Field capacity and moisture loss during active deposition on Tailings Dams

Capacité au champ et perte d'humidité pendant le dépôt actif des résidus

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ABSTRACT: A common method to manage tailings in semi-arid environments is to self-impound the waste as it dries. This research investigated the degree of in-situ drying of platinum tailings. Following sedimentation and drying a steady state developed. This was marked by gravimetric water contents varying within a narrow range related to the materials field capacity. Low water contents indicative of significant suctions were only recorded following 6 months of dormancy. Liquidity indices indicated that during normal operation only the outer 50 m dried sufficiently to impound the waste stream.

RÉSUMÉ : Les résidus miniers dans des environnements semi-arides sont souvent mis en dépôt et font prise. Cet article présente l'étude du degré de séchage in situ des résidus de platine. Suite à la sédimentation et au séchage, un état permanent d'hygrométrie est atteint. Cet état est très proche de la capacité au champ du matériau. Les indices de liquidité montrent que pendant l'opération, un séchage suffisant pour retenir l'écoulement des résidus, s'effectue seulement sur une profondeur externe de 50 m.

KEYWORDS: Tailings, Reference Evapotranspiration, Moisture Loss, Field Capacity, Strength Gain.

1 INTRODUCTION

The self-impoundment of mine tailings is dependent on whether the geotechnical behaviour enables strength gain within realistic time frames. In semi-arid environments this is aided by the drying effect of evaporation.

This paper presents results of research carried out on the in-situ drying behaviour of platinum tailings. This was done by monitoring gravimetric water contents following successive field depositions on two back-to-back tailings dams over eleven months. The rate of drying is correlated with Reference Evapotranspiration with the extent of drying illustrated to be controlled by field capacity. Liquidity indices are presented to illustrate the strength gain that occurs.

1.1 *Test Work*

Test work was carried out on two back-to-back facilities; Dam 1 a 100 ha conventional upstream spigoted facility (raised at 2.3 m•year^{-1}) and Dam 2, a 100 ha waste rock impoundment filled via a series of spigots (raised at 4.6 m•year^{-1}). Two separate processing plants supplied similar tailings; the South Plant to Dam 1 and the North Plant to Dam 2.

Sampling took place every 50 m along a 400 m test section on Dam 1 with access by a specially constructed catamaran drawn by a steel cable. On Dam 2 sampling took place every 50 m along a shorter 200 m test section accessed via scaffold from the pool wall. In both cases the test section ran from the spigot points to the pool in the interior. Table 1 details the raw data obtained during the study.

Test depositions were scheduled to deposit 400 mm of material on each test strip at similar cycle intervals. However the depth of material deposited was not uniform due to the inherent beaching behaviour. This resulted in only the outer 100 m having a similar rate of rise of 2.5 m•year^{-1} on both test strips. On Dam 1 less material was deposited past 100 m whereas on Dam 2 more material was deposited, resulting in rates of rise of 1.2 m•year^{-1} and 4.0 m•year^{-1} respectively for these sections.

Table 1. Raw Data

Activity	Raw data obtained
Beach sampling via bulk samples, grab samples, and auger samples	Particle size distributions, particle specific gravities, gravimetric water content, calibrated gypsum block suction tests and triaxial permeability tests.
Site climatic data	A-Pan evaporation, rainfall and daily minimum and maximum temperatures.
South African Weather Service, Mokopane Station	Daily temperature, wind speed and relative humidity.
Historical monitoring and design data	Atterberg limits, evaporative drying tests, filter paper suction tests

2 ANALYSIS OF RESULTS

2.1 *Rate of Moisture Loss*

The results following the sampling of three depositions on Dam 2 were analysed to determine the rate of moisture loss during sedimentation and drying to steady state.

The rate of sedimentation was determined by linear regression using water contents determined from slurry densities during deposition and grab samples following cessation of deposition. The density of the slurry varied considerably with the water content on average 94 % with a standard deviation of 33 %. Sedimentation was observed to be complete within 65 hours (7 hour standard deviation) with a final water content of 41 % (1.3 % standard deviation). The water released during sedimentation is available for recovery.

Similarly the rate of drying was determined by linear regression using the water contents following sedimentation, surface samples recovered during the drying stage, and the average steady state value. Figure 1 shows a composite graph of the sedimentation, drying and steady state curves with respective raw data at 50 m along the beach. The rates of drying for the respective depositions along the beach are given in Table 2.

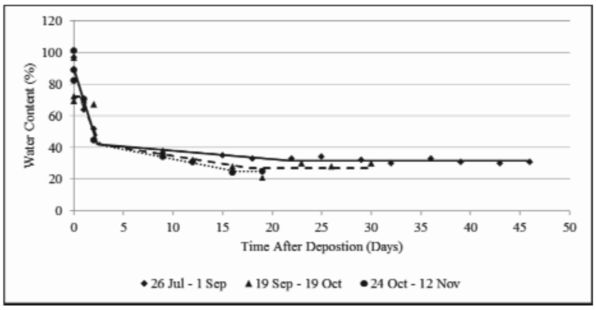


Figure 1. Regression curves at sampling point 50 m along beach

2.2 *Reference Evapotranspiration*

Reference Evapotranspiration (ET_0), a measure of macroclimatic evaporative energy, was calculated using methods outlined in Allen et al (1998). Climatic data from the Mokopane weather station maintained by the South African Weather Bureau was used to develop a regional calibration of the Hargreaves method based on the Penman-Monteith method. The calibrated Hargreaves method was then used to calculate ET_0 values for the test site.

An A-Pan was also maintained, however although results agreed with ET_0 values a great deal of scatter was observed. This is considered a consequence of variable microclimatic conditions on the dams and operational constraints.

2.3 *Empirical Correlation*

In order to enable the correlation to be compared with other sites it was necessary to correlate the rate of drying with a macroclimatic measure of evaporative energy. This is independent of the dam surface microclimate that resulted in scattered A-Pan data.

Table 2 shows the values used to develop the empirical correlation defined by the k – value. This is the ratio between the change in water content per day and average daily ET_0 value during the drying stage.

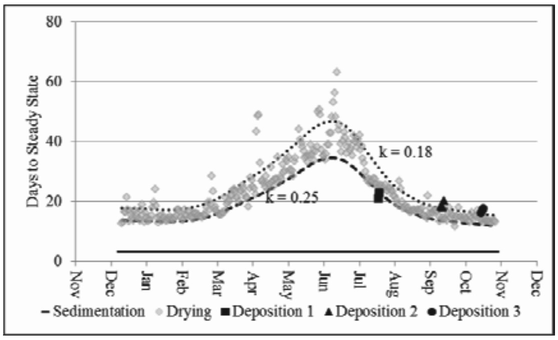
Table 2. Development of empirical correlation

Deposition ↓	Change in water content per day			Average daily ET_0 (mm·day^{-1})	Combined k – value per deposition	Average k – value
Distance along beach →	0 m	50 m	100 m			
1	0.96	0.54	0.71	3.0	0.25	0.21
2	1.24	0.98	0.87	5.3	0.20	
3	1.03	1.23	0.88	5.9	0.18	

During winter as the evaporative energy is lower, more moisture may be lost through seepage with the opposite being the case during summer. It is also likely that this water bleeds up to the surface as the material consolidates and is recovered. This is illustrated by the k – values being slightly higher during winter and lower during summer but a longer study would be required to quantify this variation.

Figure 2 illustrates the time required for the sedimentation step and then, using the average k – value, the number of days to reach steady state based on daily ET_0 values. Such relationships can be used to optimise the safe development of tailings dams.

Figure 2. Predicted drying behaviour



2.4 *Steady State*

The steady state after drying was investigated by analysing auger samples taken at 200 mm intervals to a depth of 1 m increasing to 2.5 m as the study progressed. Within the time frame of sampling following drying of each test deposition no trend of water content with time was observed. Rather values varied from sample date to sample date within a narrow distribution. To investigate this steady state various laboratory tests were done. This was supplemented by computer analysis and predictive modelling. Table 3 summarises these results which were used to assess the steady state.

Table 3. Geotechnical Parameters

Parameter		Value			Determination
Air Entry Value		27 %			Laboratory determined Volumetric Shrinkage Curves
Peak Dry Density (kg•m^{-3})		1 700			
Porosity		0.48			
Field Capacity, at 33 kPa (Miller & Donahue, 1990)		21 % (4.3% standard deviation)			Laboratory determined Suction-Water Content Curves
Saturated Hydraulic Conductivity (m•s^{-1})		7.5 ×10^{-8}			Triaxial tests on remolded samples
Liquid Limit		Min	Max	Ave	Casagrande cup BS1377:Part 2 (1990)
		20	25	23	
Plastic Limit		Min	Max	Ave	BS1377:Part 2 (1990)
		18	21	29	
Particle Specific Gravity		3.10 (0.03 standard deviation)			Vacuum method BS1377:Part 2 (1990)
Grading Parameters (μm)		Min	Max	Ave	Particle size corresponding to 60 % and 10 % passing on the particle size distribution curves.
	Dam 1, D_{60}	20	60	31	
	Dam 1, D_{10}	1	4	2	
	Dam 2, D_{60}	21	30	26	
	Dam 2, D_{10}	1	4	2	
Residual Volumetric Water Content, at 1500 kPa (van Genuchten, 1980)		4.6 %			Laboratory determined Suction-Water Content Curve
Field Capacity, Water Content at a Hydraulic Conductivity of 10^{-11} m•s^{-1} (Meyer & Gee, 1999)	Dam 1	22 % (6 % standard deviation)			Modified Kovács method (Aubertin et al, 2003) on full range of grading parameters for each dam.
	Dam 2	23 % (4 % standard deviation)			

The mean water content for the entire 11 month data set from both dams was 27 % (Standard deviation of 6 %). This corresponded to the air entry value. Assuming a normal distribution 98 % of the water contents were between 41 % and 14 %. These values corresponded to the average settled water content and the water content below which asymptotic suctions developed.

With depth the mean water content remained constant at 27 %. The variance on the other hand was 50 $\%^2$ for the top 400 mm, 35 $\%^2$ from 400 mm to 1000 mm decreasing to 20 $\%^2$ at 1500 mm and then remaining constant. Large dispersion in the upper layer is due to this being the freshly deposited layer. During deposition water seeps into the underlying layers and is then drawn up during evaporative drying. This process is reflected in the variance below the freshly deposited layer. The decreasing dispersion with depth reflects the decreasing influence of evaporation. The constant variance below 1500 mm suggests this is the limit of evaporative influence.

To explore the controlling effect of field capacity on the degree of moisture loss the following null and alternative hypothesis were tested:

H_0: Water contents at each sampling point have a different population mean to the field capacity mean

H_1: Water contents at each sampling point have the same population mean to the field capacity mean

The two-tailed t-test with unequal variances was used to test the hypothesis. The variances were assumed to be different as the field samples were taken at various stages of drying whereas field capacity has a narrower variance. Field capacity values predicted by the modified Kovács method (Aubertin et al, 2003) for each dam were used. It was assumed that these values better represented the grind differences.

Figure 3 and 4 illustrate the distributions of water content at each position along the Dam 1 and 2 beaches for the entire study. Results of the hypothesis testing are included along the bottom.

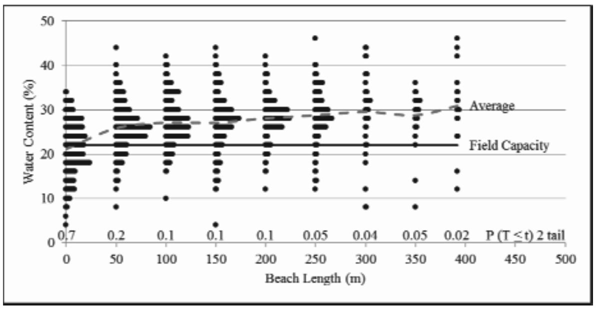


Figure 3. Dam 1 beach relationship

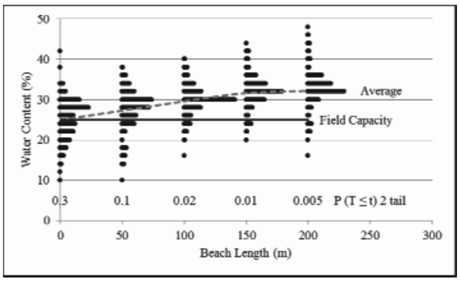


Figure 4. Dam 2 beach relationship

On Dam 1 the alternative hypothesis is accepted for the outer 250 m although the degree of confidence decreases from being high at the head of the beach. Past 250 m the hypothesis is rejected as the probability is less than 0.05. On Dam 2 the alternative hypothesis is accepted for the outer 100 m albeit with less confidence and rejected for the remainder of the beach.

These results suggest that during active deposition the steady state water contents are controlled by field capacity with only partial suctions developing. Seepage into the beach during deposition rises to replenish deficits preventing suctions greater than field capacity developing. Closer to the pool the distributions were observed to be in equilibrium with the phreatic surface due to the greater portion of saturated values. This observation was more pronounced on Dam 1 than on Dam 2, presumably due to the fact that phreatic surfaces become more depressed along longer beaches.

Prior to test work on Dam 1 the test section was left dormant for 6 months during high evaporative conditions over spring and summer. Water contents obtained during the baseline sampling showed extensive drying had taken place. The mean water content for the upper 1000 mm was 21 %. Based on the quartile ranges 75 % of the values were below the air entry value of 27 %. And 25 % of the values had water contents indicative of large suctions being below 15 %. This suggests that during active deposition sufficient moisture is available to replenish deficits. Only after long dormancies is this moisture expended and air dry conditions reached.

2.5 *Strength Gain*

The impact of this limitation on drying to strength gain during active deposition was investigated by calculating the liquidity indices based on the average Atterberg limits. The liquidity indices were then divided into three categories: less than 0 (i.e. above the plastic limit), between 0 and 1 (i.e. between the plastic and liquid limit) and greater than 1 (i.e. above the liquid limit). These categories are plotted in Figure 5 and 6 respectively to sampling position relative to the final elevation at the end of test work.

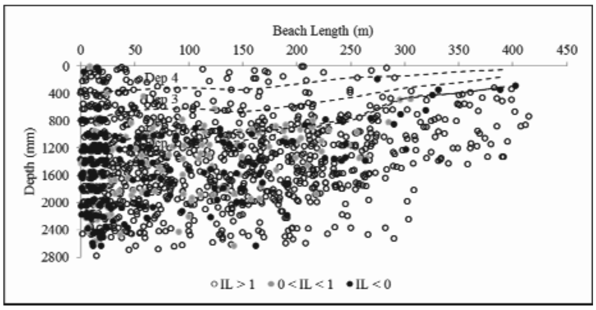


Figure 5. Dam 1 distribution of liquidity indices

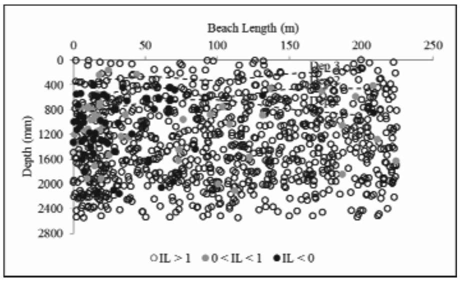


Figure 6. Dam 2 distribution of liquidity indices

On Dam 1 it is apparent that only the outer section reached a state of high shear strength (Bovis 2003), with 48% of the samples having a liquidity index less than 1 and 34% less than 0. However, 75 % of the water contents at this position were lower than the maximum liquid limit. After 50 m the proportion of liquidity indices less than 1 was on average 15% for all sampling points, being slightly higher at 50 m and decreasing towards the pool. Thus the majority of the interior is prone to fail under shear (Holtz & Kovacs 1981) although it was able to support a man and prevent the auger hole collapsing.

Baseline sampling on Dam 2 indicated that it had not gained significant strength, with only 30 % of the samples at the head of the beach having a liquidity index below 1 and the average for the remainder of the beach being 5 %. This is attributed to the high rate of rise prior to the test deposition. Analysis at the head of the beach within the first two test depositions indicated that 51 % of the samples had a liquidity index below 1 with 75 % of the samples below the maximum liquid limit; as was the case for Dam 1 at this position. This drying front also appeared to extend roughly 1 m below the first deposition yet insufficient strength gain appeared to have occurred during the shorter sampling window of the final deposition.

3 CONCLUSION

This paper reported on extensive test work carried out over an 11 month period on two back-to-back platinum tailings facilities. The following conclusions are drawn from the analysis presented:

1. The beach acted as a natural thickener with the tailings slurry settling within 65 hours from a water content of on average 95 % to 41 %. This water is available for recovery.
2. Following sedimentation water is lost through evaporative drying. The gravimetric water content decreased at a higher rate during summer and a lower rate during winter. The k – value or ratio between water content loss and reference evapotranspiration per day was not constant for all depositions. The k – value was lower during lower evaporative conditions. This suggests that seepage and bleed water may contribute a larger portion of moisture loss during lower evaporative periods. A longer study is required to quantify this relationship.
3. After the drying stage a steady state developed. This was marked by water contents varying from sample date to sample date within a narrow distribution. No apparent trend with time was observed. This narrow distribution was found to reflect the seepage of water into upper layers during deposition and capillary rise during drying. Closer to the edge of the dam this distribution was defined by the materials field capacity as sufficient moisture was available to prevent further suctions developing. Only after long dormant periods was this source of moisture observed to deplete. Closer to the pool the water contents were observed to be saturated with the closer phreatic surface preventing any suctions developing. This observation was more pronounced on Dam 1 presumably as the phreatic surface became more depressed along the longer beach.
4. This limitation on drying during active deposition on strength gain was investigated. Only at the outer position did liquidity indices show that substantial shear strength developed. Liquidity indices for the remainder of the beach indicated that the material was prone to fail under shear. This observation was made for all test depositions where the rate of rise for the outer sections was 2.5 m•year^{-1}. The baseline conditions on Dam 2 did not exhibit this strength gain at the beach head due to the 4.6 m•year^{-1} rate of rise thus the requirement of a waste rock impoundment.

4 ACKNOWLEDGEMENTS

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5 REFERENCES

Allen R.G., Pereira, L.S., Raes, D. & Smith, M. 1998. *Crop evapotranspiration guidelines for computing crop water requirements*. FAO:Rome.

Aubertin, M., Mbonimpa, M., Bussière, B. & Chapuis R.P. 2003. A model to predict the water retention curve from basic geotechnical properties. *Canadian Geotechnical Journal*, NRC Canada, 40(3):1104–1122.

Meyer, P. & Gee, G. 1999. Flux Based Estimation of Field Capacity. *Journal of Geotechnical and Geoenvironmental Engineering*, 125(7):595–599.

Miller, R.W., Donahue, R.L. 1990. *Soils, An Introduction to Soils and Plant Growth.* Prentice Hall:New Jersey.

van Genuchten, M. Th. 1980. A closed form equation predicting the hydraulic conductivity of unsaturated soils. *Soil Sci. Soc. Am. J*, 44: 892-898.

Bovis, M.J. 2003. Atterberg Limits. *Encyclopaedia of Sediments & Sedimentary Rocks*, Middleton, G.V. ed. Kluver Academic Publishers:Dordrecht, 22 – 24.

Holtz, R.D. & Kovacs, W.D. 1982. *An Introduction to Geotechnical Engineering.* Prentice Hall:New Jersey.