Strength Gains Versus Effective Stress Development in Williams Mine Cemented Paste Backfill

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Abstract
Effective and efficient use of binders is critical to optimizing underground backfill performance while minimizing operating costs. Controlled laboratory studies demonstrate the strong influence of binder efficiency (ie, strength development) on bulk properties (eg, density or porosity). While it might be hoped that backfill self-weight consolidation during placement will increase binder efficiency, there are several high-quality field studies that indicate this self-weight consolidation mechanism may be inconsequential. The underlying causes for the lack of consolidation are studied in detail in the laboratory using Cemented Paste Backfill (CPB) from Williams mine. A specialized hydraulic conductivity test quantifies permeability reductions due to binder hydration on samples with as-prepared bulk properties. A servo-controlled oedometer quantifies stiffness changes with variable time delays to the onset of effective stress development and with variable effective stress loading rates. A 1.8 m high column test with carefully controlled boundary conditions and representative backfilling rates is used to simulate the full-scale response expected in the topmost layers of deposited backfill. The column test results are interpreted using Biot-type analysis for accreting sediments, modified to incorporate time-dependent material properties. The backfill void ratios determined from the column tests are consistent with field observations, and the integrated interpretation of laboratory physical and numerical test results is that the enhanced backfill strength and stiffness due to hydration occurs faster than the onset and rate of effective stress development as pore water pressures dissipate.

While the results are specific to the Williams mine CPB, the result probably have broad implications for other mines, because the Williams fieldwork demonstrated that its CPB is one of the fastest to develop effective stresses during placement. Therefore, all mines should carry out fieldwork to quantify any self-weight effects that may occur at their mine if they intend to rely on such effects to increase binder efficiency.

Key words: binder efficiency, backfill strength development, as-placed backfill properties

Introduction
In underground mining, the binder used for CPB constitutes a significant operating cost, and considerable attention is paid to ensuring binder is consumed as efficiently and effectively as possible. Controlled laboratory tests have demonstrated that seemingly small reductions in void ratio (or corresponding increases in density) result in tangible strength increases, whether these void ratio changes are due to mixing at different water contents (Rankine and Sivakugan, 2007), rapidly consolidating samples using surcharges (Fahey et al., 2011) or consolidating samples under generalized total stress conditions using servo-controlled equipment (Yilmaz et al., 2014). However, there are now a few well-documented field

studies where samples were taken throughout the depth of as-placed backfill and reduction of void ratio with depth in the fill mass was not observed, including at Neves Corvo (Been et al., 2002), Golden Giant (le Roux et al., 2005), and Williams, Kidd, and Cayeli mines (Grabinsky et al., 2014; 2013). Been et al. (2002) suggested that "…higher cement content result[s] in less consolidation. The effect of the cement is to bond the material more strongly and, therefore, little volume change and consolidation can take place as the applied stress is increased." However, because consolidation is governed by effective stresses, it would be better to interpret Been et al.'s comments in the context of the rate of effective stress development (ie, determined from applied or total stress increases as well as pore water pressure changes) versus the rate of backfill strength and stiffness development due to binder hydration effects.

To provide a practical context for understanding rates of effective stress development during backfilling, Figure 1 shows the results of field measurements at several mines where both vertical total pressure and pore water pressure were measured during backfilling. An initial period of zero effective stress is observed in all cases, which occurs when the total stress due to overlying backfill is equal to the pore water pressure, resulting in zero effective stress being applied to the backfill solids. However, measurements of temperature and electrical conductivity (not shown here) were also used at several of the mines to confirm that binder hydration had begun, so some amount of backfill strengthening and stiffening was likely to have occurred. Therefore, the question is whether these changes in backfill mechanical properties will be sufficient to resist the effective vertical stresses being applied to the backfill.

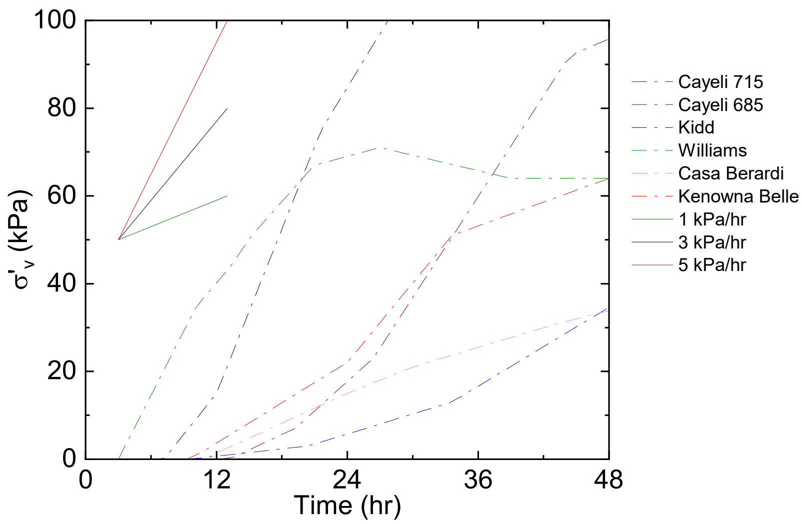

Figure 1. Examples of vertical effective stress development during backfilling.

It was decided to investigate such effects in the controlled laboratory environment using CPB from Williams mine. Williams was selected for two main reasons: 1) the Williams CPB (and its close counterpart Golden Giant CPB, from the mine adjacent to Williams and forming part of the same orebody) had already been extensively studied in several PhD and MSc theses; and 2) the duration of zero effective stress was the shortest and the subsequent rate of effective stress development the fastest observed in field measurements (Figure 1), and yet the binder content was lowest. If self-weight consolidation was to be important for any of the mines carefully studied, it should be Williams.

The experimental approach comprised the following. First, detailed measurements of hydraulic conductivity and stiffness development were made on backfill elements prepared and tested at the same bulk properties as used in the backfill plant of the mine. Then, a 1.5 m high column test was carried out, paying attention to both appropriate drainage condition at the bottom surface and relative humidity boundary condition at the top surface, and by replicating the backfill rise rates as continuously as practicable. Electrical conductivity and pore water pressure measurements were made at several heights in the column so that pore pressure distribution curves could be inferred for different stages of backfilling. It was confirmed that the column test resulted in void ratios representative of those obtained from field samples. Then, numerical analyses were carried out based on a Biot-type solution for accreting sediments but incorporating changing engineering properties associated with binder hydration. The individual components of this work have been reported on in detail in peer-reviewed journal articles (Shahsavari et al., 2022a,b; 2023), but this conference article provides an opportunity to present a high-level overview of the work and consider its practical implications for mining operations.

Williams CPB Engineering Properties

The main engineering properties relevant to consolidation analyses are hydraulic conductivity and stiffness. The bulk properties of these samples must be representative of the as-prepared, and as-placed properties at the mine.

Hydraulic conductivity

Conventional hydraulic conductivity measurement devices do not work well for freshly prepared CPB because either they require the material to be confined (ie, the flexible wall permeameter) or the imposed hydraulic gradients enhance consolidation (ie, fixed wall permeameters). In either case, it could take a few hours to configure the sample for testing and by this time the onset of hydration will already have occurred. Instead, the testing done for the Williams CPB used a commercially available device called Ksat manufactured by the METER group. As freshly prepared backfill sample is placed in the sample container and covered with a porous top cap (Figure 2). This is then attached to the base of the testing apparatus (Figure 3) and an upward gradient is applied to determine the hydraulic conductivity using either the constant head or falling head method. The upward gradient reflects the plausible flow direction in the very top deposition layer in the field and resists the settling mechanisms of the solids that might otherwise occur. The individual tests are fast (tenths of seconds) and can be repeated as long as required, allowing the change in hydraulic conductivity to be evaluated while binder hydration is ongoing.

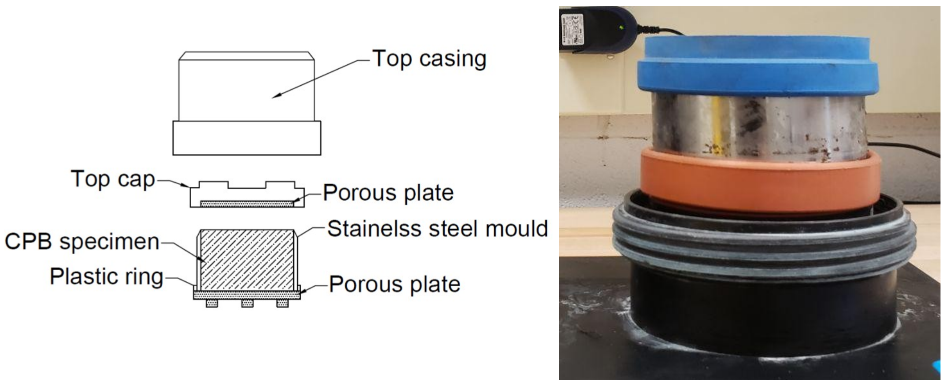

Figure 2. Diagram and photographs of the Ksat specimen holder.

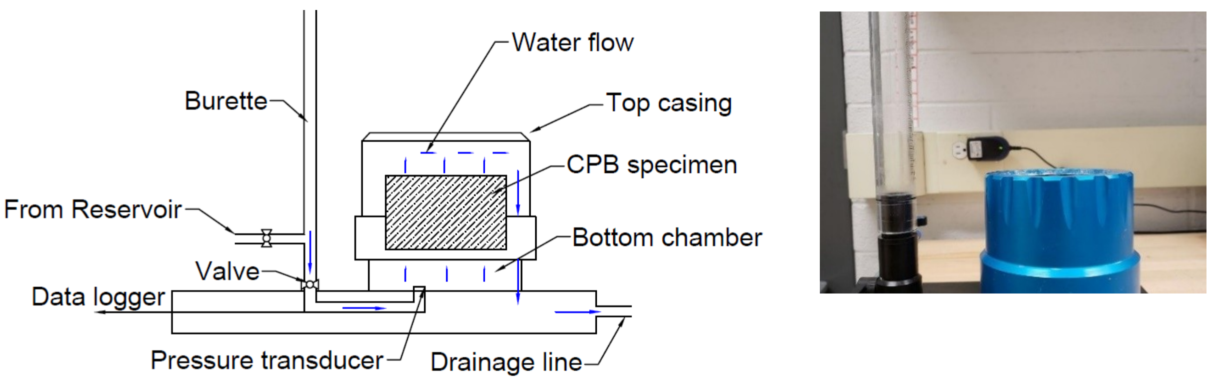

Figure 3. Sample in place in the Ksat testing device.

Shahsavari et al. (2022a) correlated changes in hydraulic conductivity to changes in electrical conductivity (EC) as measured in control samples. Changes in EC can also be correlated with strength and stiffness development as shown by Jafari et al. (2023). EC is also a useful non-destructive test technique and more robust field monitoring tools continue to be developed so that EC correlations developed in controlled laboratory environments may soon find practical applications for field monitoring so that changes in field engineering properties can be inferred.

Significantly, Shahsavari et al. (2022a) determined that the hydraulic conductivity for the freshly prepared CPB was many times higher than previous tests had indicated using conventional testing equipment. Reductions in hydraulic conductivity were then correlated with different hydration stages, as shown in Figure 4.

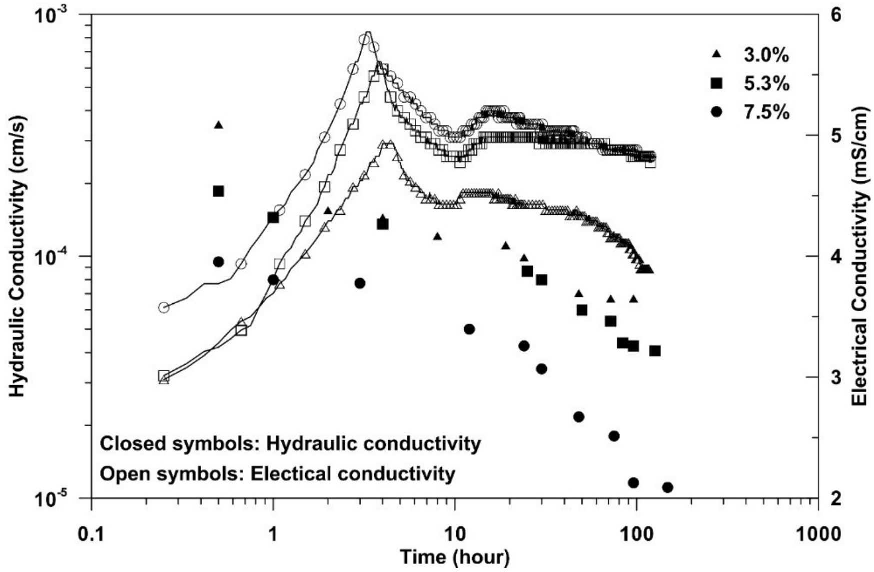

Figure 4. Changes in hydraulic conductivity and EC with time, for different binder contents.

One-dimensional stiffness

As shown in Figure 1, several hours of curing under zero effective stress may occur before the backfill experiences potential consolidation effective stress. Previous backfill consolidation studies have not adequately considered this delay. The load paths shown in Figure 1 can be replicated using a servo-controlled consolidation device (Figure 5), where the load is adjusted automatically. Shahsavari et al. (2022b) calculated the consolidation coefficient, required to achieve 99% excess pore water pressure dissipation over a 1 min period of constant load adjustment, and found that the resulting value was a factor ≥ 20 less than the consolidation coefficient determined from conventional oedometer tests on Williams CPB material (Jafari et al., 2020; Jamali, 2012). Therefore, every loading step shown and simulated using the device (Figure 5) will result in essentially complete pore water pressure dissipation and so the total stress path applied by the device will be equivalent to the effective stress path shown in Figure 1.

Figure 6 shows the stress paths applied considering time delays (ie, periods of zero effective stress) between 4–48 hours, and with subsequent effective stress development rates between 5–20 kPa per hour. Although the final applied effective stresses are dramatically higher than those observed in Figure 1, the experimental design was intended to provide larger loading ranges for better interpretation of void ratio changes. Also shown in Figure 6 for each stress path is the stress value corresponding to when the sample achieves a void ratio 95% of its original value (shown using coloured square, circular, and triangular markers) and a best-fit line through these data. The fact that the data points follow a reasonably consistent trend suggests that the bonds generating material stiffness are not significantly damaged during the loading process (ie, the same void ratio will be reached for a given stress level and curing time, regardless of the load path used). The loading test results therefore provide reliable determinations of one-dimensional stiffness for use in subsequent analyses.

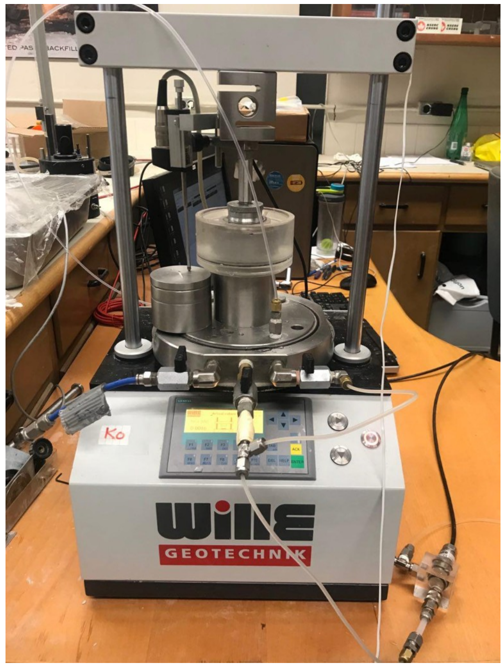

Figure 5. Servo-controlled consolidation device.

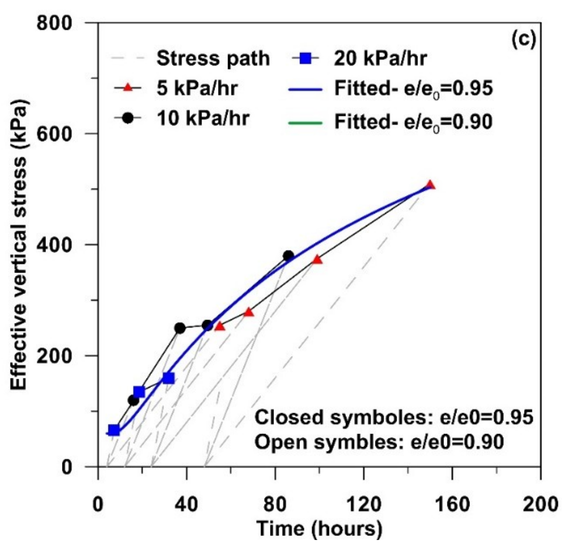

Figure 6. Consolidation under different effective stress paths.

Column Tests

Shahsavari et al. (2023) review previous column tests carried out by Abdul-Hussain and Fall (2012), Ghirian and Fall (2013), Belem et al. (2016), and Witteman and Simms (2017), and assessed that these previous studies were generally non-representative of typical field conditions because boundary conditions were not appropriately simulated, as fill rates used in the simulations significantly exceeded those occurring in field applications. The experimental design of the column tests used by Shahsavari et al. (2023) is shown in Figure 7. The bottom boundary condition consists of a free-draining, granular filter intended to maximize drainage potential and therefore self-weight consolidation potential. Draining water is collected on an electronic scale and recorded along with time in the pouring simulation. The top boundary condition is connected using flexible tubing to a water source to provide a near 100% relative humidity (RH) top boundary condition, thereby minimizing evaporation potential and suction development at the top surface.

This high RH condition is also consistent with field observations. A digital video camera is located proximate to the most recently deposited backfill surface to monitor settlement between deposition lifts. Water pressure and suction is monitored at six vertical locations using T5 tensiometers from METER group. EC is also measured at six locations using GS3 devices, also from METER group. The column was constructed in sections to facilitate slowing pouring the backfill and increasing the column height as the total backfill height increased. Most importantly, the backfilling is replicated as continuously as practicable considering the time required to prepare small backfill batches and pour them into the column. Two backfill rise rates were considered, 25 and 50 cm/h, so that the total time to fill the column was 6 and 3 h, respectively.

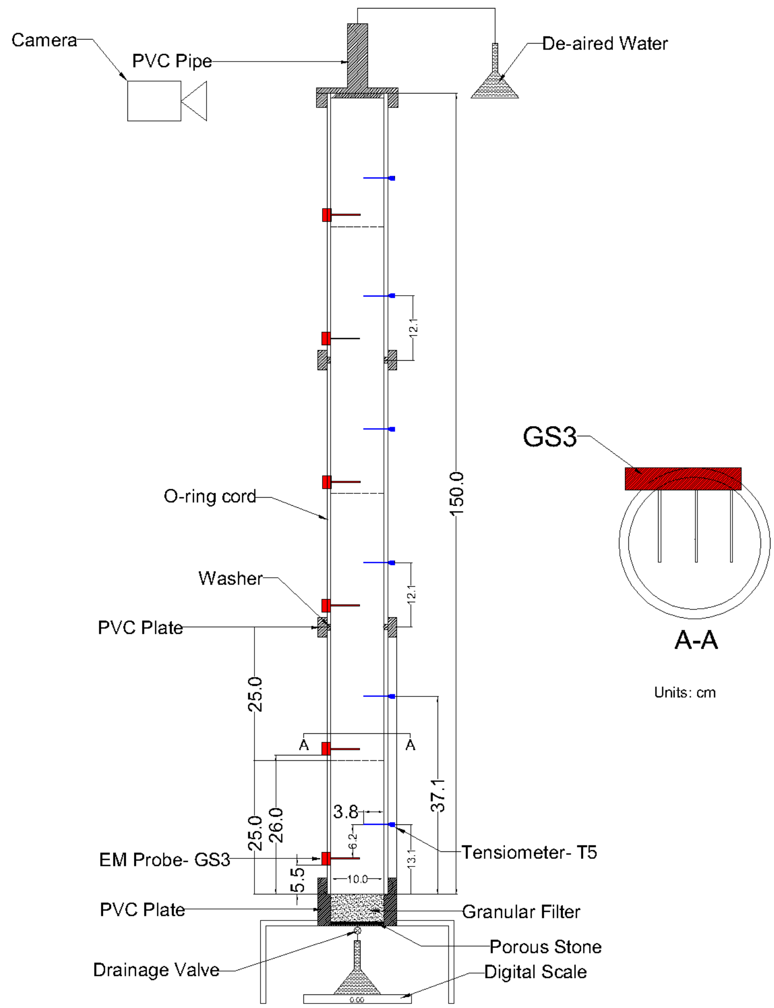

Figure 7. Design of column tests used by Shahsavari et al. (2023)

Column test results

Three column test results are considered here. The base case is filling at 25 cm/h with 3% CPB which represents the field condition for the monitored stope. A variation with filling at 0.25 cm/h with uncemented paste is used to compare with the base case and assess the effect of binder hydration. Finally, a variation with filling at 50 cm/h with 3% CPB is used to compare with the base case and assess the effect of faster backfill rise rates. The water pressure distribution occurring at the end of backfilling can be compared with Biot accreting sediment type analyses, but the column is also monitored for a further five days to evaluate ongoing changes in drainage and water pressure (or suction) distribution. Figure 8 shows the water pressure and suction results. Note that the uncemented paste has the highest water pressure immediately after filling, and the addition of 3% binder (the base case) dramatically reduces the water pressure by comparison. However, the influence of binder on mitigating pore water pressures is suppressed by the faster fill rate. Following complete filling, the water pressures continue to dissipate and eventually become negative, ie, suctions develop. Figure 8 also shows the theoretical hydrostatic matric suction distribution that should exist when the backfill is in equilibrium with a free-draining bottom boundary condition. This is the case for the uncemented paste, but the suctions are marginally more significant for the CPB cases reflecting the additional suction effect arising from binder hydration.

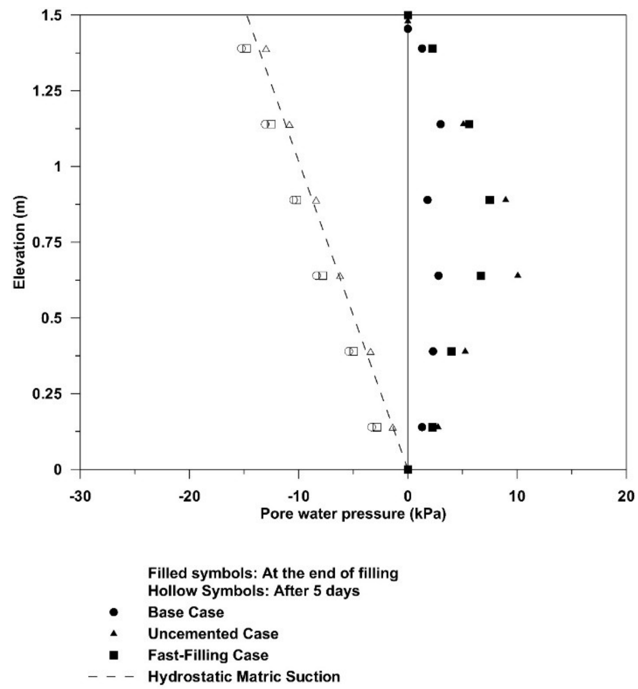

Figure 8. Water pressures immediately after filling, and suctions at 5 days.

The mass of water draining from each column was converted to a volume equivalent and used to calculate the corresponding volumetric strain of the column, assuming the backfill remains saturated. These changes can be compared with settlement observations from each test. The results are shown in Figure 9 and the two methods of evaluating volume strain correspond well. Note that the uncemented column continues to consolidate after filling stops, whereas the two CPB cases do not.

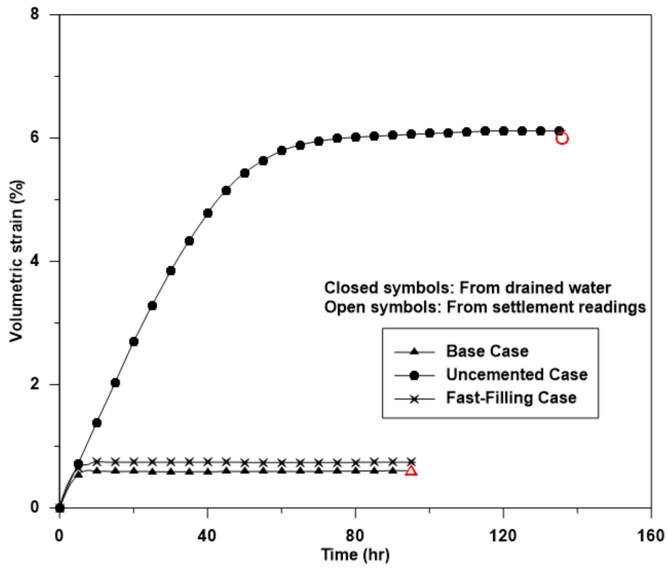

Figure 9. Volumetric strains determined from drained water and from settlement observations

As the column was disassembled the CPB was sampled to determine bulk properties. Similar to field observations from the previously cited case histories, the void ratio and degree of saturation do not correlate to height within the column. The variation of as-placed water content, between 34.5–38%, is thought to be due to variations in mixing during sample preparation. Within this range of water content, the void ratio correlated linearly with the degree of saturation, suggesting that air was entrained during sample preparation and the entrained air bubbles were unable to escape the viscous CPB mixture. This observation is also consistent with field observations from the previously cited case histories. The column test results are therefore considered to be representative of the full-scale backfill behaviour at the topmost deposition surface at Williams mine.

Biot and Numerical Analysis

The Biot solution for the pore water pressure distribution in an accreting sediment is expressed in the normalized form shown in Figure 10 and compared with the column test results. The variables in this figure are the following: z is the elevation above the free draining base and H is the height of the deposit, so that z/H is the normalized height above the base; u is the pore water pressure, γ is the saturated backfill unit weight, so that γH the maximum possible slurry pressure at the base and $u/\gamma H$ is the normalized pore water pressure. The 1:1 line in Figure 10 would be the water pressure distribution if the bottom was impermeable and the deposit was filled with slurried backfill (ie, zero effective stress). The time factor T is similar to Terzaghi's time factor for consolidation analysis, except that higher time factors indicate higher pore water pressures and lower degrees of consolidation (recall that in Terzaghi's analysis, a higher time factor correlates to lower excess pore water pressures and higher degrees of consolidation). The uncemented case closely follows the $T = 8$ contour in the upper half of the column and suggests the top 40% of the column is close to the slurried state. The lower portion of the uncemented result deviates from the $T = 8$ contour because an imperfect seal between column sections allowed for some leakage and pore water pressure dissipation. The 3% binder content, 25 cm/h rise rate base case follows the $T = 1$ contour in the lower half of the column indicating greater pore water dissipation due to binder hydration as compared to the uncemented case, but the upper half progresses towards higher *T* value contours probably because the binder has not yet started to hydrate and so the backfill is closer to an idealized slurry state. The 3% binder content, 50 cm/h rise rate case is intermediate between the previous two cases because the faster rise rate means there is less hydration time at every level in the column.

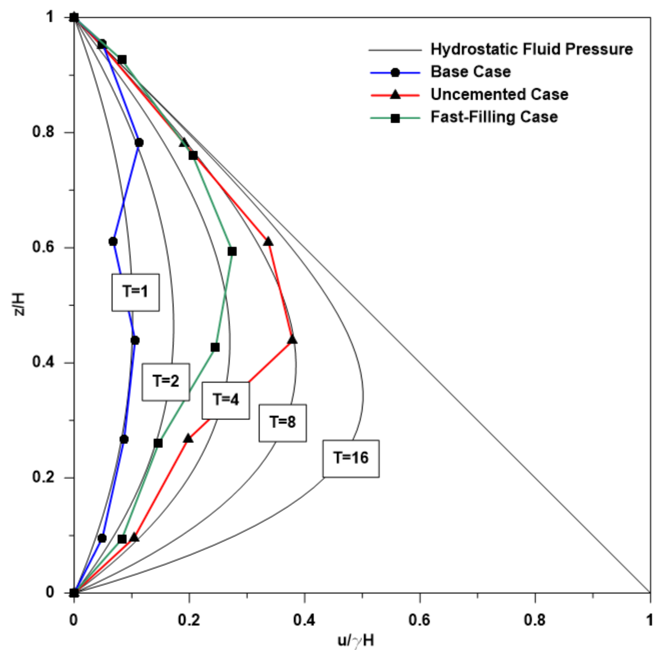

Figure 10. Comparison of theoretical and measured normalized pore water pressure profiles.

The Biot analysis assumes constant engineering properties (hydraulic conductivity and stiffness) which is only approximately achieved for column filling times of 3–6 h, and the deviations of measurements from the Biot curves can be explained by hydration as stated above. However, for taller backfills and longer filling times, the variations of hydraulic conductivity and stiffness with curing time become increasingly significant. Figure 11 shows numerical analysis results that consider the effects of time-dependent properties, for a 10 m high fill with a rise rate 25 cm/h (40 h filling time). Upper and lower bound stiffnesses as well as time-dependent stiffnesses are determined from the consolidation test results described previously. The influence of hydraulic conductivity is considered in two ways: the time-varying values determined from K_{sat} tests, and the constant values determined from conventional permeameter tests, which is an order of magnitude less than the initial value from the K_{sat} test. Figure 11a shows results assuming the constant low value of hydraulic conductivity and using the different stiffness assumptions. In all cases, the approximate Biot *T* values would be greater than 4 and the different stiffness assumptions have a marked effect on the corresponding contour magnitude. However, when the time-varying hydraulic conductivity is used (Figure 11b) the predicted pore water pressures are considerably less, with approximate Biot *T* values all < 4, and the effect of different stiffness assumptions is markedly less important. Therefore, for the Williams CPB, it is more important to appropriately characterise hydraulic conductivity changes with time (and binder hydration) than it is to determine stiffness changes. It is also interesting to note that the predicted pore pressure response is like the column test result for the 3% binder content, 25 cm/h rise rate case even though the simulation in Figure 11 is for a 10 m high fill as compared to the 1.5 m high column test.

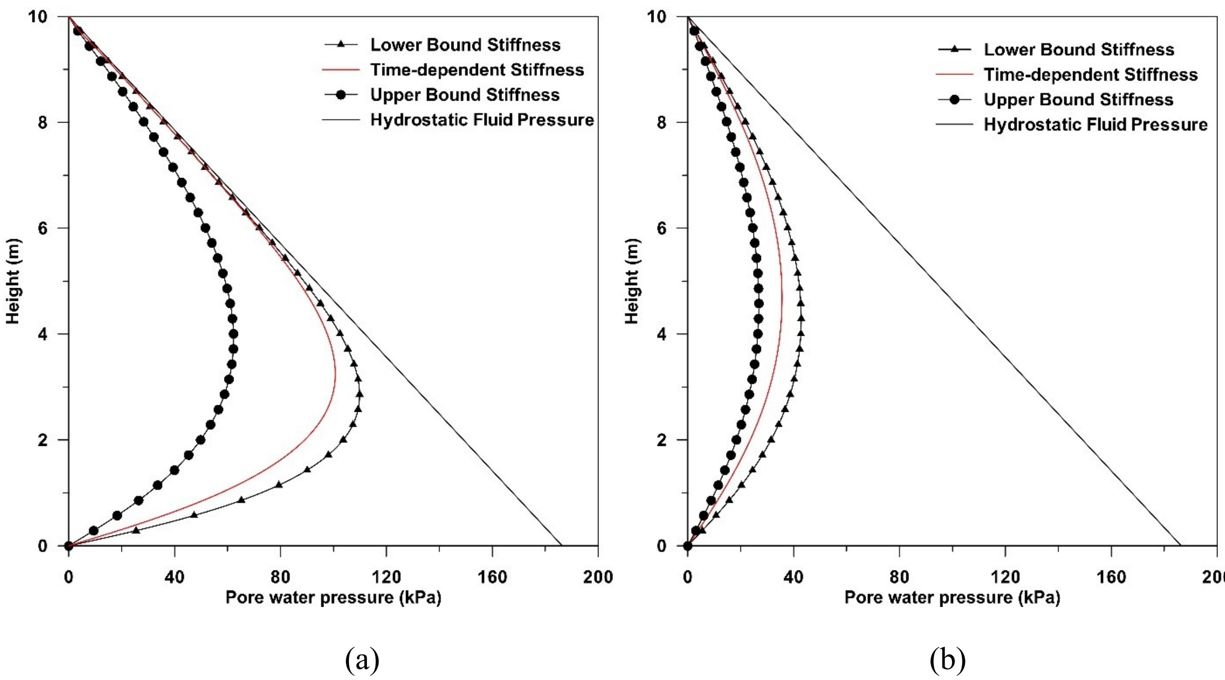

Figure 11. Comparison of predicted pore water pressure distributions assuming a) upper-bound hydraulic conductivity, and b) time-varying hydraulic conductivity.

Conclusion

Given that field monitoring results at Williams mine showed the least amount of time to onset of effective stress development, and the fastest effective stress increases thereafter, and that the Williams CPB has relatively low binder content at 3%, one might reasonably expect self-weight consolidation effects to be most prevalent in Williams backfill. However, this was not the case from field sampling results which suggested no significant consolidation had occurred. The detailed test work and numerical modelling results summarized here (and presented in detail in the corresponding journal articles) offer a compelling explanation for why such consolidation does not occur in the field and is consistent with Been et al.'s hypothesis that strength and stiffness gains associated with binder hydration are sufficient to resist significant volume changes during backfilling. For Williams mine, extrapolating the laboratory results to 10 m high backfills using numerical simulations indicates the laboratory scale results continue to be effective for much higher backfills also. Given that consolidation was effectively arrested by binder hydration even for the Williams case study, it seems implausible to expect consolidation to be significant more generally at other CPB operations. Mines assuming consolidation is important to their as-placed backfill strengths should therefore undertake field instrumentation and sampling programs to verify whether their assumptions have merit.

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