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ORIGINAL PAPER

Hydraulic Backfill Consolidation in Underground Mine Stopes

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Abstract

This paper highlights the importance of considering hydraulic backfill consolidation and wet arching when determining the stresses in underground mine stopes and acting on the barricade. The wet arching is introduced here as an arching effect during consolidation. Most studies consider hydraulic backfill consolidation as an instantaneous process and ignore its effects on stress within the stope and acting on the barricade. Mainly the reasons would be the granular behaviour and higher permeability of mine tailings used for hydraulic backfills. Yet, recent laboratory experiments and tests carried out under this study show that the consolidation is slow enough to significantly affect the hydraulic backfill stresses. According to the literature, hydraulic backfills have a considerable amount of fine particles which can slow down the consolidation process as evident in the tests. The paper discusses available stress variation between dry and wet fills while demonstrating its significance and requirements for further studies in consolidation and wet arching. Another important factor ignored in the literature is the hydraulic backfill property variations which were evident in tests carried out in this study. The results suggest segregation occurs within the fill which follows property variations over depth and considerably influences stresses. These effects must be considered when determining the stresses within the fill and developing a hydraulic backfill stress model.

Keywords Barricade · Consolidation · Hydraulic backfill · Mine stope · Stress · Wet arching

Introduction

Backfilling plays a major role in underground mining due to the benefits it provides such as regional ground stability, reduced environmental impact, and increased ore recovery. Stoping, cut and fill, room and pillar, and caving are the main underground mining methods that create large voids called stopes. They are rectangular prisms in shape, and size can vary from 25 to 50 m in length and width, while the height can go up to 200 m or more [1]. Once the ore is extracted and valuable minerals are recovered, the crushed waste which is known as mine tailings is managed either on the surface or underground. Mine tailings are fine materials, where the typical grain sizes vary from 0 to 1 mm.

Tailing dams are used to manage mine tailings on the surface, while backfilling is used to manage the tailings underground. This paper focuses on backfilling since it has several advantages over tailing dams such as the ability to be managed safely and economically, reduced tailing volume handling on the surface, reduced environmental impact, regional ground stability and increased ore recovery. Due to the significant increase in the porosity from the rock to the tailings, just over 50% of the excavated materials can be backfilled into the stope and the rest is managed on the surface using tailing dams [2]. The three main types of backfills are dry fills, paste fills and hydraulic fills. In addition, there are several other combinations made with these main types [2–5]. Hydraulic backfill is generally placed in the underground stopes as a slurry, pumped over large distances through boreholes and pipelines. During backfilling, the drives are barricaded to prevent the slurry entering the other areas of the mine. Failure of a barricade can be disastrous; hence, it is necessary to understand the loadings on the barricades. This paper highlights the importance of hydraulic backfill consolidation and wet arching for determining the stresses within underground mine stopes and acting on the barricades. Further, it discusses laboratory experiments and

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tests carried out under this study at James Cook University (JCU) to determine hydraulic backfill property variations over depth.

Hydraulic Backfills

Hydraulic backfill is one of the most popular backfill types within the mining industry as it is comparatively more economical and can be transported over long distances through pipes and boreholes. Hence, minimum manpower and equipment are needed for the operation. Hydraulic backfill slurry consists of mine tailings and water. The solid content in the slurry varies from 65 to 80% by dry weight while the maximum possible tailing percentage is used to minimize the amount of draining water and to dispose of the maximum amount of tailings underground [1, 8]. However, with the higher solid content, the flowability reduces, causing blockages in the pipelines. Therefore, it is important to strike a balance and maintain an appropriate percentage of tailings in the hydraulic backfill for a smooth filling process. This is generally determined through a mixed design exercise trialling different mixtures.

Mine tailings generally have a significant amount of very fine materials including clay, but the common practice is to deslime the tailings before using them as hydraulic backfill. Desliming involves the removal of the clay fraction and helps to increase the drainage within the fill. The desliming process is commonly done by using sets of hydro-cyclones and only the coarse fraction is used for the backfilling. During the filling process, barricades are used to hold the tailings and drain the excess water from the hydraulic backfill.

The common practice is to use approximately 5 m × 5 m tunnels as drives, and a typical stope has several drives at different levels. Therefore, all these drives must be barricaded before the backfilling process. Typically, barricades are made very close to the stope wall with an offset called setback distance equal to the drive height. The barricades are designed either straight or curved as shown in Fig. 1. They are often made with porous bricks, which have very high permeability compared to the fill. This was concluded in research studies carried out by Berndt et al. [7] and Sivakugan et al. [8]. Therefore, it is considered that water freely drains through the barricade without building up pore water pressures. Further information on barricade properties can be found in Berndt et al. [7] and Sivakugan et al. [8].

During and after the filling process, a hydraulic backfill is subjected to three main processes: settlement, sedimentation, and consolidation. It starts with the hindered settlement, which is followed by the sedimentation [9]. Due to the granular behaviour of the mine tailings, this process is comparatively fast. The self-weight consolidation occurs at the end with draining water from the soil skeleton. During the sedimentation, soil grains are not fully in contact to develop inter-grain (or effective) stresses. The effective stresses start developing when the void ratio reduces to the critical void ratio, which is also the beginning of consolidation (e_{BC}). This is illustrated in Fig. 2, where intergranular contacts start to develop at time t_1. Once the void ratio becomes less than e_{BC} (i.e., $t > t_1$), the grains are in contact, forming the soil skeleton and effective stresses start developing. The main driving factor for both processes is the self-weight of tailings (Fig. 2). A void ratio during the consolidation process is shown as e_{DC} when time is t_2. Once the consolidation is finished, the void ratio reaches e_{EC} at time t_3.

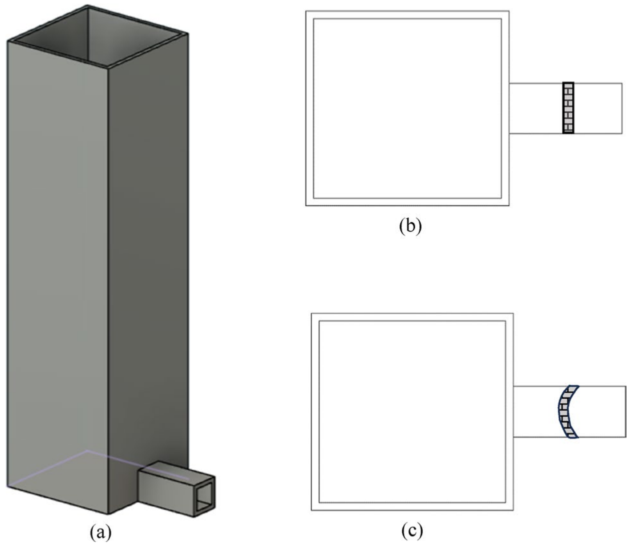
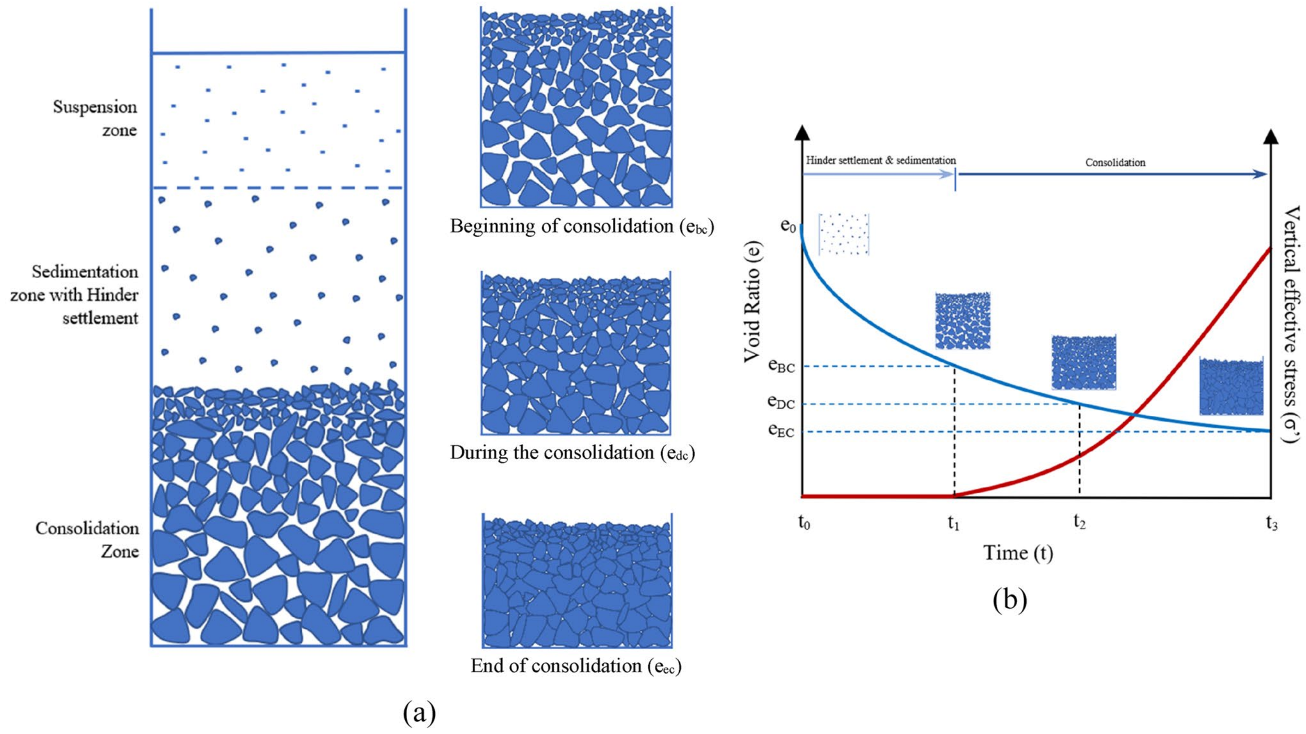


Fig. 1 **a** Typical underground stope—3D, **b** plan view of straight barricade **c** plan view of curved barricade

Qin et al. [10] carried out extended research on these two processes and concluded that consolidation plays a major role in backfills with higher solid percentages. Further, Fahey et al. [11] and Zheng et al. [12] showed the effects of wet conditions in mine fills on stresses and carried out their studies considering consolidation and arching effects. However, most of the studies carried out on hydraulic backfills ignored the consolidation by assuming it was an instantaneous process due to the granularity of grains [13, 14]. To investigate the significance of consolidation, an extensive study was carried out using available literature and laboratory tests, where the mine tailing properties were investigated, and the findings are discussed in this paper.

Hydraulic Backfill Properties

The mine tailings in hydraulic backfills typically consist of particles finer than sand-sized grains. Rankine et al. [6] and Sivakugan et al. [15] carried out a series of Particle Size



(a)

(b)

Fig. 2 Presentation of sedimentation and self-weight consolidation **a** physical **b** graphical

Distribution (PSD) tests using over 20 hydraulic backfills from mines located in Queensland and Western Australia at JCU laboratories. The results show that D_{10} varies from 10 µm to 40 µm and the fines less than 2 µm are negligible. However, there is a significant percentage of silt-sized grains remain in the hydraulic fill as shown in the results section (sub-topic 3.2). This indicates the possibility of self-weight consolidation during and after the hydraulic backfilling process.

Grain shape is another important property of hydraulic backfill tailings. Since mine tailings come freshly from the milling plants, they are generally angular and sharp. The average sphericity of imaged particles is less than 0.7, and the average roundness is less than 0.3 [16]. This makes the hydraulic fill stronger when it drains out, due to the particle interlocking. The presence of angular grains also increases the friction angle of the tailings. Sivakugan et al. [15], Rankine et al. [17] and Singh et al. [18] discussed this phenomenon in their studies and concluded that mine tailings have higher friction angles than common granular soil types. Therefore, the empirical correlations reported in the literature for the common granular soils may not be valid for the hydraulic fills.

The specific gravity of mine tailings can vary from 2.8 to 4.5 due to the presence of heavy metals in the tailings [15, 17]. According to Rankine et al. [17], self-settling hydraulic backfills settle to higher relative densities of 50–80% and a dry density (Mg/m^3) of 0.57 times the specific gravity. These values are in good agreement with Rankine and Sivakugan [13] study results. The porosity of the settled hydraulic backfill can be 37–49% and it was also evident in studies carried out by Singh et al. [18] where hydraulic backfill porosity varies from 29 to 47% over different overburden pressures up to 1600 kPa.

The absence of very fine grains results in higher permeability in hydraulic fills. In granular soils, the relationship between permeability and grain size has been widely studied and permeability can be estimated approximately using Hazen's [19] equation (Eq. 1) when the clay fraction is negligible. According to the equation, a higher D_{10} value gives a higher permeability.

$$k = CD_{10}^2 \tag{1}$$

D_{10} = Grain size corresponding to 10% passing (in µm), C = 0.03–0.05 [20], k = Permeability (cm/s).

Several studies have been carried out at JCU laboratories to better understand the drainage through hydraulic backfills. Hydraulic backfill permeability is one of the main factors that influence the drainage characteristics of the backfills. Poor draining behaviours can lead to barricade failures due to pore water pressure build-up and liquefaction. Rankine and Sivakugan [13] and Rankine et al. [20] carried out a series of constant head and falling head permeability tests at JCU using different hydraulic backfill samples and found that permeability varies between 0.5 and 55 mm/h. They concluded that the permeability values of samples, which still showed good drainage characteristics, are far less than the minimum industry specification of 100 mm/h. This is also seen in constant head and falling head permeability tests carried out by Singh et al. [18] using five hydraulic fills collected in different Australian mines. The permeability was reported to be between 7.2 and 14.4 mm/h under a 10 kPa surcharge and the range changed from 0.36 to 14.4 mm/h under a 1000 kPa surcharge.

Granular soils have very little reduction in permeability when the surcharge is increased. In clays, there can be a significant reduction in the permeability with increased surcharge. Hydraulic fills without clay fraction behave as granular soils and the permeability remains the same at all stress levels, however, in situations where the silt content is high or some clay fraction is present, there can be a reduction in permeability with increasing surcharge [18]. It is important to note that several mines have satisfactorily carried out hydraulic backfilling processes under low permeability values [13]. As a rule of thumb, the hydraulic fill fraction that passes through 10 µm is capped at a maximum of 10%, a restriction attributed to the favourable correlation between permeability and grain size.

The coefficient of consolidation (c_v) of hydraulic backfill is another important property since it governs the rate of consolidation and development of effective stresses. Hence it has a direct impact on stresses within the fill as well as the stresses acting on the barricades. Nevertheless, only a few studies have been carried out to investigate the stresses within the stope and paid adequate attention to consolidation [11, 21]. Fahey et al. [11] studied the stresses within the stope while considering the arching effect and consolidation. Their focus was mainly on the arching effect and not enough emphasis was given to the effects of consolidation on the stresses. However, they showed the importance of the effects of consolidation on the stresses by considering its influence on the arching process.

Li and Aubertin [21] carried out numerical studies on the influence of backfill properties, stope geometry, and the filling sequence of a backfilled stope and found that stope inclination has a significant effect on vertical stress. The study neglected the consolidation and settlement influence for simplicity; however, they also emphasised the importance of consolidation. Similarly, Li and Aubertin [22] studied the horizontal pressure acting on the barricades by neglecting the consolidation and underlined the importance of the consolidation for determining the pressure acting on the barricades. Zhao et al. [23] published a review paper about tailing-based backfills and emphasised the importance of studying the effective stress to understand the consolidation process in stopes with hydraulic fills. They were unanimous that the consolidation process must be considered when determining the stresses within the hydraulically backfilled stope.

Laboratory Tests on Hydraulic Backfill Mine Tailings

A series of tests were carried out under this study using tailing samples from a gold and copper mine in Queensland. The main purpose of the tests was to determine the suitability of mine tailings for hydraulic backfilling processes and characterise the property variation along the fill depth once it settles. The mine tailing properties were determined at the initial stage, from the raw tailings. Particle size distribution (PSD) using sieve analysis and hydrometer, specific gravity, plastic limit (PL), liquid limit (LL), direct shear tests, X-ray diffraction analysis (XRD), SEM analysis and falling head permeability tests were carried out on the mine tailings. The permeability tests were carried out using an apparatus made with 100 mm diameter and 320 mm long pipe. The head difference (h_1–h_2) was 400 mm, and the sample height was 237 mm (see Fig. 3). The characterisation of settled mine tailings property variation along the depth was done in the second stage by making a settled sample using a Perspex column as described below (see Fig. 4).

Undisturbed specimens from the settled hydraulic fill sediment, obtained from the settlement column, were subjected to permeability and consolidation tests in the second stage. To study the variations in the geotechnical parameters, including consolidation and permeability characteristics,

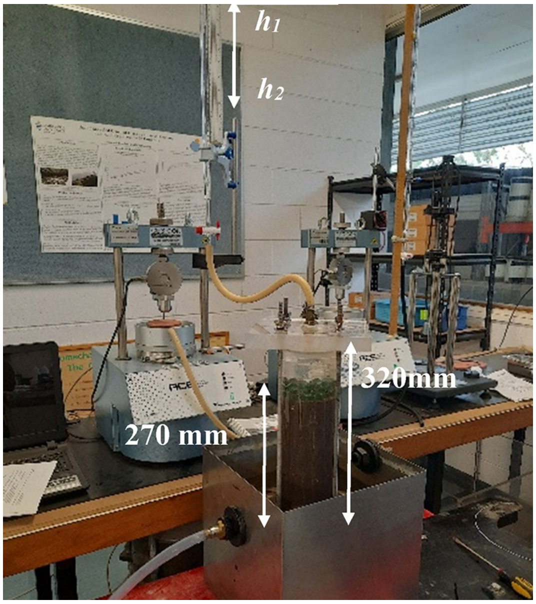


Fig. 3 Settled sample for the permeability test

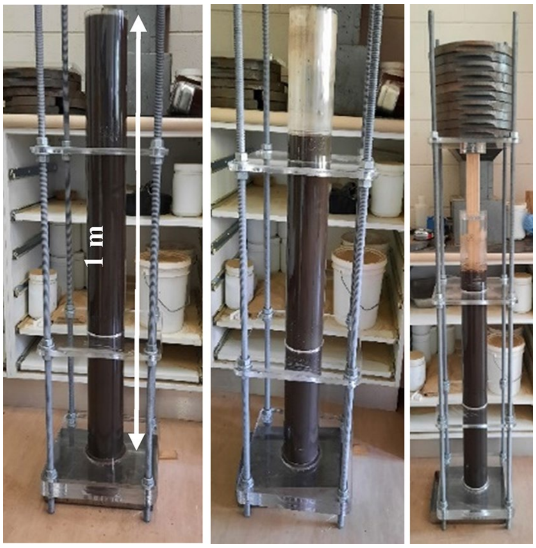


Fig. 4 Settled mine tailing column preparation

with depth, undisturbed specimens from different depths within the sediment were tested. Within each layer, PSD, PL, LL, permeability, and consolidation tests were carried out to identify the settled tailing property variations along the depth. Similar to the above-mentioned permeability column, a hydraulic fill with 70% solid content by weight was prepared and poured into a meter-high and 100 mm diameter settlement column made of Perspex. This process replicates the situation at the underground mines where the backfill slurry is similarly poured into the underground voids and drains at the bottom. The slurry underwent sedimentation initially, followed by self-weight consolidation. To make the sediment stiff enough for handling and extrusion without a significant disturbance, a surcharge was placed at the top of the sediment (Fig. 4), starting with 10 kg, and increased in steps to 100 kg, which was kept for a week for the sediment to reach equilibrium. The settled sediment was extruded from the Perspex column and divided into layers where two layers from the top and three layers from the bottom were subjected to permeability, consolidation, and PSD tests, along with the tests for Atterberg limits.

Properties of Raw Mine Tailings

The chemical composition of mine tailings was determined by X-ray diffraction analysis (XRD). According to the XRD results, the main compositions of the tailings are Ferrous Dioxide (Fe_2O_3) and Silicon Dioxide (SiO_2) which are 37.73% and 32.90%, respectively (Table 1). The X-ray fluorescence analysis (XRF) shows Quartz, Chlorite and Muscovite as the major minerals (Table 2). The SEM results are shown in Fig. 5 and according to the results, mine tailing grains show higher angularities as expected since they came from the mine processing plant. According to Liang et al. [16], the average sphericity of the imaged grains is 0.65, and the average roundness of large grains is 0.18. Further, the presence of fines in the tailings can be seen in these images (see Fig. 5).

Table 1 Chemical compounds in mine tailings

Category	Chemical compound	Percentage (%)
Major	Fe_2O_3	37.73
	SiO_2	32.90
Moderate	Al_2O_3	7.85
	CaO	5.35
	K_2O	3.85
	SO_3	3.60
	LOI	3.27
	BaO	1.77
	MgO	1.74
Minor	TiO_2	0.63
	MnO	0.52
	P_2O_5	0.35
	Na_2O	0.27
	Ta_2O_5	0.07
	Cl	0.05
	As_2O_3	0.04
Total		99.99

The PSD curves also show the presence of fine grains in the tailing sample (Fig. 6). Further, the curves show how the raw mine tailings and deslimed mine tailings fall within the narrow band suggested for hydraulic backfills by Sivakugan et al. [8]. According to the graph, a little over 50% of raw mine tailings used in the experiments is less than 75 µm, which is expected as the mine tailings were ground as fine as possible to increase the recovery of valuable minerals.

Tailings specific gravity was 2.86, which is closer to the lower limit of the range determined by Rankine et al. [17]

Table 2 Minerals in mine tailings

Abundance	Phase	Formula
Major	Quartz	SiO_2
	Chlorite	$(Mg,Fe)_6(Si,Al)_4O_{10}(OH)_8$
	Illite/muscovite	$KAl_2(Si_3Al)O_{10}(OH,F)_2$
Minor	Potassium feldspar	$KAlSi_3O_8$
	Calcite, Mg	$(Ca,Mg)CO_3$
	Magnetite	Fe_3O_4
Poss. Trace	Kaolinite	$Al_2Si_2O_5(OH)_4$
	Hematite	Fe_2O_3
Trace	Plagioclase feldspar	$NaAlSi_3O_8$
	Pyrite	FeS_2

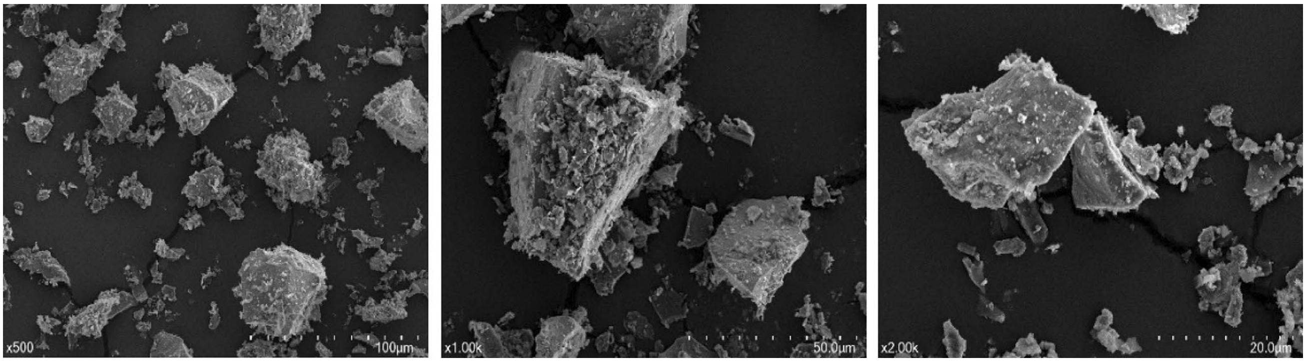


Fig. 5 Scanning electron micrograph (SEM) images of raw mine tailing

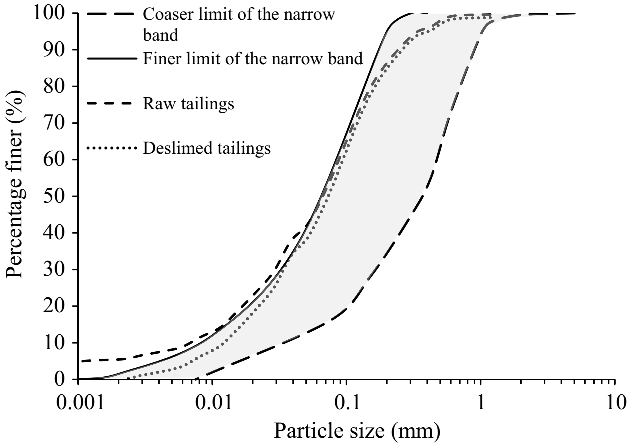


Fig. 6 Particle size distribution curves of raw and deslimed mine tailings

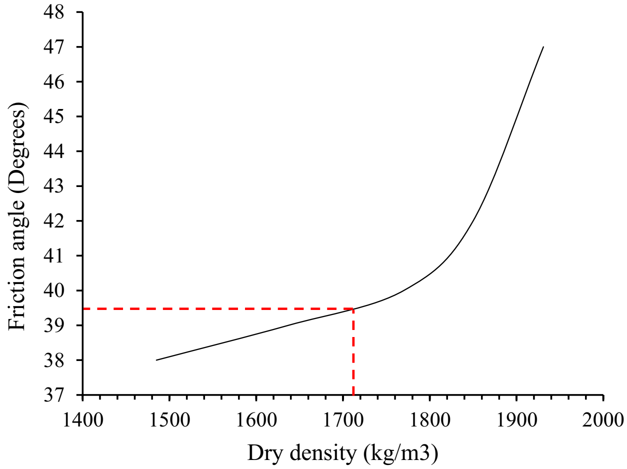


Fig. 7 Peak friction angle

and Sivakugan et al. [15] for mine tailings but lies within the specific gravity range. The value is higher than the specific gravity of typical soil due to the presence of heavy metals in the tailings.

The angular shape of the tailings has a direct influence on the friction angle. Hence, the tailings friction angle is comparatively higher than in common granular soils. Figure 7 shows the mine tailings peak friction angle variations with the dry density, as determined from direct shear tests on 100 mm × 100 mm reconstituted dry hydraulic fill samples. The friction angle values vary from 37° to 47°. According to the laboratory experiments carried out by Sivakugan et al. [15], all hydraulic fills settle to a porosity of approximately 40% and a void ratio of 0.67. Further, it can be proven that mine tailings dry density (ρ_d) and void ratio (e) have a relationship as shown in Eq. 2, where G_s is the specific gravity and ρ_w is the density of water. Therefore, the dry density of settled hydraulic backfill can be calculated as 1713 kg/m^3. The peak friction angle of settled hydraulic backfill can be determined as 39.5° using the dry density (Fig. 7).

$$\rho_d = \frac{G_s \rho_w}{1 + e} \tag{2}$$

The permeability of the settled sample was determined as 9.1×10^{-5} cm/s (3.28 mm/h). According to Rankine and Sivakugan [13], this value was in a range where hydraulic fills perform satisfactorily. Sivakugan et al. [14] showed that laboratory permeability values of hydraulic fills are often lower than in the actual mine environment using anecdotal evidence and back calculations of measured flow within the mine stopes. Therefore, the tested mine tailings would be able to satisfactorily drain the fill water.

Hydraulic Backfill Property Variations with Depth

Five layers were tested from the settled mine tailing column. The first two layers were taken from the sediment extruded

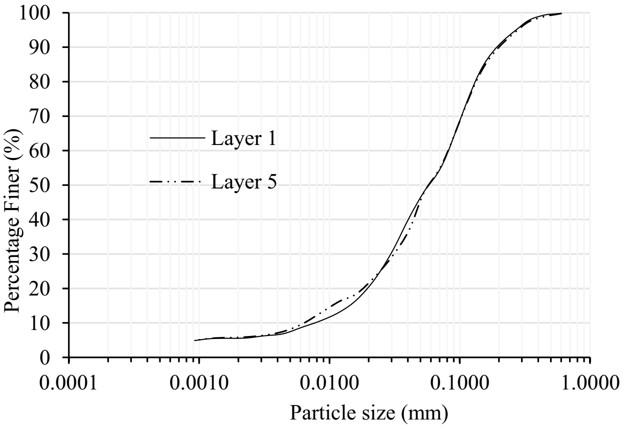


Fig. 8 Particle size distribution curves (L1 and L5)

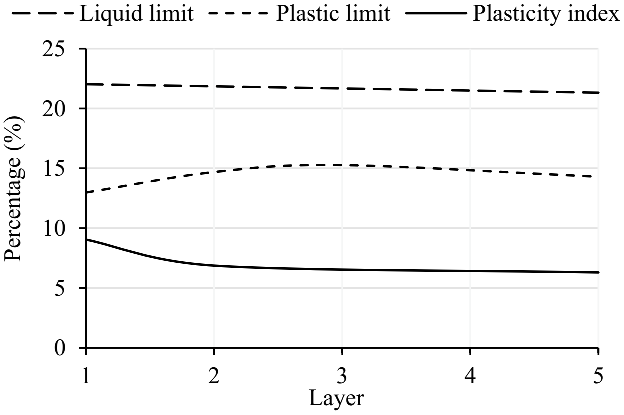


Fig. 9 LL, PL and PI variation along the depth

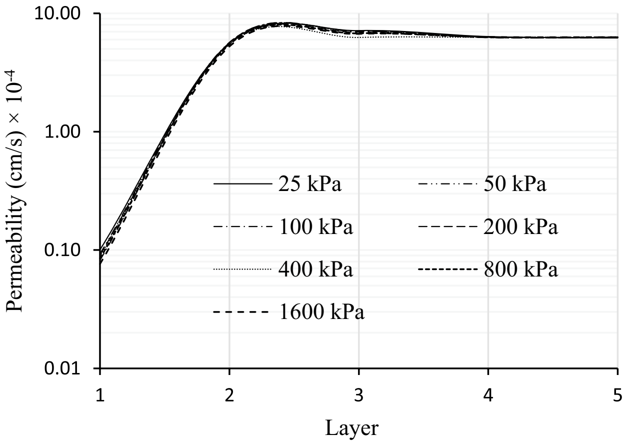


Fig. 10 Permeability variations over depth

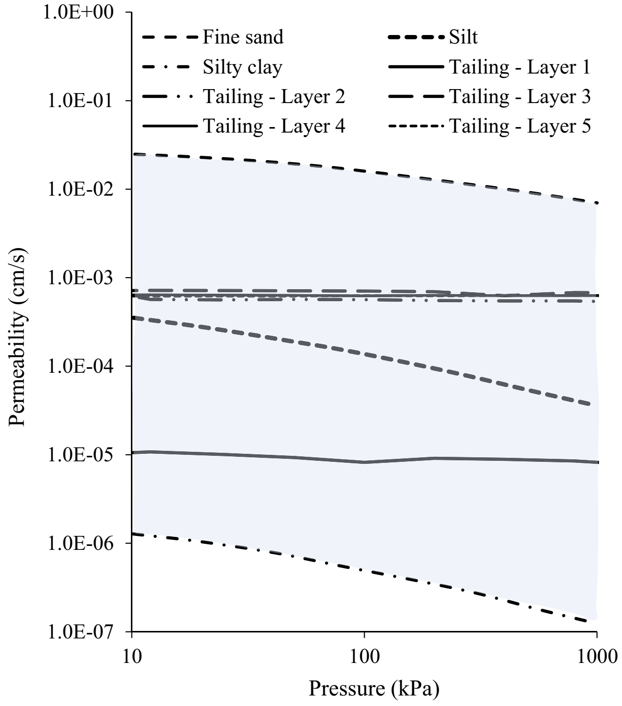


Fig. 11 Permeability variation over the surcharge

from the top and the other three were from the sediment extruded from the bottom. The particle size distribution variations are almost negligible in all five layers. The top layer (L1) and bottom layer (L5) PSD curves are shown in Fig. 8. Even with possible particle size variations, the PSD curves show similar particle sizes in these two layers. However, LL shows a clear decrease over depth while PL shows an increase from Layer 1 to Layer 5 (Fig. 9). Therefore, the PI values show a significant decrease with depth. This is a clear indication of possible segregation during the sedimentation process of hydraulic backfill, with the upper end of the column being finer than the lower end.

With the finer fraction being closer to the top and the coarser fraction at the bottom, the permeability values showed an overall increase with depth (Fig. 10). Permeability tests were carried out under different vertical stress values, and as shown in Fig. 10, the variations were almost similar, however, there was a slight decrease in permeability with higher vertical stresses. The Layer 1 values range from 7.63×10^{-6} to 1×10^{-5} cm/s where the lowest was recorded under the maximum vertical stress value of 1600 kPa. However, permeability values of Layer 5 are almost similar which vary from 6.2×10^{-4} to 6.29×10^{-4} cm/s. From the top of the hydraulic fill column to the bottom, the permeability increased by two orders of magnitude. The increase was mainly within the top 25% of the sediment and it remained constant for the bottom 75%.

Figure 11 compares the permeability values of five layers with fine sand, silt, and silty clay. According to the graph,

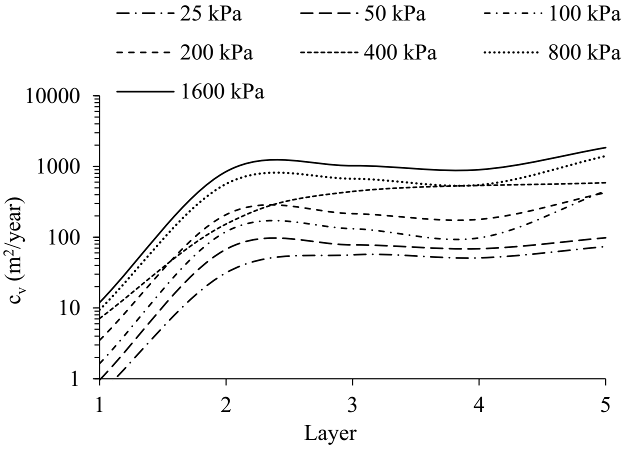


Fig. 12 Coefficient of consolidation variation

the permeability values of each layer come in between silty clay and fine sand. Most of the layers are located above the silt permeability line. Only the top layer shows a lower permeability value than silt. These results justify the mine tailing classification done in the earlier stage of this study and suggest segregation within the settled column.

Moreover, this behaviour can also be seen in consolidation tests carried out on each layer. According to the results, there was a significant increase in the coefficient of consolidation (c_v) with depth and the variations in each layer can be seen in Fig. 12. Higher c_v values give faster consolidation settlements. Therefore, the consolidation was significantly slower for Layer 1 than for the bottom layers.

Typically, coarse-grain soil has higher c_v and fine-grain soil such as clays has lower c_v values. Bardet [24] summarised c_v values for different soil types from available literature, where c_v values of clay generally vary from 0 m^2/year to 18 m^2/year. However, special cases such as marine clay and boulder clay show comparatively higher values. On the other hand, coarse-grained soil such as silty clay and silt shows large c_v values and variations. The values vary from 3 m^2/year to 31,710 m^2/year [25]. Further, Adajar and Zarco [25] summarised c_v values for different mine tailings from the available literature. Mine tailings from hard rock mining, gold and copper showed c_v variation from 12.6 m^2/year to 2188.6 m^2/year [25]. Similarly, Qiu and Sego [26] reported that c_v values of mine tailings from gold copper, coal and oil sand composite–consolidated tailings vary from 0.31 m^2/year to 104.23 m^2/year. Under self-loading conditions, the c_v values determined by oedometer tests under this study fall within the ranges specified by these studies.

Bandini and Sathiskumar [27] carried out consolidation experiments on sand and silt mixtures. They determined the c_v values for sand and silt mixtures with different silt percentages, where sand with maximum silt percentage (25%) varies from 9460.8 m^2/year to 31,536 m^2/year. Generally, mine tailings contain a higher percentage of silt than 25%, so c_v value would be reduced further. According to the trend, the value would be 315 m^2/year with 40% of silt. The current test results show c_v value variation from 3 to 2000 under similar surcharges as in Bandini and Sathiskumar's studies. These values have a good relationship with each other and demonstrate the mine tailings' granular behaviour as suggested by analysing the current experiment results.

If the average c_v is taken as 700 m^2/year for the hydraulic fill tailings, the time to reach 90% of consolidation in 100 m stope can be determined as 12.11 years, using Taylor's square root of time fitting method. This shows the importance of the consolidation process for the hydraulic backfilling process, and it must not be ignored by considering it as an instantaneous process.

An opposite behaviour can be seen in the coefficient of volume compressibility of settled hydraulic backfill samples. Since the tailings become stiffer with settlement, compressibility decreases, and the results show an overall reduction in the coefficient of volume compressibility with the vertical surcharge in all layers (Fig. 13). Furthermore, the coefficient of compressibility (m_v) reduced with depth, implying Layer 1 is more compressible than Layer 5. For surcharge pressures less than 50 kPa, there are significant reductions in m_v with depth. For larger surcharge pressures, m_v remains the same at all depths.

The compression index of each layer in the settled sample also decreased along the depth. However, the compression index values are very small (smaller than 0.06). Such small values for the compression index are typical for granular soils.

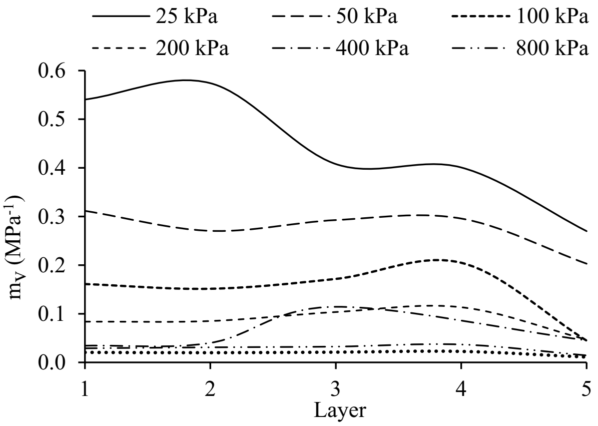


Fig. 13 Variations of volume compressibility over depth

Stresses Within Hydraulic Fills and Acting on the Barricades

Stresses within hydraulic backfill are initially dominated by water pressure, during the sedimentation stage. However, due to the consolidation, the mine tailing and stope wall interfaces create shear stresses as a result of the arching effect due to wall friction. This reduces the vertical stress within the stope and horizontal stress at the drive.

The arching effect requires a solid–solid interface to create a negative stress, so generally, a dry state of tailing or sand is used to determine the arching effect. Since water-stope wall friction is negligible, arching in slurry and consolidation states was ignored in most studies. However, recent experiments at JCU showed that considerable arching effect occurs during the slurry and consolidation state. To separate these two phenomena, a new phase is introduced as “wet arching” for the arching effect during the slurry and consolidation stages. The phrase “dry arching” is used whenever dry mine tailings or sand is used to determine the arching effect. Further information on dry arching can be found in Jayakodi et al. [3], Fahey et al. [11], Jayakodi et al. [28] and To and Sivakugan [29]. The reduced vertical stress is known as the effective stress, and it can be calculated by Eq. 3. The horizontal stress at the barricade gives the load acting on the barricade and when determining it, the ‘A’ represents the horizontal arching effect within the drive.

$$\sigma' = \sigma - u - A \tag{3}$$

σ' = Effective vertical stress, σ = Total vertical stress, u = Pore water pressure, A = Arching effect stress.

Most of the studies on hydraulic backfill stresses ignored the consolidation effect and worked with dry hydraulic backfills. Several relationships are available for dry hydraulic backfills to determine the vertical and horizontal stresses within the stope. Marston [30] proposed the first rational solution for the average vertical stress within a dry granular fill in a narrow and long trench, treating it as a 2-dimensional plane strain problem (Eq. 4). Assuming an active state, the horizontal earth pressure is given by Eq. 5, where K_a is Rankine’s active earth pressure coefficient, given by Eq. 6. The equations were later modified by several researchers and further details on the equation development can be found in Pirapakaran and Sivakugan [31].

$$\sigma_v = \frac{\gamma w}{2\mu K_a}\left[1 - \exp\left(-\frac{2K_a\mu h}{w}\right)\right] \tag{4}$$

$$\sigma_h = \sigma_v K_a \tag{5}$$

$$K_a = \tan^2\left(45^\circ - \frac{\phi}{2}\right) \tag{6}$$

ϕ = Friction angle of the backfill (degree), δ = Angle of wall friction at the fill-wall interface, K_a = Rankine’s active earth pressure coefficient, γ = Bulk unit weight of fill, μ = Coefficient of friction at the fill-wall interface (tan δ), w = width of the trench, h = height of the trench.

Li and Aubertin [22] and Kuganathan [32] also introduced empirical equations to calculate the stress acting on the barricade by considering the arching effect within the drive. However, all these studies neglected the most important factor of wet conditions in the hydraulic fill and studied the settlement of dry tailing without considering the moisture and the consolidation process. Since the effective stress is generally measured in experiments under these assumptions, the actual stress acting on the barricade may be higher than the measured value. Also, under dry conditions, the vertical (σ_v) and horizontal (σ_h) stress relationship can be given using the earth pressure coefficient (K). Nevertheless, the above relationships may be unsuitable for determining the horizontal stresses acting on the barricade due to the wet backfill consolidation condition in the stope and the common setback distance in each drive.

Further, the arching effect is not under full action when the mine tailings are wet (wet arching). As explained above, wet arching influence is different from dry arching and studies of dry arching cannot be implemented for wet arching. Due to this importance, detailed studies have been carried out at JCU laboratories focusing on consolidation and wet arching.

Summary and Conclusions

Hydraulic fill is one of the most popular backfills used for underground mine voids. It is a slurry made with mine tailings and water where the solid contents vary from 65 to 80% by weight. The access drives are barricaded before the filling process and water is considered freely draining through it. To make the backfilling process safer, stresses within the stope and those acting on the barricade must be effectively predicted and monitored. Most of the studies and developed models on hydraulic backfills ignored the consolidation process and wet arching by assuming it is an instantaneous process. However, the available literature on hydraulic backfill mine tailings and experiments and tests carried out under this study showed that the consolidation process is not instantaneous as assumed before. The availability of fine grains makes sure the consolidation is considerably slow and the permeability values are not very high to become instantaneous water drawdown.

As shown in the results section in this paper, the coefficient of consolidation is significantly smaller to neglect the consolidation effect. Also, the study results and previous studies clearly show that the permeability values of hydraulic backfills are smaller than the suggested minimum industry specification. Therefore, the consolidation effect and arching effect (wet arching) during the consolidation must be considered for the stress measurements as well as for future modelling.

There is a significant stress variation between dry and wet fills as described above and arching is an important part of that. The wet arching effect activates with the grain deposition, and it plays an important role in reducing the total stress within the stope and acting on the barricade.

Moreover, the hydraulic backfill properties show considerable variations over depth, which suggests segregation during the sedimentation phase. This means the consolidation and draining are faster at the bottom levels. These property results must be used to determine parameters for numerical studies carry out to predict stresses within the stope and acting on the barricade.

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Data Availability To the author's knowledge, all associated data and other relevant information have been embedded in the paper.

Declarations

Conflict of Interest The authors have no conflict of interest that link to the research. Authors are not employed or paid by any organisation which can have financial benefits or damages from the paper.

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