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Emplaced geotechnical characteristics of hydraulic fills in a number of Australian mines

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Abstract. Hydraulic fills used in Australian mines have similar grain size distributions whilst having quite different specific gravity values, typically in the range of 2.7–4.4. When produced and distributed in slurry at 65–75% by solid content, they settle to produce fills with similar geotechnical characteristics. The fills under investigation have been found to settle, in the laboratory, to a dry density of about 0.56 × specific gravity, a saturation water content of about 17–34%, and a porosity of 37–49%. A quick estimate of the optimum water content that gives the minimum porosity may be obtained by locating the intersection of the saturation curve and minimum porosity line, which may simply be done on a water content vs. porosity plot. However, transportability of the slurry requires it to be mixed at water content substantially greater than the optimum water content. As the tailings settle out of suspension, they settle to relative density of 50–80%. This paper shows that the current empirical relationships relating relative density and *N*-value to friction angle for sands will significantly underestimate the friction angle of the hydraulic fills. Based on limited experimental data, a unique relationship between relative density and friction angle is proposed for hydraulic fills placed in some Australian mines.

Key words. Australian mines, friction angle, hydraulic fill, permeability, relative density, specific gravity.

1. Introduction

In large scale, underground, metalliferous mining operations, ore body extraction may result in excavations that are tens to hundreds of metres in at least one dimension. These excavations, or stopes are created by carefully controlled sequences of blasts. On completion of extraction of the blasted ore, the voids are generally filled using the by-products of ore extraction and mineral processing.

The most common by-products are development waste derived from the tunnels that are not in ore and the discharge, named tailings, from the surface processing plants. The mining industry is the largest generator of solid wastes in Australia (Boger, 1998). Mine filling techniques, which generally use these by-products, provide ground support to permit removal of adjacent, remaining ore, and are also effective means of disposal of waste materials.

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There are several types of mine fills, including paste fill, hydraulic fill and cemented hydraulic fill, based on tailings, and sand fill, cemented sand fill, rock fill, cemented rock fill, aggregate fill and cemented aggregate fill (Bloss, 1992), generally based on development waste or quarried rock. Hydraulic fills are simply silty sands or sandy silts, with negligible clay fraction. The clay fraction with some parts of the other elements of the grain size distribution, is removed in the process of partially de-watering and de-sliming the tailings.

On discharge from the surface process plant, the tailings are typically in the range of 20–40% by weight solid content. To satisfy the requirements of adequate recovery (the amount of usable hydraulic fill as a function of the ore mined) and acceptable drainage and reticulation characteristics, the tailings are usually processed through hydrocyclones, which may be in a variety of sizes and configurations, depending on the properties of the tailings slurry and the desired characteristics.

The resulting hydraulic fill is generally produced at a pulp density of 65–75% solids by weight and with a coarser particle size distribution, as shown in Figure 1. It is then transported through pipes and boreholes to the stopes, where it can drop for tens to hundreds of metres.

Prior to filling, barriers, or barricades as they are known in Australia, are constructed in each of the access ways into the stope to retain the fill, whilst it settles and drains. Individual stopes may take from several days to several months to complete filling, depending on the size and geometry of the stope, shown simplistically in Figure 2. During this time, the fill settles under its own weight and excess water

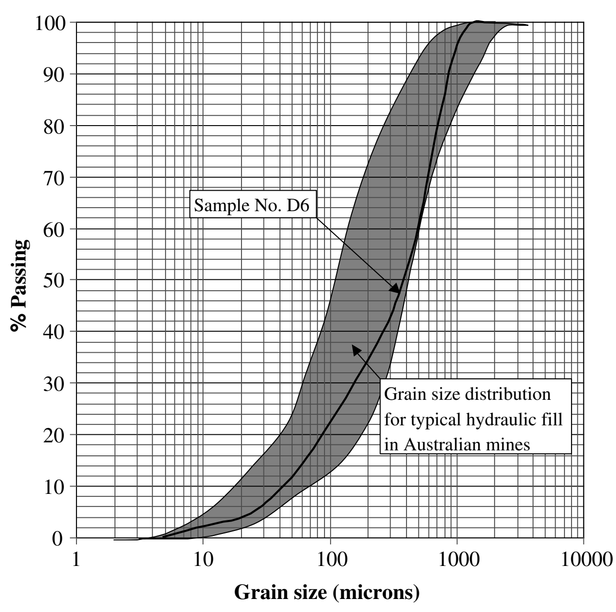

Figure 1. Generalised grain size distribution for Australian hydraulic fills.

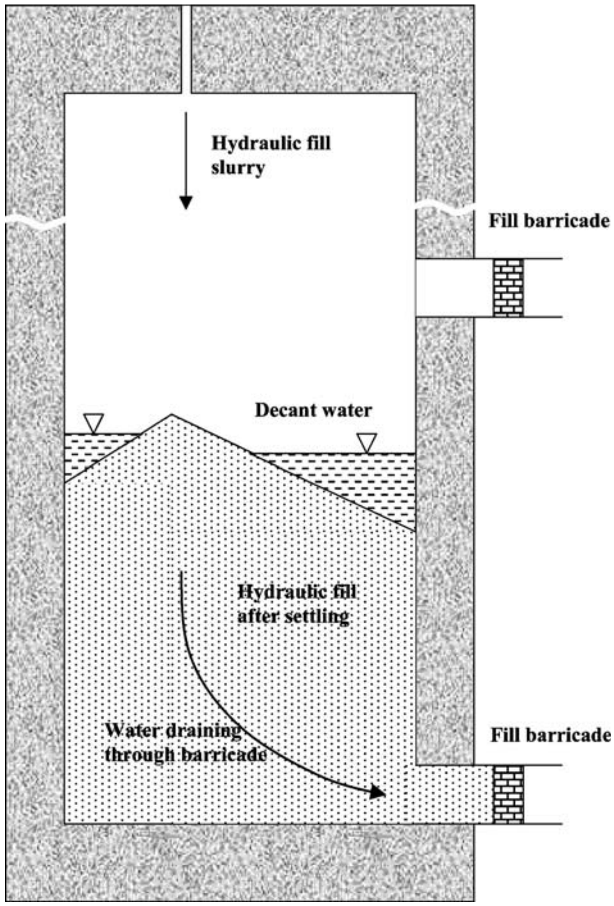

Figure 2. An idealised hydraulic fill stope.

drains from the stope, either by drainage through the fill and barricades, or by decanting through upper barricades (Figure 2).

Drainage is often assisted by a number of features, including pipes and valves through the barricades, internal drainage columns and, most commonly in Australia, by specially manufactured porous bricks, which have permeability that is comparable to coarse gravels. Drainage may continue for several months after completion of filling.

For a typical hydraulic fill of 70% solids by weight and specific gravity of 2.9, there is 55% water by volume in the slurry. Depending on the residual moisture content of each fill, variable amounts of water remains within the fill, tied up in the interstices, and the remainder either drains through the barricades or decants at the top of the fill and discharges through higher level barricades.

Fill barriers of various types are used throughout the mining world. For the greater part, these barriers perform as designed, but failures have been recorded, again globally. Most of these failures, whilst unacceptable, usually result in additional cleaning and the like, but occasionally the failures are catastrophic. Extreme examples have seen one mine cease all production for 8 months, with another 6 months before full production was re-started. In at least two examples, multiple fatalities resulted.

Several mechanisms, including piping and liquefaction, have been suggested to explain barricade failures (Bloss and Chen, 1998; Grice, 1998a). More recent research has suggested that the major cause of failure is attributed to the build-up of high pore water pressures behind the barricade, or blasting-induced damage resulting in cracking and failure of the barricade, with liquefaction or piping soon following. Liquefaction and piping substantially amplify the damage, but are not the direct cause of the initial damage (Kuganathan, 2001).

The objective of this paper is to summarise the permeability and strength characteristics of typical hydraulic fills used in a number of Australian underground metalliferous mines, and to discuss some specialised laboratory test procedures for assessing these characteristics. The geotechnical parameters summarised herein are based on a series of laboratory tests conducted on more than 20 different hydraulic fills from mines from Western Australia and Queensland, operated by five different companies. The paper also describes an empirical technique for estimating the friction angle of hydraulic fill. This new method is compared to the standard geotechnical empirical relations used for granular material.

2. Permeability of Hydraulic Fills

Ideally, hydraulic fill should be free draining to enable water to be removed from the stope as quickly as possible, without any build-up of excess pore water pressure. Therefore, one of the most important design parameters for hydraulic fills is permeability. One of the currently practised rules-of-thumb to achieve good drainage characteristics is to ensure that the effective grain size D_{10} is greater than 10 μm (Grice 1998b). Further to this specification, some restricted testing suggested that by ensuring the permeability of the hydraulic fill be at least 100 mm/h, good drainage would be optimised and the potential for liquefaction minimised (Herget and De Korompay 1978). However, the permeability measurements of 24 different hydraulic fill samples in the laboratory, shown in Table 1, indicate that the actual permeability values are substantially less than 100 mm/h and most of the mines have operated satisfactorily. It should be noted that these samples of hydraulic fill were not as used at the mine sites, but rather re-constituted mixes of some components of the hydraulic fills from the various sites. In the mining industry, mm/h is the preferred unit for permeability (1 cm/s = 36000 mm/h).

2.1. TEST PROCEDURE

All hydraulic fills were mixed to water contents corresponding to the slurries used at the mines. The water contents were typically in the order of 30–35%. The slurry

Table 1. Void ratios, water contents, dry densities and permeabilities of hydraulic fills

Sample no.	Specific gravity	Void ratio	Porosity (%)	Water content (%)	Dry density (g/cc)	Permeability (mm/hour)
A11	2.79	0.67	40.1	24.0	1.69	9.1
A12	2.79	0.61	38.0	22.0	1.75	8.9
A13	2.79	0.64	39.1	23.0	1.71	8.4
A14	2.79	0.67	40.1	24.0	1.73	8.3
A21	2.80	0.69	40.8	24.4	1.66	19.1
B11	2.85	0.66	39.9	23.3	1.67	2.0
B12	2.85	0.66	39.7	23.1	1.71	7.3
B13	2.85	0.66	39.9	23.3	1.70	1.8
B21	2.77	0.94	48.4	33.8	1.47	0.6
B22	2.77	0.92	48.0	33.3	1.44	0.6
B23	2.77	0.96	48.9	34.5	1.41	0.6
C11	4.26	0.73	42.3	17.2	2.48	19.4
C12	4.38	0.77	43.5	17.6	2.39	21.5
C13	4.37	0.83	45.5	19.1	2.42	24.2
C14	4.37	0.79	44.3	18.2	2.41	17.4
D11	3.42	0.58	36.8	18.4	2.16	20.7
D21	3.71	0.66	39.8	17.5	2.23	22.7
D31	3.53	0.70	41.2	20.1	2.08	37.8
D41	3.50	0.72	41.8	20.1	2.04	24.4
D51	3.50	0.70	41.2	20.0	2.06	30.3
D61	3.53	0.66	39.6	18.8	2.13	33.1
D71	3.32	0.68	40.4	20.1	1.98	27.8
D81	3.12	0.72	41.9	23.7	1.81	33.2
D91	3.42	0.72	42.0	20.8	1.98	28.2

samples were allowed to settle under self-weight in a 153 mm diameter and 306 mm high cylinder, without any surcharge. Constant head and falling head permeability tests were carried out on these reconstituted hydraulic fill samples of 306 mm height (Figure 3). The grain size distribution plots show that the fills are uniformly graded (the range of particle sizes falls within a relatively small band) and therefore it is reasonable to assume void ratios will not be significantly reduced by vertical stresses. The experimental data presented in this paper suggest that the relative densities of the slurry sedimented hydraulic fills are in the order of 50–80%, limiting further compaction due to the overburden stress. Therefore, the in situ fill can be expected to have 50–80% relative density throughout the depth. In other words, the sample prepared by the above sedimentation process will give a good representation of the in situ hydraulic fill.

2.2. DISCUSSION OF RESULTS

Mitchell et al. (1975) determined the permeability of cemented hydraulic fill using 152 mm diameter and 305 mm high samples prepared in the laboratory. They found that the drainage characteristics in the mine stope agreed with the predictions based on the permeability values measured in the laboratory. They found the permeability

(a) Constant head test (b) Falling head test (c) Extruded fill sample

Figure 3. Permeability test set-up.

decreased exponentially with curing time, from approximately 54 mm/h measured between 10 and 20 days, to a minimum of approximately 25 mm/h, obtained at 150 days. The permeability values seemed to plateau after approximately 120 days of curing. The in situ result, varied between 7.2 mm/h and 23 mm/h for the period of about 144 days which took to fill the stope. Herget and De Korompay (1978) conducted permeability tests on 32 mm diameter and 300 mm high laboratory specimens, and compared them with those obtained in the field using three different permeameters. The limited data indicated that the field permeability values were slightly higher but were of the same order as those obtained from the laboratory. Using the adjustment factors suggested in the paper to initially standardise both sets of results to indicate values representative for a sample at 20 °C, and 100% saturation, and then a factor to make the laboratory permeabilities which were obtained at a porosity of 0.37 more representative of the in situ porosity values of 0.47, the laboratory permeability of 101 mm/h compared very well to the in situ measurements, which ranged from 86 mm/h to 97 mm/h over two sites and three different measurement techniques for each site.

It can be seen from Figure 1 that the grain size distribution for many Australian hydraulic fills fall into a very narrow band. According to USCS (The Unified Soil Classification System), they can be classified as silty sands with symbol of SM, which are mostly uniformly graded. Even in some extreme cases, where they can be classified as well graded, the coefficient of uniformity (which is defined as D_{60}/D_{10}) is generally only slightly larger than 6, the lower limit for well-graded soils. In Figure 4, it is shown that the permeability values determined from constant head and falling head tests on the 153 mm diameter and 306 mm high laboratory samples are in good agreement with ones estimated from Hazen's (1930) empirical relationship given in

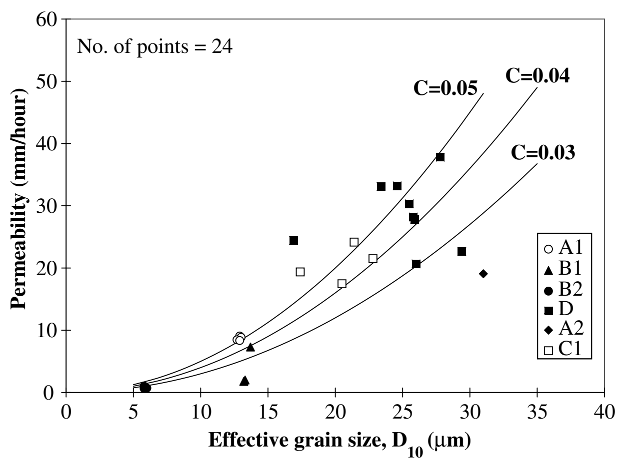

Figure 4. Permeability vs. effective grain size.

Equation 1, with the constant C in the range of 0.03–0.05 when D_{10} is in μm and k is in mm/h.

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

Hazen's equation was originally developed for fairly uniform clean filter sands in a loose state.

The void ratio, water content and densities of the settled hydraulic fill are summarised in Table 1, and the available $e_{\max}$, $e_{\min}$, and relative density values are given in Table 2. It is evident from Table 1, that the Australian hydraulic fills settle to a porosity of about 38–49%, with a saturation water content of about 17–35% when sedimented in the laboratory at the same slurry water content. The residual moisture content of the hydraulic fill material will be significantly less than the saturated values given in Table 1 (Clarke, 1988). Sample B had excessive fines with the average D_{10} value for Sample B being less than 10 μm, ($D_{50} \approx 48$ μm), which is substantially less than the minimum value for all other hydraulic fill materials tested for this

Table 2. Relative densities of hydraulic fills

Sample no.	Minimum void ratio	Maximum void ratio	Hydraulic fill void ratio	Relative density (%)
A14	0.452	0.944	0.670	56
C14	0.673	1.048	0.790	71
D11	0.431	0.829	0.583	62
D21	0.438	1.559	0.663	80
D31	0.477	1.166	0.700	68
D61	0.412	0.937	0.660	53
D71	0.544	1.184	0.678	79
D81	0.567	0.975	0.721	62
D91	0.534	1.036	0.724	62

research. Herget and De Korompay (1978) quoted 35 μm as the typical value for D_{10}, and many other researchers with extensive experience have quoted hydraulic fill D_{10} values in excess of 10 μm (Cowling et al., 1988; Bloss, 1992; Brady and Brown, 2002; Kuganathan, 2002). Therefore, Sample B is not considered a typical hydraulic fill and is not shown with the grain size curves, but was included in the permeability vs. effective grain size plot (Figure 4). Herget and De Korompay's (1978) field measurements also indicated porosity of 45–48%, similar to the values observed in the laboratory on the Australian hydraulic fills (see Table 1).

The specific gravity of soil grains typically varies in a very narrow range of 2.6–2.9. In hydraulic fills, however, due to the presence of heavy metals, the specific gravity can exceed 4. Having all the fills settle to porosity values in a range of 37–49%, it can be inferred that the dry density is proportional to the specific gravity of the soil grains. Variation of dry density of the settled fill against the specific gravity, for the 24 different hydraulic fill samples sedimented in the laboratory, is shown in Figure 5. Also shown in the figure are five in situ measurements in mines by Pettibone and Kealy (1971) from mines in the United States, and three Australian mines, as observed by the third author who has been working with the Australian mines for more than 30 years. It is quite clear that dry density of the hydraulic fill is directly proportional to the specific gravity, and can be given by the following equation:

$$\text{Laboratory dry density } (\text{g/cm})^3 = 0.56 \times \text{specific gravity} \tag{2}$$

Maximum dry density and minimum dry density tests were carried out in an attempt to estimate the relative densities of the hydraulic fills when they settle. The values shown in Table 2 suggest that the hydraulic fills settle to a dense packing of grains, giving relative densities in the range of 50–80%. Pettibone and Kealy (1971)

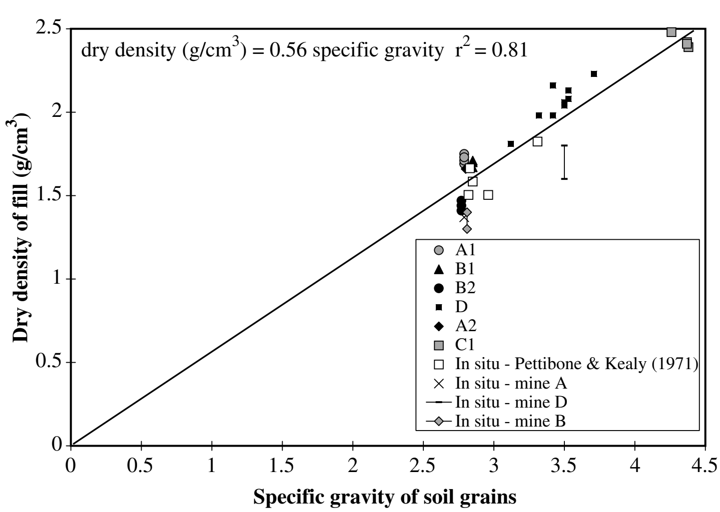

Figure 5. Dry density vs. specific gravity.

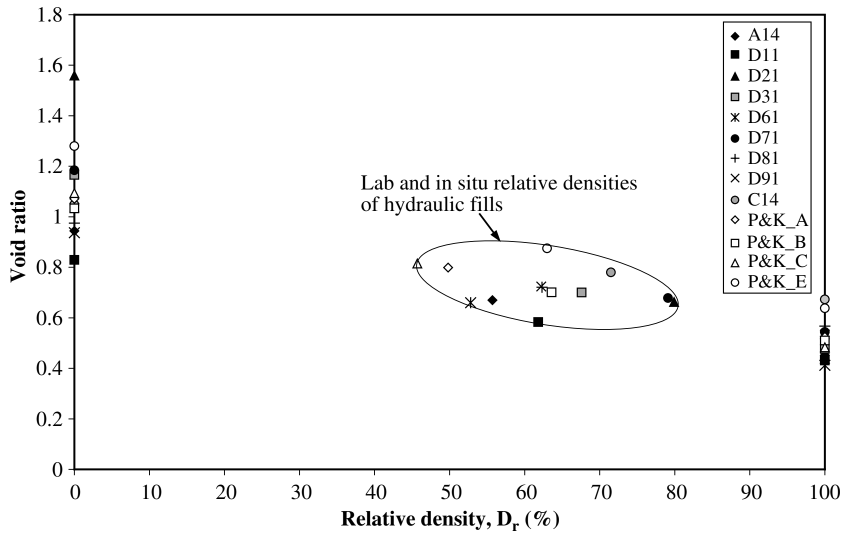

Figure 6. Void ratio vs. relative density.

reported similar relative density values based on field measurements within some hydraulic fill stopes in the US. It is interesting to note that the in situ hydraulic fills and the ones re-constituted in the laboratory were placed without any compaction and still attain medium dense to dense state. It is suggested this may be a result of the disturbance and impact energy applied as a result of placement during which the material may fall considerable distances, or as an effect of suction during the draining of water.

In Figure 6, void ratio is plotted against relative density for nine laboratory sedimented samples of hydraulic fills from Australian mines and four *in situ* measurements in US mines. All 13 points lie within the shaded area shown, suggesting 45–80% relative densities and void ratios of 0.6–0.8 for all hydraulic fills whether sedimented in the laboratory or placed in situ. The minimum and maximum void ratios for the laboratory samples, as determined from the maximum dry density test (ASTM D 4253-93, 1996) and minimum dry density test (ASTM D4254-91, 1996), are also shown in the figure.

3. Placement Property Study

The initial water content of hydraulic fill has significant influence on the in situ void ratio. Clarke (1988) suggested a procedure to study this through placing the hydraulic fills, mixed at different water contents, in a glass cylinder and vibrating for 5 min before measuring the porosity. The bottom of the cylinder can either be perforated to allow for drainage or sealed and undrained, depending on how rapid the drainage is expected in the mine. The main objective of the placement property test is to identify the optimum water content for the hydraulic fill that gives the minimum porosity (and thus maximum dry density) on placement in the stope, which indicates the point of optimum water content. The placement property test carried out on one of the fills, D_6, is shown in Figure 7, where porosity is plotted against water content. The same data is also presented as a plot of dry density against water content in Figure 8. The placement property test is a form of compaction test, but the results are presented slightly differently. The 5-min vibration suggested by Clarke (1988) is the compactive effort in this exercise.

The shaded region, bounded by the horizontal maximum porosity (or minimum dry density) and minimum porosity (or maximum dry density) lines at the top and bottom, and the saturation line on the right, is where the fill can exist with interparticle contact. The optimum water content for sample D_6 is about 14%, which will give the minimum porosity and maximum dry density when placed. However, the fill materials are transported by pipes, and should have sufficient flow characteristics that require the hydraulic fill be transported and placed in the form of slurry, with water content higher than the optimum water content. The intersection of the minimum porosity line and saturation curve give a first estimate of the optimum water content, which is 12% in the case of sample D_6. Such estimate can be obtained simply from a Maximum Dry Density Test (ASTM D 4253-93, 1996) and does not require the placement property test discussed above.

When the initial water content is very high, in the order of 40–50%, the suspension followed the saturation line and settled to a porosity value slightly less than the

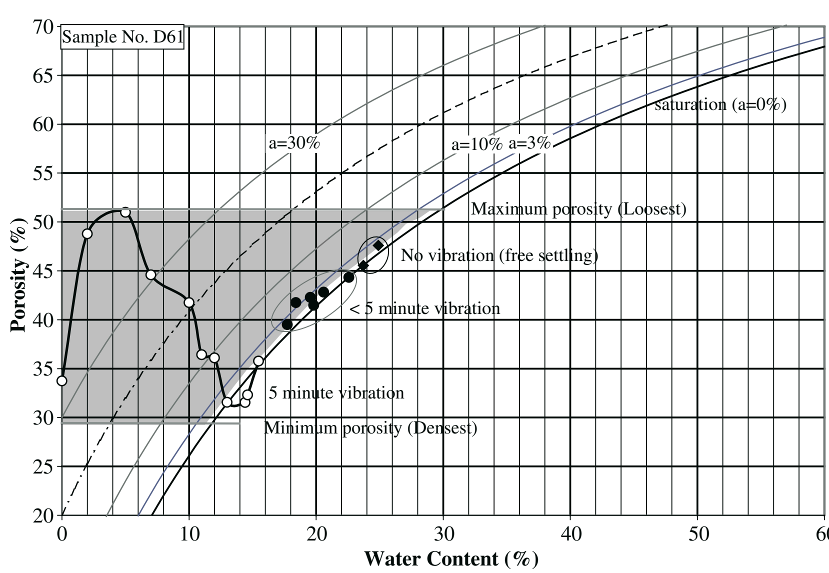

Figure 7. Placement property curve: porosity vs. water content.

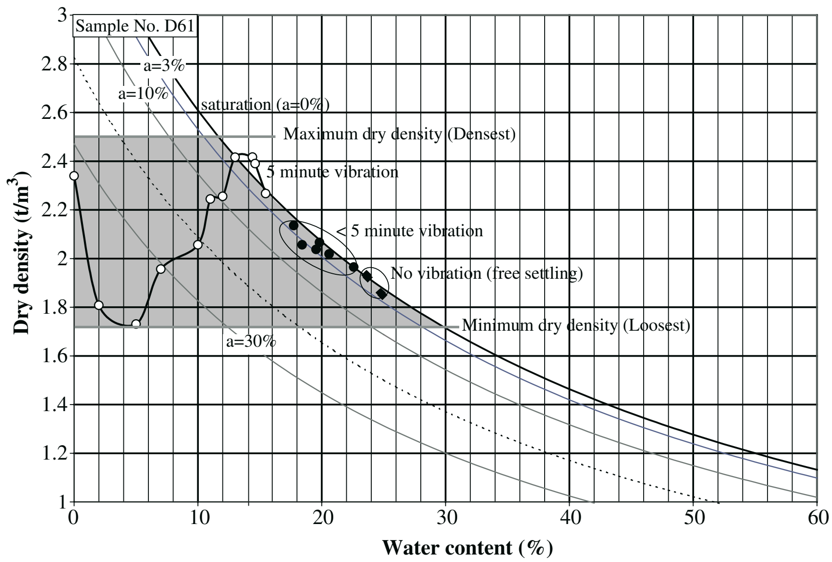

Figure 8. Placement property curve: dry density vs. water content.

maximum porosity. The two points are shown by "♦" symbol in Figures 7 and 8. The higher the water content of the suspension, the closer the porosity is to the maximum porosity. The points shown by "•" symbol were obtained from slurries mixed at water contents ranging from 20–50%, but were vibrated for less than 5 min.

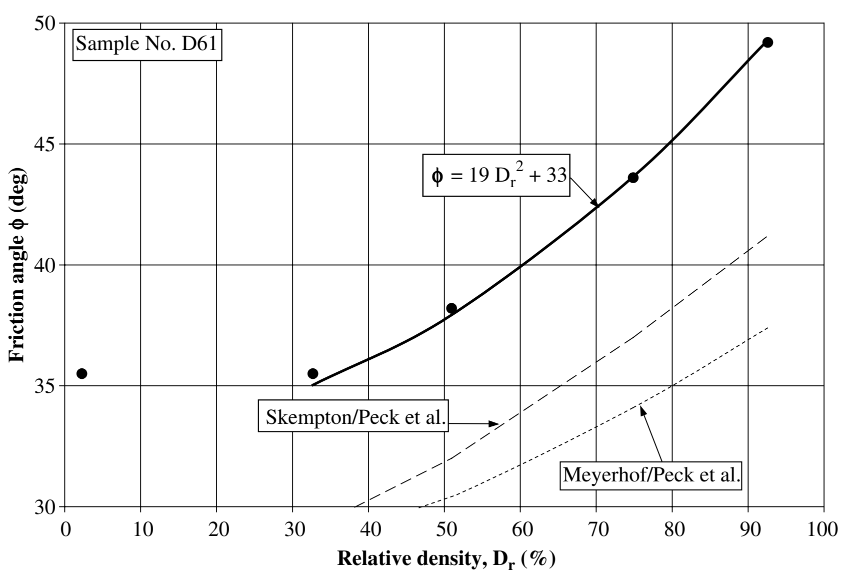

Figure 9. Friction angle vs. relative density.

They follow the saturation line in the shaded zone, and will move towards the optimum point with increased duration of vibration.

4. Friction Angles of Hydraulic Fills

Friction angle (ϕ) is an important parameter in the static and dynamic stability analysis of hydraulic fill. Underestimation of friction angle will result in underestimation of the arching effect in hydraulic fills and hence the overall stability of the material (Mitchell et al., 1975). Due to limited access and safety issues, it is often difficult to carry out in situ tests within the stopes. Therefore, laboratory tests such as direct shear test on reconstituted samples are the preferred alternative. Direct shear tests were performed on Sample D_6, over a range of relative densities, to observe the relevance of existing empirical relationships developed for clean, granular materials (see Figure 9).

Friction angle, relative density and N-value from standard penetration test are interrelated for granular soils. Meyerhof (1957) suggested that $N_1/D_r^2 \approx 41$ for clean sands. Skempton (1986) suggested that $N_1/D_r^2 \approx 60$ in sands for $D_r > 35\%$. Cubrinovski and Ishihara (2001) showed that N_1/D_r^2 for granular soils can vary in the range of 10–100, depending on the void ratio range $e_{max} - e_{min}$. Therefore, the ratio N_1/D_r^2 should be quite different for uniformly graded hydraulic fills than what is observed for granular soils in general.

In the case of hydraulic fills, it is more useful to relate the friction angle than the N-value to the relative density. The variation of peak friction angle with relative density for Sample D_6 is shown in Figure 8. For relative density greater than 35%, the friction angle and relative density can be related for Sample D_6 by Equation 3.

$$\phi = 19D_r^2 + 33 \text{ for } D_r > 35\% \quad (3)$$

where D_r is relative density.

As shown in Table 3, the measured friction angles for Sample D_6 are substantially higher than what was estimated using Skempton's (1986), Meyerhof's (1957) and Peck et al. (1974) relations for granular soils. It can be seen in Table 2 and Figure 1 that most hydraulic fills used in Australian mines have an e_{max}–e_{min} range of about 0.5 and that they all have a similar grain size distribution. Therefore, these hydraulic fills will have a unique N_1/D_r^2 ratio (Cubrinovski and Ishihara, 2001), and consequently a unique relationship between ϕ and D_r.

Table 3. Measured friction angle for hydraulic fill sample D_6 with estimates based on empirical relations for granular soils

D_r	Meyerhof (1957)		Skempton (1986)		Measured
(%)	$N_1 = 41D_r^2$	ϕ(deg)*	$N_1 = 60D_r^2$	ϕ(deg)*	ϕ(deg)
51	10.6	30.0	15.6	32.0	38.2
75	23.1	34.2	33.8	37.0	43.6
93	35.5	37.5	51.9	41.2	49.2

*From N_1 - ϕ correlation after Peck et al. (1974)

Conclusions

Unlike the typical granular soils, hydraulic backfill materials have a wider range of specific gravity, from 2.8 to 4.5. Twenty-four different hydraulic fills studied have shown similar and unique settling characteristics. When sedimented as slurry with 65—75% solid content, they all settle to a dry density (g/cm^3) of about 0.56 times the specific gravity.

Hazen's empirical equation, with $C = 0.03$–0.05, can be used for first estimates of permeability values of the hydraulic fills. Substantial laboratory permeability testing of over 20 reconstituted hydraulic fill samples, showed the permeability values were in the order of 10–30 mm/h, which is much less than the 100 mm/h often desired in the mining industry.

Placement property tests show that when the hydraulic fill is sedimented from a very dilute suspension, the resulting fill will have porosity close to the maximum porosity, implying very low relative density. However, laboratory placement tests have demonstrated that when the hydraulic fill is mixed in the form of slurry, with typical water content of 30–35%, the resulting hydraulic fill is rather dense, with relative densities of 55–80%, thus reducing the liquefaction potential.

From limited experimental data, it was shown that for hydraulic fills the friction angle and relative density are interrelated with a unique relationship. Further investigations into this relationship will have significant implications on the predictions of initial stresses and hence the liquefaction potential of the hydraulic fill material.

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