Geotechnical Engineering, Vol. 23, 1992

CONSOLIDATION BEHAVIOUR OF MINERAL SANDS TAILINGS

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SYNOPSIS

This paper describes work conducted to explore the rehabilitation characteristics of mineral sands tailings. The study comprised a series of centrifuge model tests to investigate the self-weight consolidation behaviour of the tailings under various water regimes, including the formation of surface "crusting" due to desiccation. The project has shown the viability and efficiency of centrifuge modelling in the area of mine tailings disposal. The model tests have provided essential data to determine the amount and rate of consolidation, and strength profiles of the tailings at different times and under different water regimes. The work has also indicated situations under which additional soil improvement might be necessary in order to allow development of the rehabilitated mine site. Centrifuge modelling also provides consolidation parameters that may be used, in conjunction with numerical modelling, to extend predictions of the rehabilitation performance of mine tailings beyond the boundary conditions of the model tests themselves.

INTRODUCTION

Safe and economical disposal of mine tailings is one of the major problems that confront the mining industry, especially in recent years with increasing pressures being brought to bear on all aspects of mining by the environmental lobby. This necessitates changes in traditional disposal methods, and the development of new methods that can minimise the impact of the mining operation on the environment.

For proper management of tailings disposal, both during the active life and subsequent rehabilitation period of the disposal, it is essential to understand the processes that control the movement of water in the tailings, the rate and final amount of surface settlement, and the changes in the strength profile through the depth of the tailings. This involves understanding the processes of initial sedimentation, self-weight consolidation under various boundary conditions and formation of surface "crusting" due to the combined effects of water table lowering in the tailings and surface desiccation.

A research project has been undertaken to explore the rehabilitation characteristics of mineral sands tailings. The mineral sands tailings consist of a mixture of 'slimes' (virtually pure kaolin clay and water) and silica sand. Previous operations

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have re-deposited the two types of tailing material separately. However, from an operational point of view, it would be preferable to mix the two material types and then re-deposit the mixture in a single operation. The aim of the project was to assess the feasibility of such an approach.

This paper presents the results of the project, which comprised a series of centrifuge model tests to investigate the self-weight consolidation behaviour of the tailings. A complementary programme of laboratory tests was performed to obtain fundamental material parameters.

TAILINGS PROPERTIES

The mixture of the mineral sands tailings was based around target figures for the mining operation. It consists of slimes at 39% solids content, to be combined with sand at 80% solids content, in a ratio of approximately 1 (slimes) to 2.5 (sand).

The grading curve for the sand tailings is shown in Fig. 1. The tailings are uniformly graded, with a D_{50} of 0.37 mm, and a coefficient of uniformity (D_{60}/D_{10}) of 2.5. Other properties are listed in Table 1. It may be seen that the void ratio range is 0.56 to 0.83, corresponding to dry densities of 16.7 kN/m^3 down to 14.2 kN/m^3. Under fully saturated conditions, the maximum solid content (by weight) would be 83%, corresponding to a void ratio of 0.56. In the centrifuge tests, the sand tailings were prepared at a solid content of 80%, corresponding to a void ratio of 0.66.

The results of a hydrometer test on the slimes are shown in Fig. 1. They indicate some 60% of the material is finer than 0.5 μm. Other properties are given in Table 2. The slimes have a plasticity index of 64. They were supplied fully saturated, at a solid content of 39% (water content of 157%).

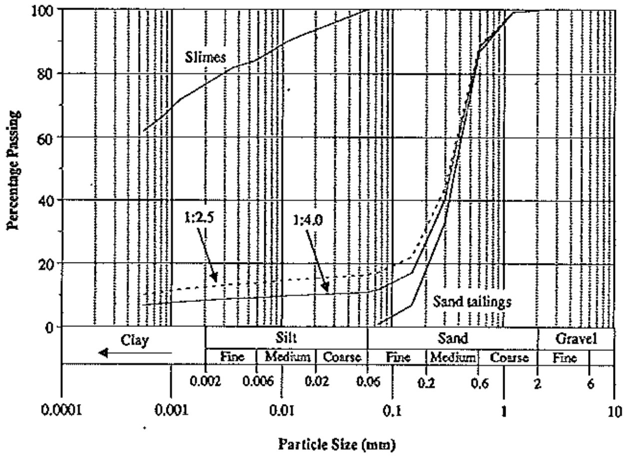

Fig. 1 Grading Curves for Sand Tailings and Slimes

The solid content of the slimes : sand mixtures may be determined from the solid content of the constituent parts and the ratio of mixing. Thus, for a ratio of 1 : 2.5, the solid content of the mixture is 68% (water content of 46% and dry density of 11.7 kN/m^3). Furthermore, the ratio of dry slimes to dry sand (by weight) of the mixture is 1 (slimes) to 5.13 (sand). For a ratio of 1 : 4.0, the solid content of the mixture is 72% (water content of 39% and dry density of 12.8 kN/m^3) and the ratio of dry slimes to dry sand is 1 : 8.2. The grading curves for the slimes : sand mixtures are shown in Fig. 1.

Consolidation tests were carried out using a Rowe cell to detemine the consolidation parameters of the mixture. Permeability tests were also conducted. The results of these tests, over the stress range 25 to 50 kPa, are given in Table 3 for the two different mixtures considered.

Table 1 Fundamental Soil Properties of Tailings Sand.

Specific Gravity (G_s)	2.65
Median Diameter (D_{50})	0.37 mm
Effective Diameter (D_{10})	0.17 mm
Coefficient of Uniformity (D_{60}/D_{10})	2.50
Maximum void ratio (e_{max})	0.83
Minimum void ratio (e_{min})	0.56

Table 2 Fundamental Soil Properties of Slimes.

Specific Gravity (G_s)	2.70
Liquid Limit (LL)	99.0%
Plastic Limit (PL)	35.0%
Linear Shrinkage (LS)	15.5%

Table 3 Summary of Key Consolidation Parameters.

Ratio Slimes : Sand	Compress'n Index, C_c	Swelling Index, C_s	Consolid'n Coeff, c_v (m^2/yr)	Compress'y m_v (m^2/MN)	Permeab'y k (m/yr)
1 : 2.5	0.249	0.024	45	2.13	0.94
1 : 4	0.190	0.021	210	1.01	2.07

Note :
Values of consolidation coefficient, compressibility and permeability are for the loading stage from 25 kPa to 50 kPa.

CENTRIFUGE MODELLING

The primary research tool for the investigation of the consolidation behaviour was the geotechnical centrifuge. The aim of a centrifuge model test is to obtain similitude of stress and strain in model and prototype. It is the ideal method of investigating self-weight consolidation, since it allows the full-scale problem to be properly simulated, but in a much reduced time. In a centrifuge test, if the model dimensions are N times less than the prototype dimensions and the gravity is artificially increased to N gravities (N g), the scaling laws indicate that consolidation occurs N^2 times than for the equivalent prototype. Thus, 1 day of consolidation on the centrifuge, at an acceleration of 100 g, is equivalent to 100^2 days (27 years) consolidation at prototype scale.

Centrifuge testing was carried out using the Geotechnical Centrifuge (Acutronic Model 661) which is installed in the Department of Civil and Environmental Engineering at The University of Western Australia (Randolph et al, 1991). The model tests were conducted to model one-dimensional consolidation of the tailings deposit with two-way drainage conditions. The progress of consolidation was monitored by measuring the surface settlement and pore pressures within the tailings. At different stages of the consolidation process, strength profiles and foundation capacity of the tailings deposits were determined "in-flight" using a cone penetrometer and a model footing respectively.

Sample Preparation

Sand tailings at a solid content of 80% were mixed with slimes at a solid content of 39%, in a ratio of 1 (slimes) to 2.5 (sand). The overall solid content of the mixed tailings was then 68%. A centrifuge test with tailings mixture of 1 (slimes) to 4.0 (sand) (solid content of 72%) was also conducted to investigate the effect of different clay content on the consolidation behaviour of the tailings. The tailings were mixed under vacuum, and then transferred to the strong-box, endeavouring to minimise entrapment of air. The tests incorporated a base drainage layer of coarse sand, overlaid by an initial 200 mm of tailings (representing a prototype depth of 20 m at 100 g).

The surface settlement of the tailings was measured by a Linear Variable Differential Transformer (LVDT) resting on a disk at the surface and suspended by a pulley system. The pulley system counteracted the increase in self-weight of the LVDT with increasing acceleration, thereby preventing the LVDT from sinking into the soft tailings during the early stages of the test.

Miniature 'Druck' pore pressure transducers were inserted into the tailings at different depths to monitor the progress of consolidation. The transducer leads were brought up at the sides of the strong-box.

The strong-box was then mounted on the swinging arm of the centrifuge, and two actuators placed in position on top of the strong-box. One actuator has a cone penetrometer, 10 mm in diameter, that enables several cone tests to be undertaken "in-flight", retracting the cone and relocating it by moving it laterally after each penetration test. The second (footing) actuator allows surface loading tests to be conducted, using model footings of 50 mm or 60 mm diameter (modelling prototype foundations of 5 m or 6 m diameter respectively).

Drainage from the tailings occurs both at the surface and at the base of the sample. Base drainage was maintained closed by a solenoid valve until the centrifuge had achieved the required acceleration level. The water table was controlled by means of an external stand-pipe with a preset overflow.

The layout of the package for the centrifuge tests is shown in Fig. 2. Generally, preparation of the package would be completed the day before testing, and the tailings would be allowed to settle overnight, before starting the main test. This led to about 10 mm of settlement (with clear water overlying the tailings). Thus, at the start of each centrifuge test, the depth of tailings was close to 190 mm (19 m equivalent prototype).

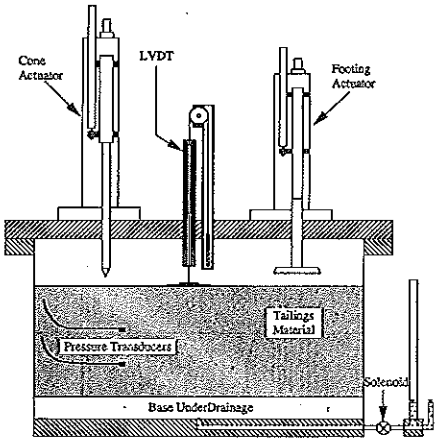

Fig. 2 Schematic Diagram of Centrifuge Model Setup

Model Testing

Tests with two different drainage boundary conditions and slimes : sand mixture are presented in this paper. They are :

Case 1 : Mixture ratio of 1 : 2.5 and top-bottom drainage with the water table maintained at the same level as the surface of the tailings deposit.
Case 2 : Mixture ratio of 1 : 2.5 and top-bottom drainage with the water table maintained at the same level as the base of the tailings deposit.
Case 3 : Mixture ratio of 1 : 4 with similar drainage conditions to Case 2.

From the centrifuge tests, the following consolidation characteristics of the tailings deposits have been deduced :

- consolidation times for tailings deposits of up to 20 m thick;
- typical consolidation settlement of the tailings;
- the engineering strength of the tailings, from the point of view of subsequent land development;
- the effect of different water regimes on the consolidation performance of the tailings.

Furthermore, the centrifuge tests are not merely a simulation of field behaviour of filled tailings deposit. They may also be utilized to obtain consolidation parameters, in particular the effective stress vs. void ratio relationship (σ'-e) of the tailings. This relationship can be obtained from the final water content distribution with depth, determined after the centrifuge test, for the case where the tailings remain saturated throughout the test (Case 1).

TESTS RESULTS

Case 1

This test was conducted with the water table maintained at a level above the soil surface so that soil was fully saturated at all times. The results of the test are presented in Fig. 3 and 4 (a) to (d). From Fig. 3, it may be seen that 90% of the consolidation settlement occurs in the first 150 days (prototype time). The final pore pressure profile (Fig. 4 (a)) is hydrostatic over the 15 m depth of tailings.

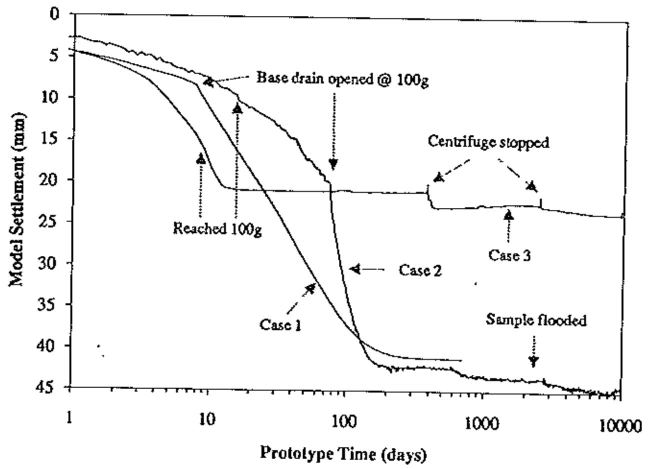

Fig. 3 Surface Settlement of Soil Sample for All Cases

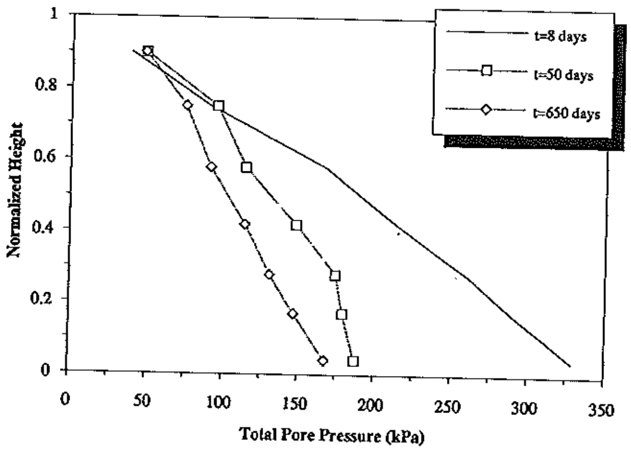

Fig. 4 (a) Total Pore Pressure Isochrones of Soil Sample (slimes : sand = 1 : 2.5) for Case 1

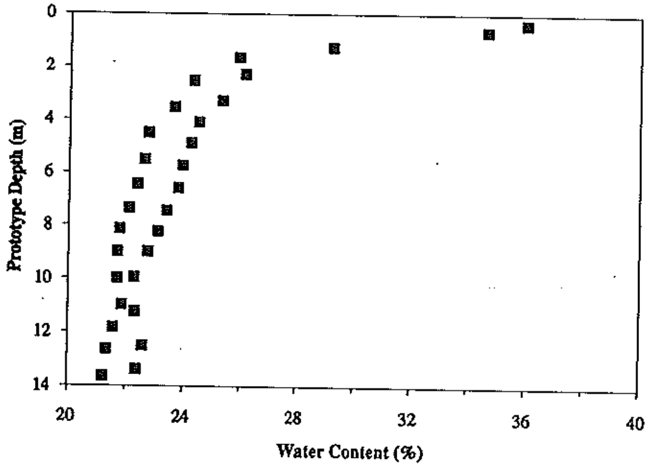

Fig. 4 (b) Water Content Profile of the Soil Sample (slimes : sand = 1 : 2.5) at the End of Centrifuge Test (Case 1)

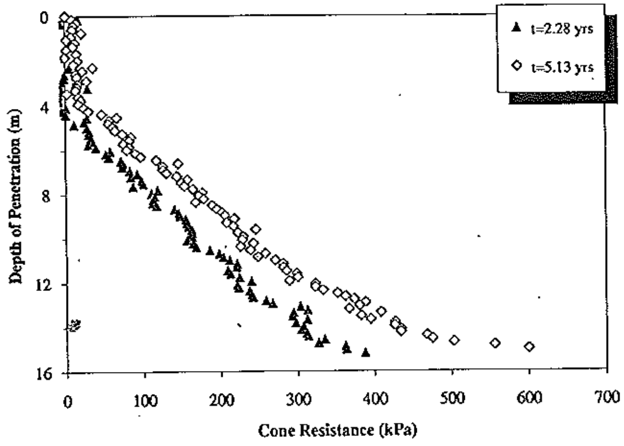

Fig. 4 (c) Cone Penetration Tests Results of Soil Sample (slimes : sand = 1 : 2.5) for Case1

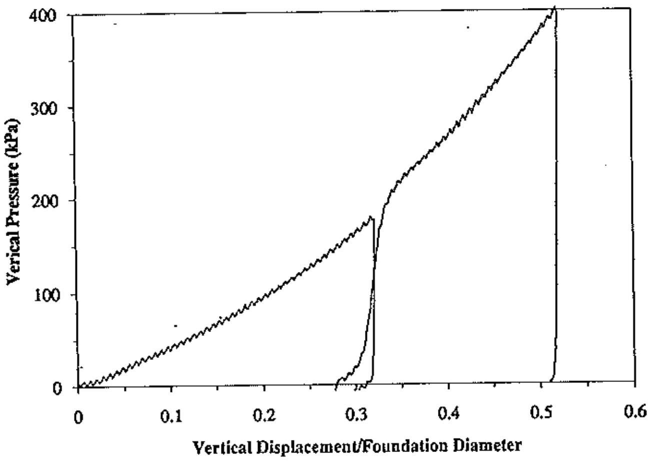

Fig. 4 (d) Foundation Test at Prototype Time of 2.8 Years of Soil Sample (slimes : sand = 1 : 2.5) for Case 1

The water content profile at the end of the test is shown in Fig. 4 (b). Since the soil sample was fully saturated, the void ratio profile could be calculated using the expression,

$$e = \omega G_s$$

where ω is the water content and G_s is the average specific gravity of the tailings solids. From the pore pressure profile in Fig. 4 (a), the dissipated pore water pressur

represents the effective stress of the soil sample at the end of the test. With the information on the void ratio and the effective stress profile, the (σ'–e) relationship of the sands tailings was obtained as shown in Fig. 5. The (σ'–e) relationship may be used for the prediction of the consolidation of the sands tailings. Toh and Fahey (1991) have described similar techniques for estimating the (σ'–e) relationship for soft clay, and used of the relationship for numerical predictions of large strain consolidation.

Rowe cell and oedometer tests are used routinely for determining consolidation parameters. However, while the accuracy of results at moderate to high stress levels may be reasonable, their suitability for conducting accurate tests at low stress levels on slurries is questionable. A more effective way of applying low stresses (for example, 10 to 20 kPa) is to use suction pressure. Two simple and quick suction tests, with pressures of 10 kPa and 18 kPa, were carried out and the void ratios obtained are indicated along with the Rowe cell and centrifuge results in Fig. 5. The results of the suction tests agree well with the centrifuge results. This confirms the usefulness of centrifuge testing as a calibration tool to determine (σ'–e) relationships for tailings.

However, the form of the (σ'–e) relationship from the Rowe cell test shown in Fig. 5 is interesting, in that it shows that, while the initial response shows reasonably high compressibility (compression index of about 0.25), the compressibility reduces at effective stress levels greater than about 200 kPa. This behaviour is thought to result from the influence of the (small) clay content at low stress levels, while the response at higher stress levels becomes dictated more by the sand matrix.

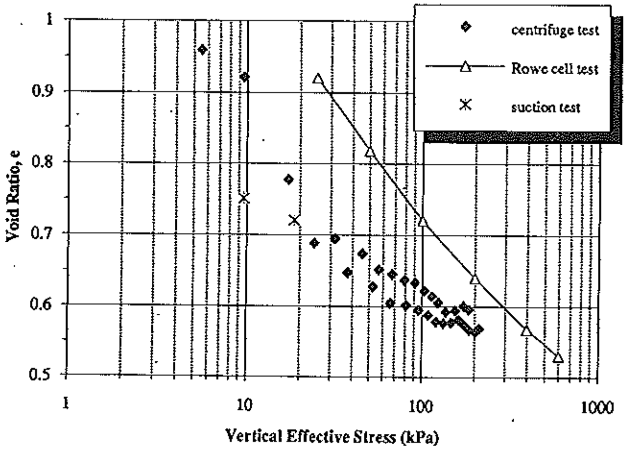

Fig. 5 Void Ratio and Vertical Effective Stress Relationship of Soil Sample (slimes : sand = 1 : 2.5)

The cone resistance (Fig. 4 (c)) and footing response (Fig. 4 (d)) are weak. Clearly, under fully saturated conditions with a high water table, the tailings are not capable of supporting significant load. A bearing pressure of only 40 kPa is sufficient to cause vertical displacement of 10% of the foundation diameter (Fig. 4 (d)).

Case 2

In this test, the water table was maintained close to the base of the tailings. The results are presented in Fig. 3 and 6 (a) to (d). The settlement response (Fig. 3) shows consolidation is virtually completed within 150 days. At that stage, a certain amount of standing water was still evident on the surface of the tailings. During the remainder of the test, the water continued to drain from the tailings, allowing air entry from the surface. Some negative pore pressures were measured. However, the miniature pore pressure transducers quickly reached cavitation point at a time of about 2 years (prototype), after which the readings are no longer reliable (they mostly returned to a reading close to zero).

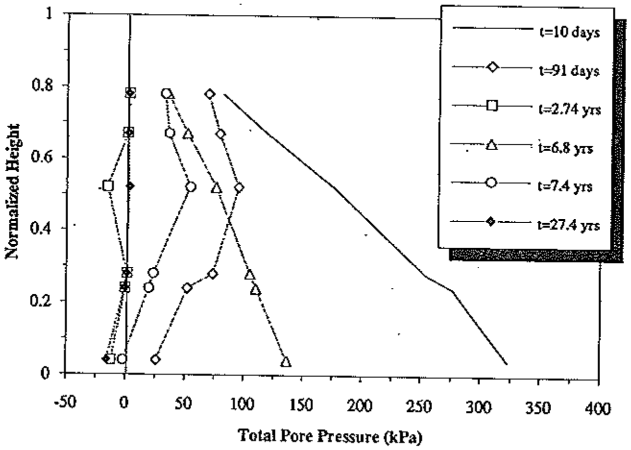

Fig. 6 (a) Total Pore Pressure Isochrones of Soil Sample (slimes : sand = 1 : 2.5) for Case 2

The sample was then flooded by closing the base drain and introducing water onto the surface of the tailings. The pore pressure profiles in Fig. 6 (a), at times of 2.74 years (zero measured pore pressure) and 6.8 years (back to hydrostatic profile), show the effect of flooding the sample. After reaching hydrostatic, the base drain was opened to allow water to drain from the tailings. By the end of the test (27.4 years prototype), the water content profile (Fig. 6 (b)) was nearly linear, varying from 6% at the surface to 18% near the base.

The cone resistance profiles are shown in Fig. 6 (c). Of particular note is the buildup of a surface crust at time 5.33 years (tailings drying out), and the significant reduction upon wetting the tailings (time 7.42 years, sample re-saturated). The final maximum cone resistance of over 12 MPa indicates large suctions existing within the pores of the tailings mix.

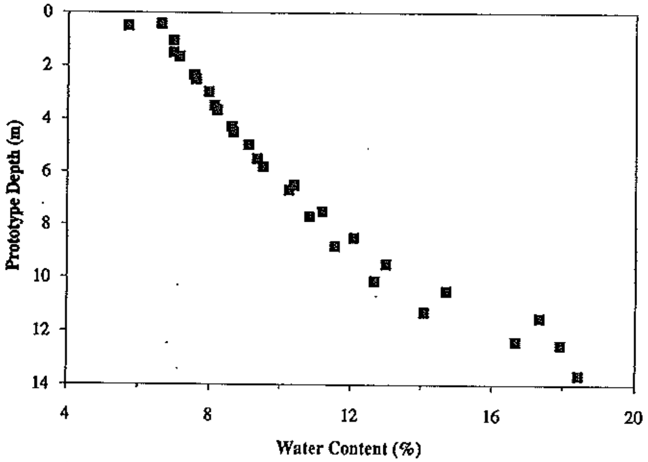

Fig. 6 (b) Water Content Profile of the Soil Sample (slimes : sand = 1 : 2.5) at the End of Centrifuge Test (Case 2)

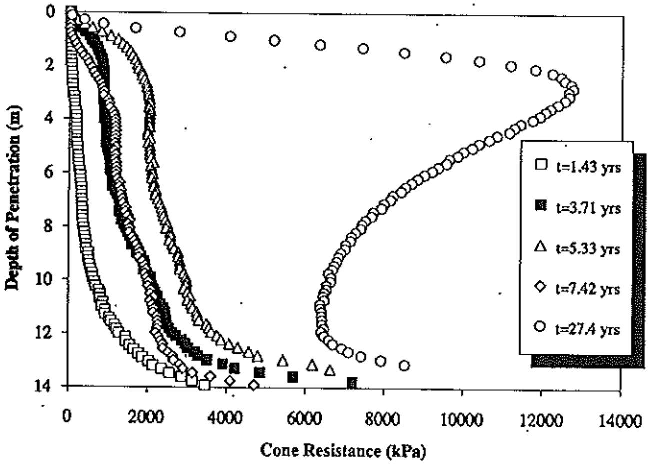

Fig. 6 (c) Cone Penetration Tests Results of Soil Sample (slimes : sand = 1 : 2.5) Case 2

Footing tests were carried out on a 6.0 m diameter circular foundation (60 mm diameter model), at times of 5.33 years (before re-saturating the sample) and 27.4 years. The first test shows no 'yield' point, but a pressure of 350 kPa was required

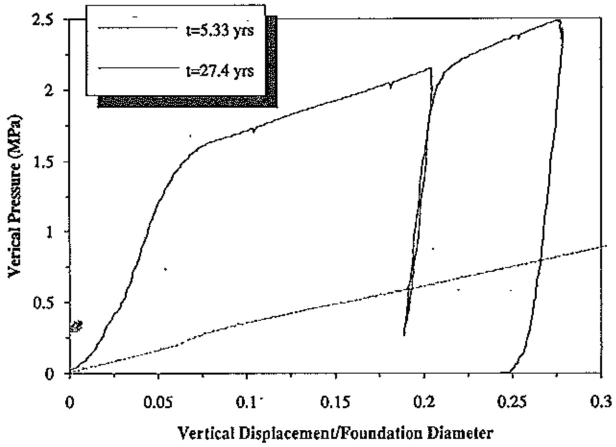

Fig. 6 (d) Foundation Tests on Soil Sample (slimes : sand = 1 : 2.5) for Case 2

for a penetration of 10% of the footing diameter (this criterion is commonly used to indicate the 'capacity' of the foundation). The later test shows a clear yield point at a pressure of about 1.6 MPa. The gradient of the unload-reload loop corresponds to a shear modulus for the soil of about 50 MPa (Young's modulus of about 125 MPa).

Case 3

The final test was conducted on tailings with a slimes : sand ratio of 1 : 4. The purpose of this test was to assess whether, with the lower clay content, the tailings would still exhibit the very high suctions and strengths measured in Case 2. The results of the test are shown in Fig. 3 and 7 (a) to (d).

Due to a malfunction of the base solenoid valve, the main consolidation of the tailings was carried out under fully saturated conditions, with the water table at the soil surface. Even with the single surface drainage, the consolidation was much more rapid than for Case 1, with 90% consolidation occurring within the time taken to accelerate the centrifuge (about 1 month prototype time). After the initial drop to hydrostatic conditions, the pore pressures remained sensibly constant over the next hour (model time), until the centrifuge was stopped to open the base drain. From then on, the pore pressure transducers dropped to zero readings as water drained out of the tailings.

The final profile of water content is shown in Fig. 7 (b). The water contents are significantly lower than in Case 2, apart from very near the base of the tailings (in the zone of full saturation). The cone resistance profiles showed the characteristic increase in strength, particularly in the upper half of the deposit. From the footing tests (Fig. 7 (d)), the bearing capacity increased with time from about 300 kPa (settlement of 10% of foundation diameter) to over 2.5 MPa (yield point). It is noteworthy that high strengths in the upper desiccated zone were obtained, even with the relatively low ratio of clay to sand (just under 11% by dry weight).

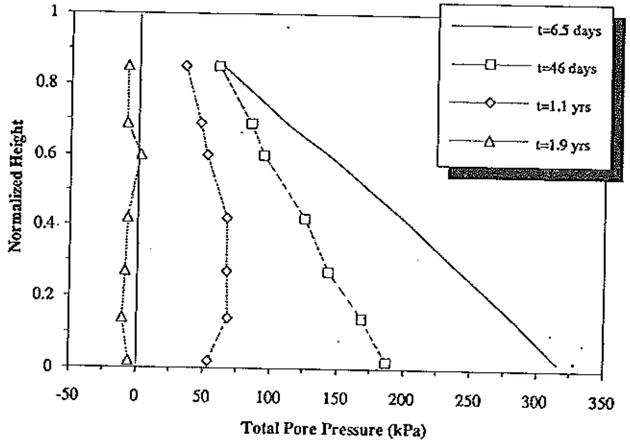

Fig. 7 (a) Total Pore Pressure Isochrones for Soil Sample (slimes : sand = 1 : 4.0) for Case 3

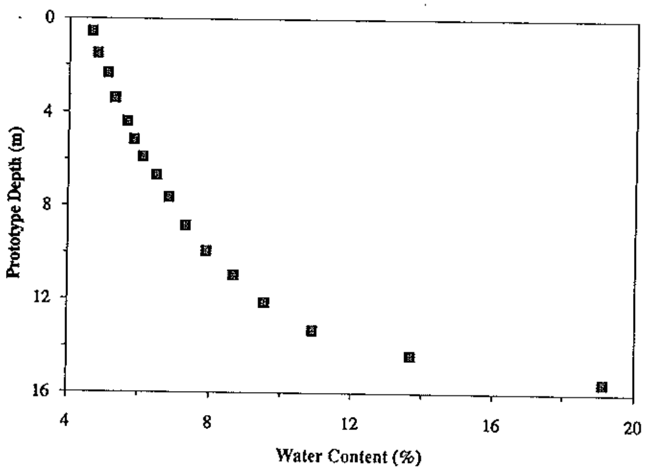

Fig. 7 (b) Water Content Profile of the Soil Sample (slimes : sand = 1 : 4.0) at the End of Centrifuge Test (Case 3)

DISCUSSION AND CONCLUSIONS

A summary of the amount of settlement of each test is given in Table 4. The total compression of the tailings (slimes : sand mixture ratio of 1 : 2.5) amounted to

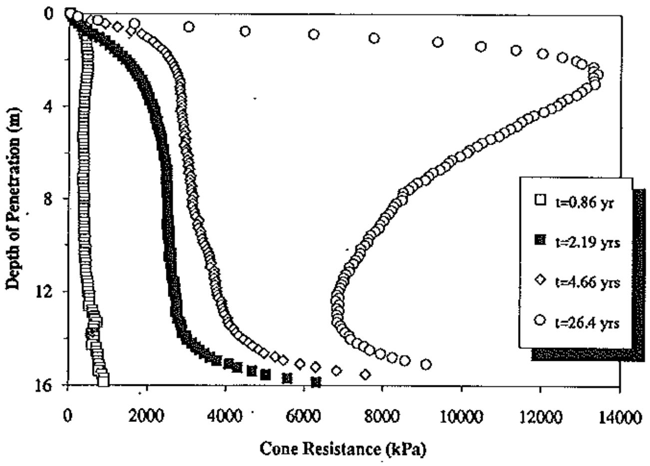

Fig. 7 (c) Cone Penetration Tests Results of Soil Sample (slimes : sand = 1 : 4.0) for Case 3

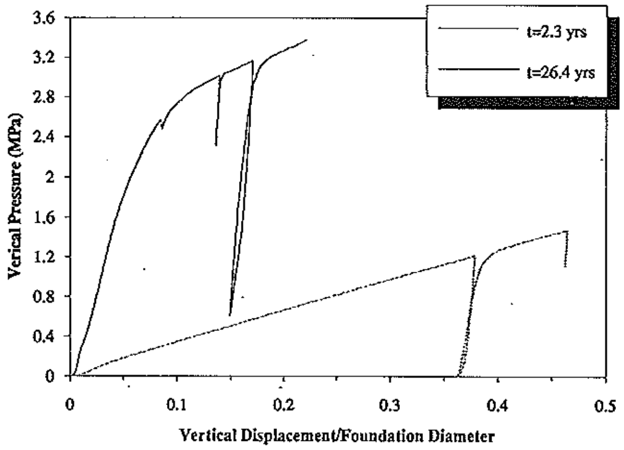

Fig. 7 (d) Foundation Tests on Soil Sample (slimes : sand = 1 : 4.0) for Case 3

some 20% with a typical consolidation time of about 150 days. In practice, much of this compression would occur during the back-filling process. The component remaining after completion of the filling process would probably be less than 10% of the depth of the tailings fill depending on the time-scale of the fill operation. The total compression for the mixture ratio of 1 : 4 was about 16% with consolidation time of less than 1 month.

Table 4 Summary of Centrifuge Tests Results.

Centrifuge Test	Mixture Ratio (slimes : sand)	Initial Mixture		Soil Model Thickness	
		w (%)	S (%)	Initial (mm)	Final (mm)
Case 1	1 : 2.5	46.4	68.3	190	150
Case 2	1 : 2.5	44.6	69.0	190	148
Case 3	1 : 4.0	39.3	71.8	190	160

Note :
w = water content
S = solid content

After a further elapse of time, with water allowed to drain out from the tailings, significant crusting and strength increase were measured in the centrifuge tests where the water table was maintained at a low level. Cone resistance values as high as 12 MPa were achieved after a period of 27 years (prototype time). Even after 2 or 3 years, crusting caused a cone resistance of 1 MPa at 2 m depth. Despite the large increase in strength, an additional compression of only about 1% occurred.

The high values of cone resistance indicate significant suctions in the upper layers of the tailings. However, subsequent inundation of the surface showed a reduction in strength. High suctions were also evident in the test where the slimes : sand ratio was 1 : 4, in spite of a clay content of less than 11%.

Model footing tests showed that the foundation capacity was relatively low immediately after consolidation where the tailings were still fully saturated. This indicates that the tailings are not capable of supporting significant load. However, as crusting developed, the foundation capacity improved remarkably.

From the results of the centrifuge tests, it appears that the proposed placement of premixed tailings is viable in terms of the time for consolidation. Furthermore, no significant compression occurred after consolidation in spite of the crusting and inundation of the surface. This demonstrates the stability of the tailings deposits. However, some improvement of the surface strength would be necessary for any subsequent building development on the land. Such strength increase could occur naturally, through suctions in the soil, with a low water table, or may be achievable with a moderate covering of sand fill. To prevent loss of strength due to rises in water table following heavy rain, it would seem prudent to ensure the water table is maintained at some metres below the ground surface. This could be achieved by incorporating regular sand drains into the fill at appropriate depths.

The formation of surface crusting occurs frequently in mine tailings disposal areas, especially in arid parts of Australia where net evaporation rates of the order of metres per year are common. It can have a strong influence on the design and rehabilitation strategies for disposal areas; the mining industry in Australia has started to explore effects of evaporation, which can contribute significantly to the strength gain near the surface of slurried wastes. It is therefore important to simulate surface desiccation and crusting in the centrifuge model tests. At this stage, the extent to which quantitative scaling of evaporation to cause desiccation is possible in centrifuge model tests is still being explored. However, the key qualitative effects may certainly be modelled.

In summary, an improved understanding of the development of a new tailings disposal method has been outlined in this paper. The physical processes and the rehabilitation of the tailings deposits were investigated by model tests using a geotechnical centrifuge. The research programme has direct application to mining operations in Australia and the Southeast Asian region.

Furthermore, the programme has provided fundamental understanding of the consolidation behaviour of mineral sands tailings. There is still scope for future work. For instance, in field practice, the water table is often maintained at only a few metres (eg. 5 m) below the surface of a consolidating tailings deposit, compared with a depth of 15 m in the case presented here. The consolidation behaviour, strength profile and foundation capacity of the tailings under such condition require further research. In addition, the results of specific model tests can be extended to new situations by means of numerical analysis that allows for the large strains that occur during consolidation (Toh and Fahey, 1991).

One such extension would be to analyse the gradual increase in tailings thickness that occurs in the prototype situation. While this could be modelled on the centrifuge, many stops and re-starts would be necessary to place more slurry, and there would be significant delays if instrumentation had to be removed and mounted at each stage. Thus it is more efficient to use centrifuge modelling of a single fill stage, followed by consolidation, to calibrate the numerical analyses and derive the necessary parameters for the fill material. Then, the real prototype situation of gradual filling may be analysed with confidence using the calibrated numerical models.

ACKNOWLEDGMENT

The laboratory tests were conducted by B. Bhattarai. The first author is supported by a research scholarship at the University of Western Australia.

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