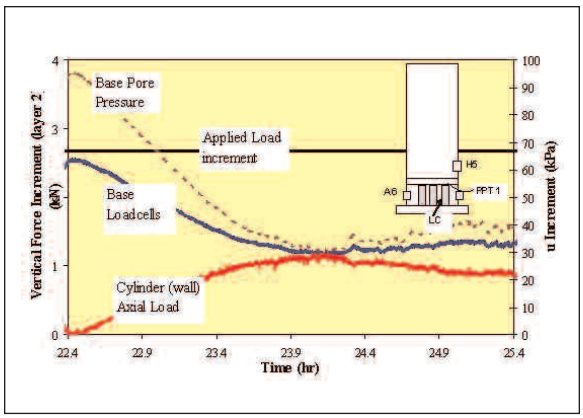

Fig. 4. Variation of applied load, measured vertical total stress and axial force in supporting cylinder during centrifuge test on cemented fill.

stress-strain relationship that is demonstrated by cemented fill material. Therefore, for a given strain level, the level of mobilized stress will be overestimated when using the rigid plastic model. Determining the stress distribution using this technique will therefore underestimate loads.

Other techniques, such as those of Belem, Harvey, Simon, and Aubertin's (2004) that were developed to take better account of the arching stresses within a stope, are based on the unit weight of the fill and geometrical parameters, such as stope height, width, and length. These techniques were derived empirically using in-situ stress measurements that were obtained during filling and were, effectively, an empirical approach based on measured data. This approach is heavily dependent on the measurement of stress within a cemented mass. It is now widely accepted in the soil mechanics community that the measurement of stress in a soil mass is heavily dependent on the stiffness of the fill relative to that of the load cell being used. In addition, the backfill application is even more complex as the stiffness of the fill increases during the hydration process (often by more than an order of magnitude). A relatively soft inclusion in a stiff medium, such as a cemented fill, results in the stress being redistributed around the soft inclusion. As a result, for a given increment of stress, the value registered by the load cell is reduced as the fill hydrates—a phenomenon known as under-registration. The degree of under-registration was investigated numerically and experimentally by Clayton and Bica (1993) who produced Figure 6, which relates the degree of the actual stress that is registered to the flexibility ratio F, where F is defined as:

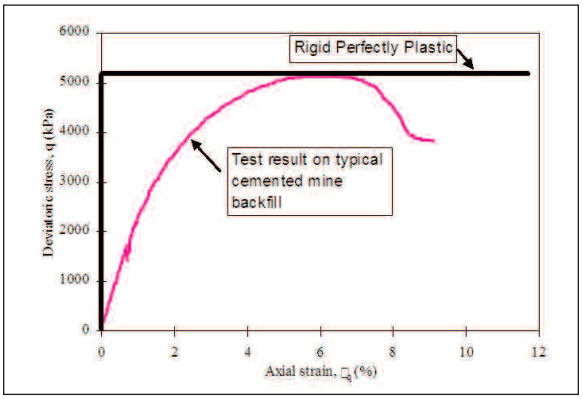

Fig. 5. Comparison of rigid perfectly plastic assumption inherent in Limit State approach to typical stress-strain curve for cemented backfill.

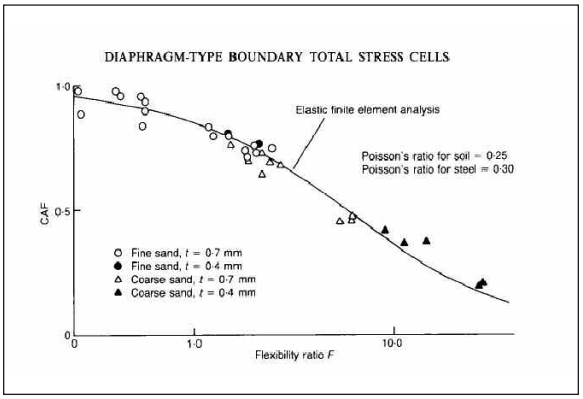

Fig. 6. Variation of degree of under-registration of a load cell with the flexibility ratio (after Clayton and Bica, 1993).

$$F = \frac{E_{soil}R^3}{E_{cell}t^3}$$

where E_{soil} is the small strain Young's Modulus of the soil, E_{cell} is the Young's Modulus of the load cell, and R and t are the radius and thickness of the load cell, respectively.

As cement hydrates, there will be a significant increase in the small strain stiffness of the fill (E_{soil}) and as a result F will increase causing the load cell to progressively under register. Figure 6 shows where a typical Australian earth pressure cell with cemented backfill (having a 28-day UCS of 800 kPa) would plot on this figure. As can be seen, the increase in stiffness causes a progressive under-registration. After a curing period of 24 hours, the material would only register 75% of the applied load, while, after 100 hours, the cell would only register 60% of they applied load. This calculation was done using the theoretical compressibility of the oil within this cell. However, Bond (1989) suggested that the entrainment of as little as 0.01% of air into this oil will reduce the stiffness by 400 times. This would obviously result in significantly more under-registration, the final point being that these cells are typically calibrated in water (which has no shear strength) so, under these conditions, E_{soil} would be zero. As a result, regardless

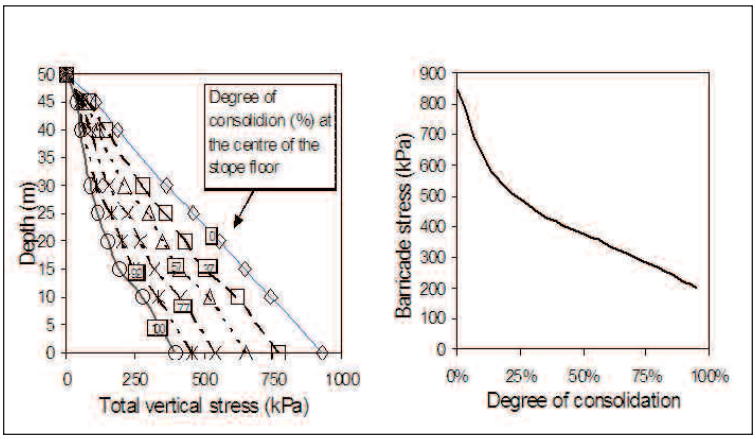

Fig. 7. (a) Vertical stress along stope centre line, and (b) barricade loads versus degree of consolidation.

of how "soft" the cell is (due to air entrainment or other), this would never be recognized during the calibration process.

Overall, none of the previous methods account for the stiffness of the backfill or for the stresses induced within the fill or along the fill/wall interface as consolidation of a CPB occurs. To illustrate the importance of this process, consider Figure 7, which shows the distribution of total vertical stress with depth as a function of the degree of consolidation of the fill (0% degree of consolidation represents undrained conditions and 100% consolidation represents the fully drained and consolidated condition), as well as the effect of degree of consolidation on the calculated barricade stress. This example was for a 50 m deep stope and is described in detail in Helinski et al. (2006). The differences in estimated barricade load range from about 80 kPa (for fully drained conditions) to in excess of 850 kPa (for undrained conditions). Clearly this range of uncertainty is unacceptable and begs the question, which is correct and what value would a conventional analysis produce? In this case, the calculated barricade load using the Marston approach would be about 250 kPa, which seriously underestimates the undrained (0% consolidation) load condition (which is probably the most relevant if filling were to occur rapidly). The Terzaghi solution produces a negative number (because of the high cohesion value), which clearly makes no sense. Even this simple example illustrates why it is not surprising that there have been such a large number of barricade failures in recent times.

DEVELOPING AN APPROPRIATE MODEL FOR CEMENTED PASTE BACKFILL

The preceding discussion set out a number of aspects of CPB behaviour that need to be incorporated in a constitutive model if the behaviour is to be modelled rationally.

Inclusion of the effective stress concept in constitutive models in finite element computer codes is nothing new. However, these programs are not primed to address issues such as self-desiccation, bond formation under stress, and displacement-induced damage to bonding. Furthermore, the fundamental issues of dealing with effective stresses generated in material with little or zero stiffness (e.g. a newly placed backfill) and the ability to handle changing boundary conditions cannot be addressed by the majority of available computer codes.

As a starting point for the development of a model that includes all of the above considerations, a program developed for modelling the consolidation of very compressible mine tailings (named MinTaCo) was modified. This program has been comprehensively described by Seneviratne, Fahey, Newson, and Fujiyasu (1996) and only key features are mentioned here. MinTaCo is a one dimensional model, which uses a large-strain formulation with Lagrangian coordinates and Gibson's consolidation equations (Gibson, England, & Hussey, 1967) to deal with the large volume changes that occur as tailings consolidates from a slurry. Fresh tailings slurry can be added at any desired rate and this rate can be changed at any stage during filling. The properties of the fresh layers can be different from preceding layers. The 'settled density' of the material is taken as the starting point for consolidation.

These features made the program ideal as the basis for developing a model for CPB. This was done and a modified version, named CeMinTaCo, was developed that incorporates what are considered to be the important characteristics that influence the consolidation behaviour of a cementing soil. These include the development of stiffness during hydration, the reduction in permeability, and the self-desiccation process, as well as allow for the possibility of yield and damage due to excessive loading. The model has been comprehensively described by Helinski, Fourie, and Fahey (2007) and the present discussion focuses on the insights that have been made possible through the use of the new model.

Figure 8 shows the results from a simulation that was aimed at determining the influence of the cement hydration characteristics on the consolidation behaviour. This example has been taken from Helinski et al. (2006). This simulation adopts an initial filling rate of 8 m/day, followed by a rest period of 36 hours. After the rest period, filling was resumed at 0.4 m/day. The use of a rest period such as that simulated here is not unusual and is intended to allow the development of a plug of material that can carry the overburden load of the fill material that is placed subsequently. The same filling sequence was simulated three times with the first of these neglecting any cementation, the second including the stiffness increase and permeability reduction due to cementation, and the third analysis accounting for the stiff-

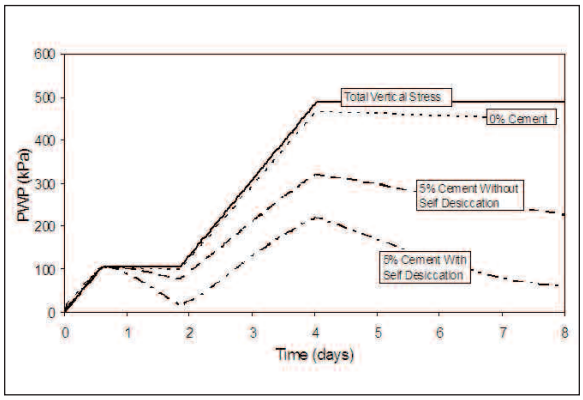

Fig. 8. Illustration of the impact of increasing stiffness and of self-desiccation on the generation and dissipation of excess pore water pressure at a point 2 m above the base of the stope.

ness increase, the permeability reduction, and the self desiccation mechanism.

The pore pressure at a point 2 m above the base has been plotted against time for each of the simulations in Figure 8. Also shown in Figure 8 is the total vertical stress against time, which has been plotted as a solid line.

Placement of the fill with no cement clearly results in virtually no pore pressure dissipation. Without consolidation, there would be no stress redistribution and the barricade would be required to carry the entire hydrostatic head of the fill. Referring to Figure 7(b), it is expected that a barricade stress in the order of 850 kPa would be experienced. Allowing for stiffness development as a consequence of cement bond formation significantly reduces the pore pressure within the fill to display approximately 40% consolidation at the completion of filling. Referring to Figure 7(b), this would correspond to a barricade load of approximately 400 kPa, approximately 50% of the undrained case. The reduction occurs because, as argued earlier in the paper, the development of a stiff fill facilitates consolidation that mobilizes shear stresses at the interface between the fill and the stope wall, which in turn reduces the loads transferred through the fill and onto the barricades. It does not mean that the fill is now draining more rapidly than in the 0% cement case, but, as the stiffness is higher, less strain (and therefore drainage) is required to mobilize a given stress. The rate at which the stiffness increases with time in the model is derived from laboratory tests on the relevant fill/binder/water mixture, as described in Helinski et al. (2007), and requires material-specific test work and characterization.

Taking account of the self-desiccation effect has an even more pronounced effect on the resulting pore pressures, increasing the consolidation to approximately 75%. Given this level of consolidation, Figure 7(b) indicates that the barricade stresses will have reduced to approximately 200 kPa. The reason for the additional lowering of the pore water pressure is the reduction in volume that occurs during the hydration process. Because the fill material is becoming stiffer with time, any reduction in volume results in an increasingly large reduction in pore water pressure. The mechanics are more fully explained in Helinski et al. (2007), but the results shown here indicate the effect very clearly.

CONCLUDING REMARKS

This paper has concentrated on highlighting the significance of some simplifying assumptions that are being made when estimating barricade loads in CPB. These include the assumption of a rigid perfectly plastic material response, the assumption of fully drained conditions, and the dependence on questionable data relating to the in situ measurement of stress.

Through experimental and numerical means, the significance of these assumptions has been highlighted, and the basis for a rational approach to determining the evolution of stress within a minefill mass has been presented. The authors believe that the development of stress during filling is absolutely imperative in understanding many areas of uncertainty relating to mine backfill. While this document has focused on the influence of stress (and effective stress) on barricade loads, it is also believed that improving our understanding of the application of effective stress during filling (and in situ curing) will also provide a useful basis for reconciling the well-documented difference between the strength of laboratory-prepared samples and that measured for in situ core samples. This application is ongoing and will be presented in the future.

The model described in this paper has recently been extended from a one-dimensional formulation to a two-dimensional (plane strain or axisymmetric) version, and plans are to eventually extend it to three dimensions. However, even the simple 1-D version is able to explain and describe some of the more complex interactions that occur in a cemented backfill.

The utilization of CPB to fill stopes is increasing and is likely to increase more rapidly with time, as the environmental benefits start to be costed and considered alongside the production and engineering benefits. There have been great strides made in the preparation, transport, and placement of CPB over the past few years, and there has been an improved understanding of the importance of rheology in this application. Our understanding of the post-placement geomechanical behaviour has probably not kept pace with these other developments and some of our existing techniques for estimating barricade loads and exposure stability appear to be over simplistic.

This paper proposes that it is only through the development of an understanding based on the principle of effective stress, which underpins all conventional soil mechanics engineering, that we can begin to accurately quantify the interaction between various fills, binders, and preparation water, and how these effects manifest in the behaviour of the CPB once placed. Aside from improving the safety of underground workers (e.g. by improving our understanding of barricade loads and thereby preventing future failures and underground inrushes), significant improvements in scheduling of subsequent excavations can be effected and unnecessary rest periods avoided by correctly understanding the rate of strength and stiffness development. Once our understanding of these processes improves, we can expect the emergence of truly "designer fills," where the characteristics of the fill material are altered to achieve particular types of behaviour as circumstances dictate.

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