Assessment of the self-desiccation process in cemented mine backfills

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Abstract: During the placement of fine-grained cemented mine backfill, the high placement rates and low permeability often result in undrained self-weight loading conditions, when assessed in the conventional manner. However, hydration of the cement in the backfill results in a net volume reduction—the volume of the hydrated cement is less than the combined volume of the cement and water prior to hydration. Though the volume change is small, it occurs in conjunction with the increasing stiffness of the cementing soil matrix, and the result in certain circumstances can be a significant reduction in pore-water pressure as hydration proceeds. In this paper, the implications of this phenomenon in the area of cemented mine backfill are explored. An analytical model is developed to quantify this behaviour under undrained boundary conditions. This model illustrates that the pore-water pressure change is dependent on the amount of volume change associated with the cement hydration, the incremental stiffness change of the soil, and the porosity of the material. Experimental techniques for estimating key characteristics associated with this mechanism are presented. Testing undertaken on two different cement–minefill combinations indicated that the rate of hydration and volumes of water consumed during hydration were unique for each cement–tailings combination, regardless of mix proportions.

Key words: cementation, tailings, self-desiccation, consolidation, pore-water pressure.

Résumé : Durant la mise en place du remblayage de mines cimenté à grains fins, les taux élevés de mise en place et la faible perméabilité résulte souvent en des conditions de chargement non drainé sous son poids propre, lorsqu'on l'évalue de façon conventionnelle. Cependant, l'hydratation du ciment du remblayage résulte en une réduction de volume nette — le volume du ciment hydraté est inférieur au volume combiné du ciment et de l'eau avant hydratation. Quoique le changement de volume soit faible, il se produit en même temps que l'accroissement de la rigidité de la matrice de ciment du sol, et le résultat dans certaines circonstances peut se traduire par une réduction significative de la pression interstitielle lorsque l'hydratation progresse. Dans cet article, on explore les implications de ce phénomène dans le cas de remblai de mine cimenté. Un modèle analytique est développé pour quantifier ce comportement dans des conditions non drainées aux frontières. Ce modèle montre que le changement de pression interstitielle dépend de la quantité de changement de volume associé à l'hydratation du ciment, des changements par incréments de la rigidité du sol, et de la porosité du matériau. On présente les techniques expérimentales pour estimer les caractéristiques fondamentales associées à ce mécanisme. Des essais réalisés sur deux différentes combinaisons ciment – remblai ont indiqué que le taux d'hydratation et les volumes de l'eau consommée durant l'hydratation sont uniques pour chaque combinaison ciment – stériles, quelles que soient les proportions du mélange.

Mots-clés : cimentation, stériles, auto dessiccation, consolidation, pression interstitielle.

[Traduit par la Rédaction]

Introduction

Backfilling with mine tailings is a process used in many underground mining operations, often with cement added to the tailings. This process involves filling tall underground voids with a free-flowing combination of mine tailings, water, and cement. Though each site has unique characteristics, the placement of over 10 vertical metres of silt-size material in a single day is not uncommon. Whereas hydraulic fills may be sufficiently permeable to allow the resulting excess pore-water pressures to dissipate rapidly during filling, the combination of rapid loading rate and a fine-grained material commonly used in paste fill operations can result in self-weight loading conditions that are close to being undrained. Further details on the process can be found in Potvin et al. (2005).

At underground openings in the mined-out voids, this material is contained using structural barricades. The loads that are likely to be placed on these containment barricades during filling depend on a number of complex mechanisms, (including self-weight effects and hydraulic boundary conditions). However, as demonstrated by Helinski et al. (2006), the presence of pore-water pressure can significantly increase the loads applied to barricades.

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The process known as "self-desiccation" has been well documented with respect to its impact on concrete behaviour. The basis of this process is that following cement hydration, the resulting hydrated volume is less than the combined volume of the unhydrated constituents (cement and water). Researchers such as Powers and Brownyard (1947), Bentz (1995), Hua et al. (1995), Koenders and Van Breugel (1997), and Brouwers (2004) investigated the impact of this mechanism on the shrinkage of conventional concrete. Most conventional concrete masses have lean (low) water contents and are placed in thin horizontal layers, resulting in a low total vertical stress. Therefore, the volume reduction of the cement–water constituents would often result in the development of negative pore-water pressure and desaturation of the mixture—hence the term "self-desiccation."

However, cemented mine fills have much higher water contents (and lower cement/water ratios) than conventional concrete and can exhibit high self-weight total stresses due to rapid rates of rise in typical filling operations. In fine-grained (paste) fills, this can result in high positive pore pressures. As a result, the processes involved in self-desiccation act in these circumstances to reduce the build-up of positive excess pore-water pressure rather than desaturating the material and creating negative pore-water pressures. In these circumstances, there is no "self-desiccation" per se. Thus, when reference is made to self-desiccation in this paper, the authors are referring to the reduction in pore-water pressure, resulting from cement hydration rather than desaturation (desiccation) of the material. The term "self-desiccation" has been used to preserve consistency with the mechanism of hydration-induced water-volume reduction rather than implying any actual "drying out" (desaturation).

The aim of the work described in this paper is to show that the self-desiccation process can have a significant effect on the behaviour of the backfill during the hydration process; to derive a model for describing the process; and to devise a laboratory testing procedure to enable the model parameters to be determined for any fill–cement combination.

This paper is divided into five sections:

(1) A theoretical analysis of the self-desiccation process that presents the previous work relating to volumetric changes during cement hydration, a conceptual discussion of how this can affect pore-water pressures, and an analytical solution that can be used to estimate the reduction in pore-water pressure as a result of cement hydration.

(2) A qualitative assessment of the self-desiccation concept that presents the results from some preliminary test work to demonstrate that pore-water pressure changes induced by self-desiccation are a real phenomenon.

(3) A discussion of the material properties likely to influence the self-desiccation process.

(4) The presentation of a series of laboratory experiments on two different minefill types to illustrate how the theoretical solution can be used along with laboratory experiments to derive the relevant material properties. The purpose of these experiments is to demonstrate that the proposed method is applicable across a broad range of tailings-based minefill types.

(5) The conclusion with a discussion of the key findings arising from the study.

Self-desiccation: background and theory

Cementation reactions

The reactions associated with cement hydration involve the chemical combination of cement and water. Assume that an enclosed volume of the soil–cement–water slurry prior to cement hydration contains a water volume (V_w) and an unhydrated cement volume (V_{cu}). After hydration, $\Delta V_{hyd} = V_{ch} - V_{cu}$, where V_{ch} is the hydrated cement volume. In this reaction, the increase ΔV_{hyd} is less than the volume of water used in hydration (V_{wh}). In keeping with the terminology used in the concrete literature, this loss of volume is denoted ΔV_{sh} (the "chemical shrinkage" volume).

For the purposes of the calculations that follow, V_{wh} can be conveniently considered to be composed of two parts—an amount converted directly into solid volume equal to ΔV_{hyd}, and a volume equal to ΔV_{sh} that is lost from the system as if it is removed via an internal water "sink."

$$[1] \qquad V_{wh} = \Delta V_{hyd} + \Delta V_{sh}$$

Thus, ΔV_{sh} represents an apparent water volume lost from the system due to the hydration reaction, whereas ΔV_{hyd} represents the water volume that is substituted by the solid volume, and hence has no overall effect on the total volume or water pressure.

All of this assumes that the soil voids can compress to accommodate the lost volume (ΔV_{sh}) in a completely unrestrained way, and ΔV_{sh}, when integrated over the total volume, would give the total shrinkage. This would be the case in a slurry where the soil matrix has zero stiffness, and the voids can compress without any change in effective stress or the pressure in the remaining water. Thus, it is only in this case that ΔV_{sh} in eq. [1] represents the apparent "unrestrained" water volume lost via the internal sink, and, when integrated, gives the overall slurry shrinkage. Conversely, in the hypothetical case of a soil matrix with infinite stiffness (assuming a fully saturated state and no inflow of water allowed), no overall volume change can occur, and the chemical shrinkage can only be accommodated by a volume expansion of the remaining water equal to ΔV_{sh}, leading to a drop in pore-water pressure equal to the bulk modulus of water multiplied by $\Delta V_{sh}/(V_w - V_{wh})$. For the general case of a soil matrix of finite stiffness, some of the volume loss is accommodated by soil matrix compression (and hence some increase in effective stress), and some by expansion of the remaining water (and hence some reduction in pore-water pressure). This will be discussed further in the next section.

Remember that minefill slurries are fully saturated, typically with an initial water content (mass of water per unit dry mass of soil) of 100% or greater and a cement content (mass of cement per unit dry mass of soil) of typically 2%–5%. Therefore, the water/cement ratio is much greater than that for the conventional concrete (for 100% water content, and 2% and 5% cement content, the water/cement ratios would be 50 and 20, respectively, in terms of mass; corresponding to about 160 and 62, respectively, in terms of volume.) Thus, the actual volume of water involved in hydration is relatively small, and hence volumetric strains in the water can be calculated relative to the original total volume of water (V_w), rather than the final volume ($V_w - V_{wh}$). In fact, in the numerical implementation of the equations, all calculations are performed in an incremental fashion, so that the volumes are continually updated, and the strains are therefore calculated using the appropriate water volume.

Following the convention used in soil mechanics, compressive stresses and strains are considered to be positive, while tensile stresses and strains are considered to be negative. Thus, the volume reduction is considered to be positive (and hence the chemical shrinkage (ΔV_{sh}) is positive).

Powers and Brownyard (1947) found experimentally that, for a fully hydrated system, ΔV_{sh} for a cement paste could be related to the mass of chemically combined water (W_n) through eq. [2]

$$[2] \qquad \Delta V_{sh} = 0.279\,W_n$$

where ΔV_{sh} is the volume reduction in cm^3 and W_n is in g (and thus the constant has units of cm^3/g). From a series of laboratory experiments, Powers and Brownyard (1947) found that W_n could be related to the proportion of the compounds that make up the cement product and the mass of unhydrated cement (W_c) in accordance with eq. [3]

$$[3] \qquad W_n/W_c = 0.187X_{C_3S} + 0.158X_{C_2S} + 0.665X_{C_3A} + 0.213X_{C_4AF}$$

where X is the proportion by mass of the subscript compound in the cement. For the proportions contained in most general Portland cements, Powers and Brownyard (1947) established empirically that W_n can be approximately related to W_c via eq. [4]

$$[4] \qquad W_n/W_c = 0.23$$

Combining eqs. [2] and [4] allows the shrinkage volume (in cm^3), which occurs in a general Portland cement paste over a full hydration period, to be determined. This relationship is shown in eq. [5] as a function of the original mass (in g) of cement

$$[5] \qquad \Delta V_{sh} = 0.064\,W_c$$

Impact on pore-water pressure

As previously mentioned, the apparent unrestrained volume change in the water resulting from hydration (ΔV_{sh}) could occur under undrained conditions only if the soil skeleton was of zero stiffness, and this volume change would result in an equal compression of the soil skeleton. To calculate the actual volume and pore-pressure changes, it is necessary to consider the water and soil matrix stiffnesses, and to use the principles of strain compatibility and stress equilibrium to calculate the actual behaviour.

The change in pore pressure is a function of the difference between ΔV_{sh}, as defined in eq. [1], and the actual reduction in void volume (ΔV_v), resulting from the soil matrix compression. The difference between these two volumes is denoted by ΔV_{rel}

$$[6] \qquad \Delta V_{rel} = \Delta V_v - \Delta V_{sh}$$

Effectively, the strain compatibility requires that the water must expand by ΔV_{rel} to accommodate the fact that ΔV_v is less than ΔV_{sh}, and hence ΔV_{rel} defined in eq. [6] is negative, signifying expansion.

Initially, when the soil matrix has a very low stiffness, ΔV_v is close to ΔV_{sh}, and hence there is very little pore pressure change. However, in the case of soil containing cement, an increase in stiffness occurs not only as a result of ongoing compression, as with uncemented soils, but also due to the formation of cement bonds, so that as the hydration proceeds, the pore-pressure reduction can be quite substantial.

Analytical model

An analysis relating the fundamental material properties to the reduction in pore pressure is discussed later in the paper. The analysis assumes that

- the material is in an undrained state with respect to the water flows across the external boundary;
- the soil compressibility is linear, corresponding to the current small-strain bulk modulus at any stage of hydration (though changing with ongoing hydration);
- soil particles are incompressible;
- the water bulk modulus (K_w) is constant; and
- the material is fully saturated at all stages of the process.

In the experimental work described later, full saturation at all stages has been assured by using high initial back pressure, so that positive pore pressures exist at all stages, even following the pore pressure reduction resulting from the hydration process.

The incremental change in pore pressure is given by eq. [7]

$$[7] \qquad \Delta u = \Delta\varepsilon_v K_w = \frac{\Delta V_{rel}}{V_w} K_w$$

where Δu is the change in pore-water pressure in the current increment, $\Delta\varepsilon_v$ is the increment of volumetric strain in the water required to maintain strain compatibility with the soil skeleton, and V_w is the current total volume of the pore water. Since ΔV_{rel} is negative (expansion), both $\Delta\varepsilon_v$ (expansion) and Δu (pore pressure reduction) are also negative.

The change in soil bulk volume is proportional to the change in effective stress. With a constant total stress, the change in effective stress ($\Delta\sigma'$) is equal in magnitude and opposite in sign to the change in pore-water pressure

$$[8] \qquad \Delta\sigma' = -\Delta u$$

The incremental volumetric strain in the soil matrix ($\Delta\varepsilon_{v\text{-soil}}$) is a function of change in the effective stress ($\Delta\sigma'$) as well as the bulk modulus of the soil matrix (K_s)

$$[9] \qquad \Delta\varepsilon_{v\text{-soil}} = \frac{\Delta V_v}{V_T} = \frac{\Delta\sigma'}{K_s}$$

where V_T is the total volume of the combined soil and water (bulk volume) and ΔV_v is the actual change in the void volume due to compression, which is identical to the change in the bulk volume ΔV_T, since the soil particles are taken to be incompressible.

Combining the behaviour of the pore water (eq. [7]) with the behaviour of the soil matrix (eq. [9]) via eq. [8] gives

$$[10] \qquad \frac{\Delta V_v}{V_T} K_s = -\frac{\Delta V_{rel}}{V_w} K_w$$

Equation [6] may then be substituted into eq. [10] to derive a relationship between ΔV_v and ΔV_{sh}

$$[11] \qquad \Delta V_v = \frac{(\Delta V_{sh} K_w)/V_w}{(K_s/V_T) + (K_w/V_w)}$$

which indicates, as expected, that $\Delta V_v = \Delta V_{sh}$ when $K_s = 0$. By combining eqs. [8], [9], and [11] and rearranging, a relationship can be obtained among the incremental change in the pore-water pressure (Δu), the bulk stiffnesses of the soil (K_s) and water (K_w), the porosity of the material (a function of V_w and V_T), and the chemical shrinkage volume (ΔV_w or ΔV_{sh})

$$[12] \qquad \Delta u = -\frac{\Delta V_{sh}}{V_w V_T} \frac{K_w K_s}{(K_s/V_T + K_w/V_w)} = -\frac{\Delta V_{sh}}{V_T} \frac{K_w}{(n + K_w/K_s)}$$

This gives $\Delta u \to 0$ as $K_s \to 0$, and $\Delta u \to -K_w[\Delta V_{sh}/(nV_T)]$ as $K_s \to \infty$, as expected.

Experimental demonstration of the effect of self-desiccation

A series of preliminary tests was carried out to demonstrate the validity and relevance of the self-desiccation concept as applied to the cemented tailings backfill. These experiments used a silty silica sand hydraulic fill (HF) from the CSA mine, which is located near Cobar in NSW, Australia, and a silt-sized paste fill (PF) from the Kanowna Belle (KB) mine, which is located close to Kalgoorlie in WA, Australia. These materials were mixed with 5% general Portland cement from the Kandos Cement Plant (Kandos, NSW, Australia) and Cockburn Cement (Perth, WA, Australia), respectively. In this paper, the cement content is defined as the mass of dry cement divided by the total dry mass of solids. Particle size distribution curves for the two tailings materials are presented in Fig. 1. The specific gravity (G_s) of the CSA material is 2.81 while that of the KB material is 2.72.

The tests were carried out on samples set up in a triaxial cell in the conventional manner. The specimens were prepared using the dry sand preparation technique explained by Ismail et al. (2000). This technique involves preparing the specimens dry before purging with CO_2 and back-pressure saturating the samples. While this sample preparation technique does not represent the mine filling process, the technique was adopted to ensure consistency between samples. Both samples were prepared at a void ratio of 0.80. After saturation in the triaxial cell, the cell pressure was increased to 550 kPa and the back pressure to 500 kPa. The purpose of the high back pressure was to ensure positive pore pressure and full saturation throughout the test, given the large pore-pressure reductions expected from the self-desiccation process. For both tests, the Skempton B value was checked and found to be >0.95. At this point, the back pressure valve was closed and the pore pressure was monitored with time. The results of the tests are presented in Fig. 2, which shows the applied total stress, the pore pressure, and the effective stress, plotted against time from the start of the test.

Figure 2 shows that, even with a cement content as low as 5%, the hydration process creates a significant reduction in pore pressure in both of the tested materials. With a constant total stress, this pore-water pressure reduction is associated with an effective stress increase of equal magnitude. It also shows that the rate and final amount of pore pressure reduction for the CSA HF specimen are significantly greater than for the finer KB PF specimen. Thus, the impact of the self-desiccation process depends on material type as well as other factors discussed later.

These tests provide a graphic illustration of the changes in pore pressure that result from the cement hydration process and the resulting change in effective stress, even where the samples are subjected to undrained boundary conditions. It is, therefore, apparent that this self-desiccation phenomenon needs to be considered when analysing the behaviour of cemented mine backfill, particularly where filling rates are rapid and fine-grained (i.e., low permeability) tailings are used, resulting in the hydration process occurring under undrained conditions.

Fig. 1. Particle size distribution of materials tested.

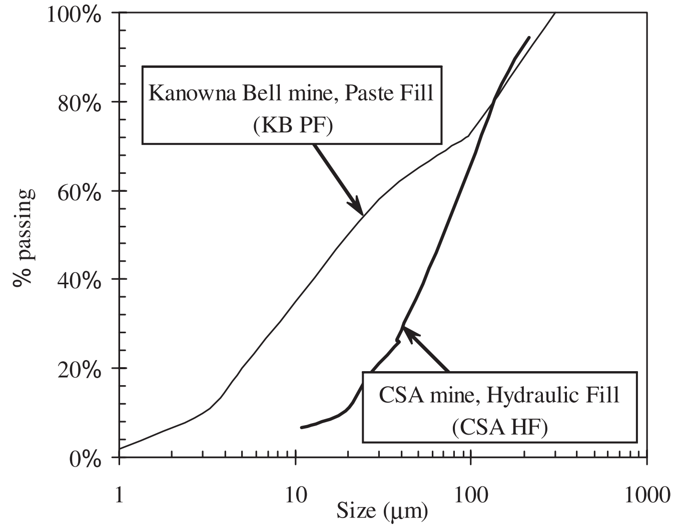
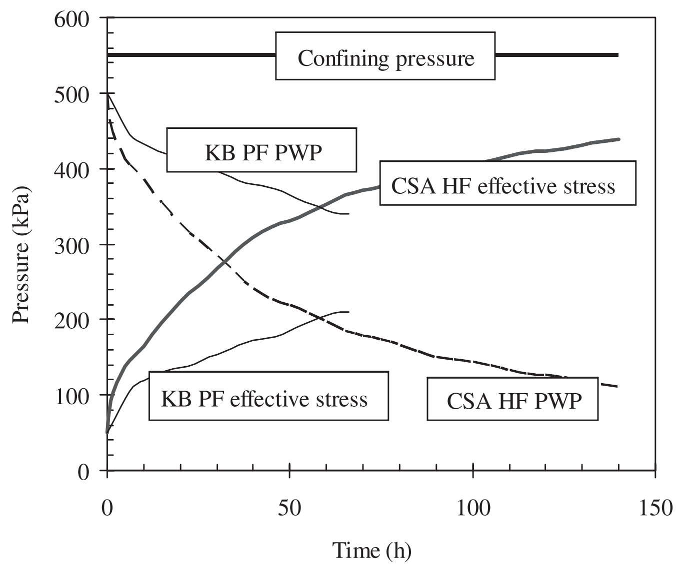


Fig. 2. Pore-water pressure (PWP) and effective stress changes in triaxial samples hydrating under constant total stress and undrained boundary conditions.



Material properties influencing self-desiccation

Equation [12] indicates that the reduction of excess pore pressure is sensitive to the water and soil bulk moduli (K_s and K_w) as well as to the rate of water consumption and the total volume of water consumed during the hydration process.

Material stiffness

Due to the growth and strengthening of the hydrates, the soil matrix undergoes an increase in stiffness during hydration. A nondestructive test that is often used in soil mechanics to monitor the "small strain" shear stiffness (G_{max}, also called G_o) of a soil matrix involves the measurement of shear wave velocity (Dyvik and Olsen 1989; Baig et al. 1997; Fernandez and Santamarina 2001). This technique consists of generating a shear wave pulse at one end of a sample using a piezoceramic "bender element," and measuring the arrival time at the opposite end of the sample using a second "bender element."

Figure 3 shows an example of the data from one of the tests carried out in this study. In this case, the transmitting bender element is excited by a single sine-wave pulse, nominally of 10 V amplitude, and the arrival of this shear wave at the other end of the sample is picked up by the receiver bender element. Based on the time of transmission and the length of the sample, the shear wave velocity (V_s) can be obtained. From V_s and the bulk density of the material (ρ), the value of G_{max} may be inferred using eq. [13]

$$[13] \qquad G_{max} = \rho V_s^2$$

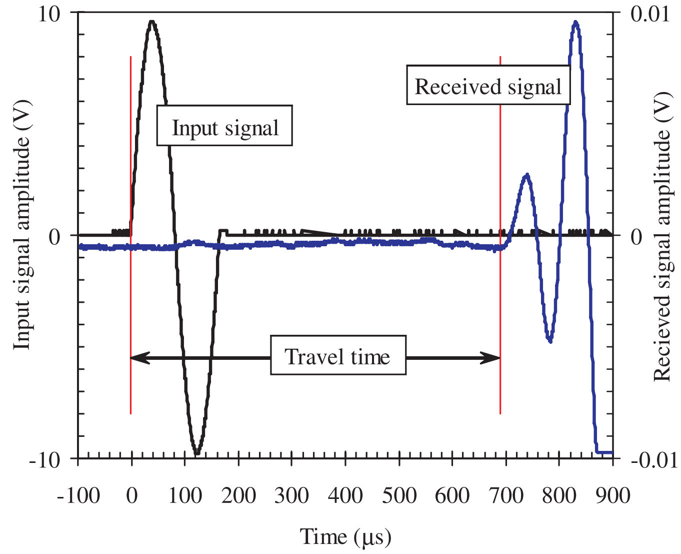
This test can be carried out at intervals during the hydration process to monitor the development of the shear modulus with time. The corresponding "small strain" effective bulk modulus, K_{max}, can be related to G_{max} via the Poisson's ratio (ν)

$$[14] \qquad K_{max} = \frac{2(1+\nu)}{3(1-2\nu)} G_{max}$$

In this paper, this value of K_{max} is assumed to be equivalent to the K_s mentioned previously (e.g., eq. [9]), which is equivalent to assuming that the incremental soil matrix stiffness is linear over the range of strain relevant to this work at each stage of the process. Santamarina et al. (2001) and Jamiolkowski et al. (1994) suggest that a "small strain" drained Poisson's ratio of 0.1 to 0.15 is appropriate for many soils, and thus, for the interpretation of the results in this paper, a small strain Poisson's ratio of 0.125 has been adopted. It should be noted that varying the Poisson's ratio over this range has minimal impact on the results.

At The University of Western Australia, bender elements are fitted as standard in triaxial setups, allowing shear wave velocity (and hence G_{max}) to be determined routinely. Measuring the compression wave velocity (V_p) and the equivalent E_{max} could also be used to indicate the progress of hydration, but doing so in the triaxial apparatus was not possible with the available equipment.

Fig. 3. Typical result from "bender element" test.



Water consumption during hydration

The process determining the rate at which pore-water volume is consumed is very complex and is made particularly difficult to quantify theoretically owing to

- the hydration of cement involving at least eight different chemical reactions;
- each reaction consuming different volumes of water;
- each reaction producing a different hydrate volume;
- each reaction commencing at a different time after the start of hydration;
- each reaction occurring at a different rate;
- only cement surfaces exposed to pore water reacting;
- the cement may be made up of different proportions of each constituent;
- the reactions are dictated by the random collision of various cement constituents; and
- not all of the total cement content in the mix may react.

Cement technology researchers have developed detailed microscopic models to predict this process for the purpose of concrete shrinkage predictions (Bentz 1995). These are complex models that involve the input of many fundamental cement properties, and further discussion of them is beyond the scope of this work.

The other complicating factor associated specifically with mine backfill is that, in addition to different cement types, different tailings mineralogy and chemicals contained in the tailings after processing may have an impact on the chemical reactions that take place. It is suggested that the most practical method of determining the net volumetric change and the rate at which this change occurs is through direct experimentation with each cement–tailings combination. Furthermore, it is suggested that, rather than adopting the total volume change (eq. [5]) determined by Powers and Brownyard (1947), the volume change should be defined using a variable (E_h) for each particular cement–tailings combination. Therefore, eq. [5] is rewritten as eq. [15], where E_h is defined as the total volumetric change (ΔV_{sh}) per unit mass of cement (W_c)

$$[15] \qquad \Delta V_{sh} = E_h W_c$$

Experimental derivation of parameters

By measuring the incremental pore-water pressure reduction and monitoring the material stiffness, the rate of water volume consumption may be back-calculated using the proposed analytical solution (eq. [12]). The rate of hydration (d) and hydration efficiency (E_h) are considered fundamental material properties. Therefore, once determined, these parameters may be incorporated into a coupled analysis model to account for the impact of this mechanism on the consolidation and filling process.

Experimental procedure

A series of pore pressure reduction experiments was carried out to verify the proposed strategy and provide examples of how the experimental process may be conducted and how the relevant material parameters may be derived. The material used in these experiments was again silty sand (hydraulic fill) from the CSA mine and silt (paste fill) from the KB mine. These materials were mixed with general Portland cement from the Kandos Cement Plant (Kandos, NSW, Australia) and the Cockburn Cement Company (Perth, WA, Australia), respectively, in various proportions.

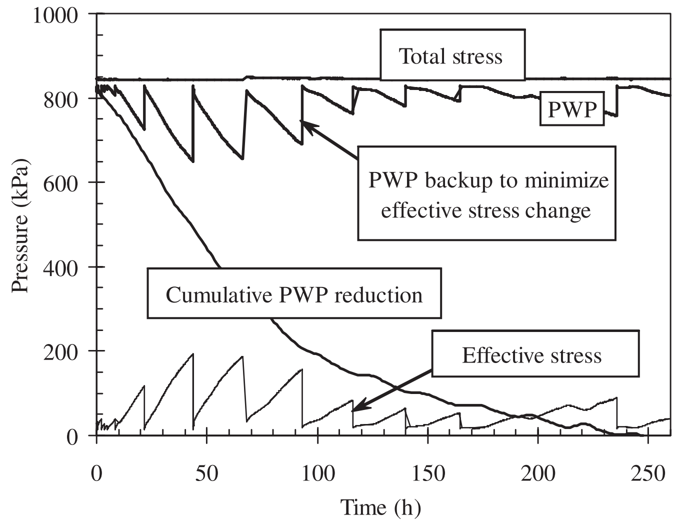
The experiments were conducted in a triaxial cell, with the specimens being prepared using the dry sand preparation technique explained by Ismail et al. (2000). During saturation, the amount of water added to the system was measured (as this would be the volume of water subject to the volumetric changes).

As was shown in Fig. 2, the hydration process results in an apparent reduction in water volume, which leads to a reduction in pore pressure and a corresponding increase in effective confining stress. This increase in effective stress could lead to yielding of the hydrating matrix, which would invalidate the assumption that the small strain stiffness (K_{max}) is the relevant bulk stiffness (K_s) for the soil. Also, depending on the initial back pressure, the reduction in pore pressure could lead to air coming out of solution, thereby changing the bulk modulus of the pore fluid.

To avoid any of these potential problems associated with decreasing pore-water pressure, the back pressure and cell pressure were initially set at values well above those recommended by Bishop and Henkel (1962) for complete saturation. To avoid the possibility of yielding due to increasing effective stress, the effective stress was kept low by regularly restoring the back pressure to its original value by opening the drainage valve at various stages during the test. This restoration of back pressure meant that, strictly speaking, the experiment was not conducted under undrained conditions, but since the material properties were only determined during the undrained stages (i.e., while the back pressure valves were closed) the application of eq. [12] remains valid. At different stages during the tests, shear wave velocity measurements were made, using bender elements to monitor the evolution of stiffness (G_{max}) with time.

Figure 4 presents the results of one of the tests on the CSA HF (hydraulic fill) material. This shows the actual pore pressure behaviour (i.e., reduction in pore pressure while the drainage valve was shut), followed by restoration of the initial back pressure in the brief intervals when the valve was opened. From this, the cumulative pore pressure change was determined to be of the order of 800 kPa for this test. The actual effective stresses during the test are also shown, with the procedure adopted limiting the effective stress to a maximum of less than 200 kPa.

Fig. 4. Typical pore-water pressure (PWP) and effective stress changes in a triaxial sample hydrating under constant total stress and undrained boundary conditions (with periodic re-establishment of back pressure, to minimize effective stress change).



An identical test on an uncemented specimen was carried out prior to those on the cemented specimens to assess the compliance of the system. The system indicated a pore pressure change of <5 kPa for the uncemented specimen over a 3 day period, indicating that the system was free of any leaks.

Stiffness development

From the measurements of G_{max} made as hydration proceeded, eq. [14] was used with a Poisson's ratio of 0.125 to determine the soil matrix small strain bulk modulus (K_{max}), which was taken to be equivalent to K_s. Figure 5 shows how this calculated value of K_s increased with time during the various experiments.

The lines shown in Fig. 5 are based on the exponential "maturity relationship" for cement hydration published in Illston et al. (1979). For this application, this relationship takes the form

$$[16] \qquad K_s = K_{s\text{-}i} + \Delta K_{s\text{-}f} \exp\left(\frac{-d}{\sqrt{t - t_o}}\right)$$

where $K_{s\text{-}i}$ is the initial bulk modulus, $\Delta K_{s\text{-}f}$ is the increase in bulk modulus at the completion of the hydration period, d is a "maturity" constant, and t_o is the time to initial set. The lines in Fig. 5 were obtained using d = 0.9 day$^{0.5}$ with all cement contents. The time until initial set was found to be reasonably consistent at about 4 h for all these tests.

Pore pressure reduction

As explained previously, the test procedure used in these tests involved opening the drainage valve at regular intervals during the test, thereby re-applying the initial back pressure. The data from pore pressure reduction in the undrained phases that followed each of these re-applications of back

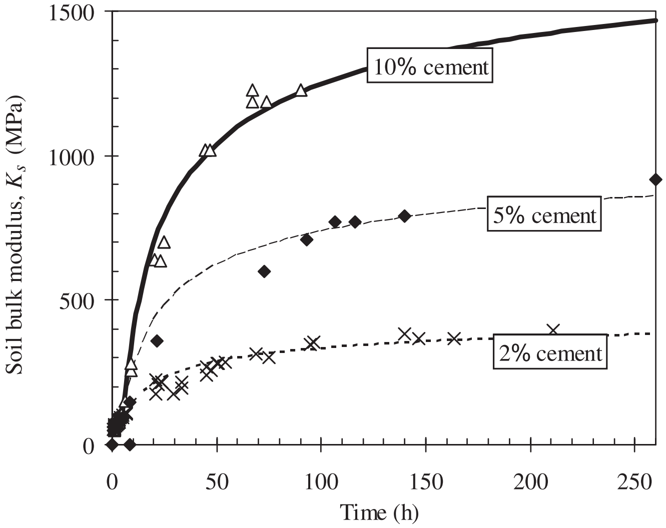


Fig. 5. The development of bulk stiffness K_s with time for CSA hydraulic fill: experimental data (symbols) and eq. [16] (lines).

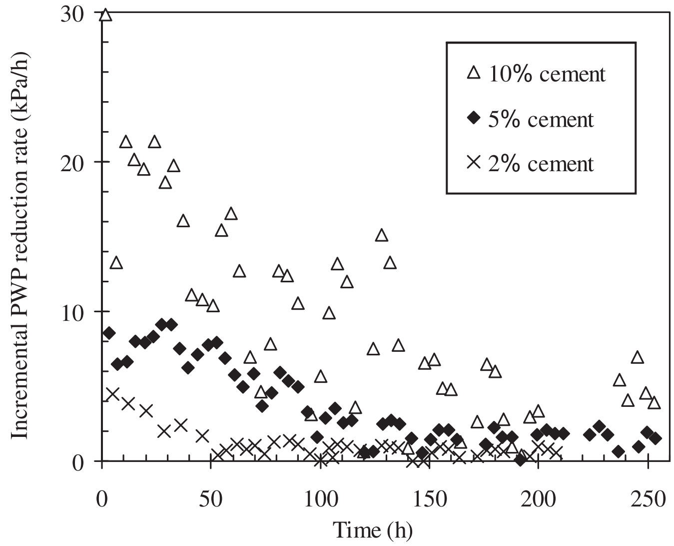


Fig. 6. Rate of pore-water pressure (PWP) reduction with time after initial set for various cement contents for CSA hydraulic fill.

pressure can be combined to form a continuous pore pressure reduction curve for each test, as shown in Fig. 4. By dividing the pore pressure reduction into 1 h increments, the incremental rate of pore pressure reduction was determined for the duration of the test. Figure 6 shows this incremental reduction rate plotted against time for the CSA hydraulic fill material with different cement contents.

While there is obviously some fluctuation in the pore pressure measurements, it can be seen that the rate of reduction diminishes with time over the duration of the test (from the start of initial set). Figure 6 also indicates that the rate of pore pressure reduction increases with an increase in cement content. It should be noted that the pore pressure fluctuation is temperature sensitive (fluctuating on a 24 h cycle), suggesting that these tests should have been conducted in a temperature-controlled environment.

Pore-water volume decrease

To incorporate the self-desiccation mechanism into a finite element (or other numerical) computer code, the incremental water volume consumption with time is required. As explained previously, this refers to the apparent water lost via a notional internal "sink," which in reality corresponds to the chemical shrinkage volume (ΔV_s) but we will continue to refer to it here as water volume loss. By substituting the instantaneous bulk modulus and the pore-water pressure reduction over a given time period into the analytical solution (eq. [12]), and rearranging, the pore-water volume loss over that given time period may be back calculated.

Direct measurement of actual water volume consumption was also attempted in these experiments. However, the volume measuring system used proved to have insufficient resolution and accuracy, given that the volumes involved were of the order of tenths of a gram per day. The use of a better system for such measurements is a priority for future experiments.

After calculating the rate of water volume change throughout the experiment as described above, the results can be divided by the relevant cement mass to determine a rate of volume change per unit mass of cement. The results of this analysis are presented in Fig. 7 as the rate of water volume loss per unit mass of cement ($\Delta V_w/W_c$) plotted against time for tests with three different cement contents.

The "maturity model" presented by Illston et al. (1979) was combined with eq. [15] (for final apparent total water consumption) to estimate the total water volume change after a given hydration time (t). This relationship has been differentiated and divided by the mass of unhydrated cement (W_c) to derive a function for the rate of volume change per unit mass of cement. This function is presented as eq. [17]

$$[17] \qquad \frac{\delta(V_w/W_c)}{\delta t} = \frac{\delta(V_{sh}/W_c)}{\delta t} = \frac{1}{2}E_h\left(\frac{d}{t^{1.5}}\right)\exp\left(\frac{-d}{\sqrt{t}}\right)$$

The same maturity constant ($d = 0.9$ day$^{0.5}$) found for the rate of stiffness development was substituted into eq. [17], and the efficiency term (E_h) was adjusted to achieve the best fit to the experimental data, resulting in a best-fit value of $E_h = 0.035$ cm^3/g. The derived curve was compared with the experimental data in Fig. 7. In this case, the fit was obtained by taking t as applying from the start of the test, rather than the initial set; slightly different parameters would be obtained if the latter had been used.

Cumulative pore pressure reduction

Combining the experimentally derived terms for hydration efficiency ($E_h = 0.035$ cm^3/g) with the maturity constant (d), the rate of pore pressure change can be determined. This rate may be integrated over a given time period to predict the cumulative pore-water pressure drop. The experimental results for CSA material are compared with the analytical solution in Fig. 8 with $d = 0.9$ day$^{0.5}$ and $E_h = 0.035$ cm^3/g.

Figure 8 indicates that the predicted pore pressure reduction due to cementation can be estimated accurately using the proposed analytical solution with appropriate values of d and E_h. The values of d and E_h are unique for a given cement–tailings combination over the range of typical cement contents. The value of E_h determined for the CSA fill

Fig. 7. Normalized apparent water loss rate plotted against time for different cement contents for CSA hydraulic fill: experimental data compared with eq. [17].

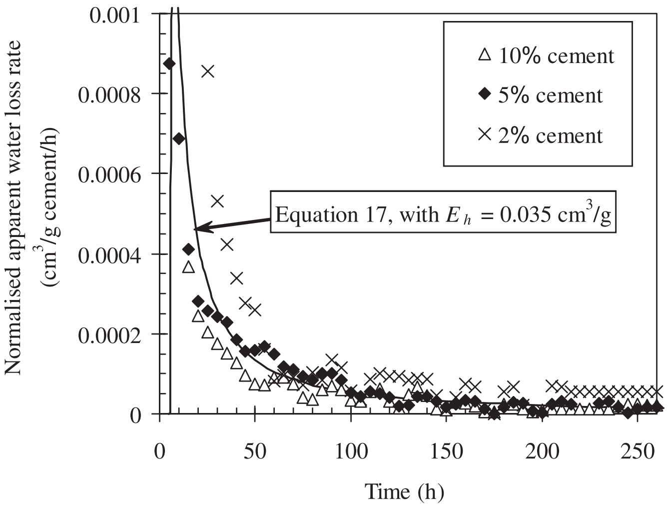
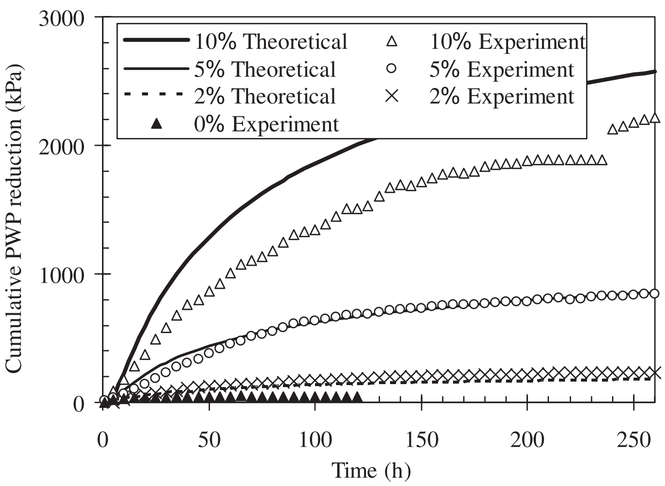


Fig. 8. Comparison of experimental reduction of pore-water pressure (PWP) against time and adjusted theoretical solution for CSA hydraulic fill.

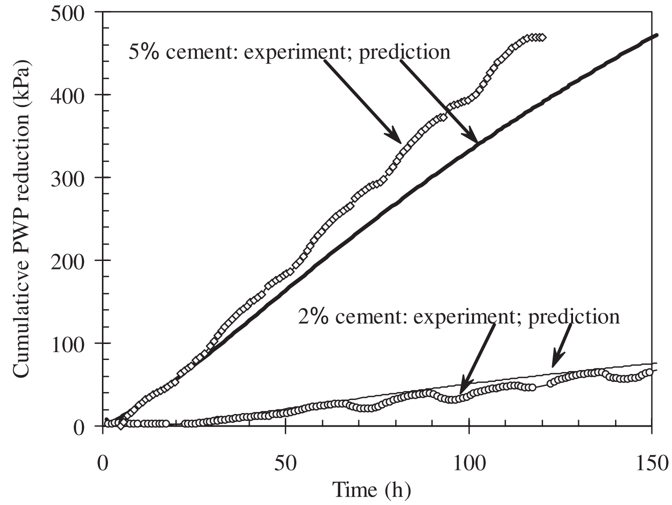


(0.035 cm^3/g) is somewhat <0.064 cm^3/g for cement paste suggested by Powers and Brownyard (1947).

Kanowna Belle paste fill experiments

Experiments were carried out using silt-sized paste backfill material from the KB mine (with cement contents of 2% and 5%) to assess the applicability of the proposed approach to a different type of minefill. The experimental technique used was identical to the one for the CSA test work. From these experimental results, the values of d and E_h of 2.5 day$^{0.5}$ and 0.055 cm^3/g, respectively, were determined. These values were substituted into eqs. [16] and [17] before combining them in eq. [12] to predict the cumulative drop in pore pressure with time; and this prediction was compared with the experimental results in Fig. 9. It can be seen that the analytical solution compares well with the experimental results in this figure. It should be noted that, again, the maturity constant (d) representing the rate of hydration appears to be similar for both the rate of pore-water volume consumption and the development of shear stiffness with time. For the KB paste backfill the E_h term of 0.055 cm^3/g corresponds closely to the value of 0.064 cm^3/g for cement paste suggested by Powers and Brownyard (1947), whereas a significantly lower value (0.035 cm^3/g) appears relevant for the CSA hydraulic fill.

Fig. 9. Predicted and measured reduction in pore-water pressure (PWP) for KB paste backfill.



Discussion and conclusion

This paper describes a mechanism that can cause significant reduction in excess pore-water pressure in cementing minefill masses due to cement hydration. The process is called "self-desiccation" in this paper, a term borrowed from the concrete literature, even though no actual desiccation (drying, desaturation) occurs in the work presented.

The analytical solution that has been developed to explain this mechanism appears to provide a good estimation of the experimental results. Constant terms that account for the rate of hydration and efficiency of the hydration reaction (d and E_h) have been introduced, with these terms being shown to be uniquely related to each cement–tailings combination regardless of proportions. This suggests that they are a fundamental property of each tailings–cement combination.

It is suggested that using the analytical solution along with the proposed experimental technique, the contribution of this self-desiccation mechanism to the overall consolidation processes in a cemented backfill mass can be quantified for any cement–tailings combination. Once the self-desiccation characteristics (d and E_h) have been determined, the mechanism may be incorporated into a fully coupled finite element code to account for other important mechanisms that occur during the backfilling process. At the time of writing, the authors were in the process of studying this and preliminary results have indicated that under conditions of fast filling and low permeability, the self-desiccation mechanism dominates the pore pressure changes that occur during, and immediately following, the filling process.

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