Bulyanhulu Mine (Tanzania) Paste Tailings Facility: Relating the unsaturated properties of gold tailings to rate of rise

M. Theron, P.C. Addis and J.A. Wates
Golder Associates Africa Pty Ltd, South Africa,
V. Martin
Barrick Gold Corp., Toronto

Abstract

Bulyanhulu Mine in Tanzania is an underground gold mine. Tailings are produced and used in part for paste as underground backfill material. The balance of the tailings is deposited on the surface as a paste. Research is currently underway to determine the optimum method of deposition. The mechanical behaviour of the tailings was assessed by means of a field monitoring program. Various soil parameters such as gravimetric moisture content, suction pressure and, in-situ density were measured for a period of approximately three months on a freshly deposited beach. Measurements were taken at regular intervals between the discharge point and the toe of the beach on a daily basis. The results of the field monitoring program provided valuable information on the unsaturated soil behaviour with particular reference to the air entry value and moisture retention curve.

1. INTRODUCTION

large percentage of the earth's surface is subjected to arid and semi-arid climatic conditions. In these regions the evaporation rate mostly exceeds that of precipitation with the result that an unsaturated zone with suction pressures is established in the upper section of the soil profile. The negative pressures generated by suction in these soils govern their engineering behaviour and are therefore of great importance. The extraction and processing of most mineral ores result in the generation of large volumes of fine-grained tailings. The safe disposal of tailings, which generally exhibit slow rates of sedimentation and consolidation, is of prime concern in the management of mining operations (Concoli and Sills, 2000).

Rassam and William (1999) investigated the mechanical behaviour and hydraulic conductivity of mine tailings and found that a loss of strength is mainly due to re-wetting of the tailings caused by rainfall, deposition of fresh tailings and the upward flow of water from consolidation of capped tailing deposits. The loss of strength could thus be attributed to an increase in moisture content and saturation resulting in a decrease in matric suction.

In order to assess the change in strength with time of a layer of freshly deposited tailings at Bulyanhulu tailings facility where tailings are deposited as a paste. The moisture content and suction pressure were investigated. A field scale experiment was set up at Tower 6 (see Figure 1) of the tailings storage facility with an average beach depth of 0.6 m. Daily measurements of the various moisture content related parameters were taken at regular intervals along the beach. These parameters were monitored for a period of 90 days, commencing once access to the freshly deposit was possible.

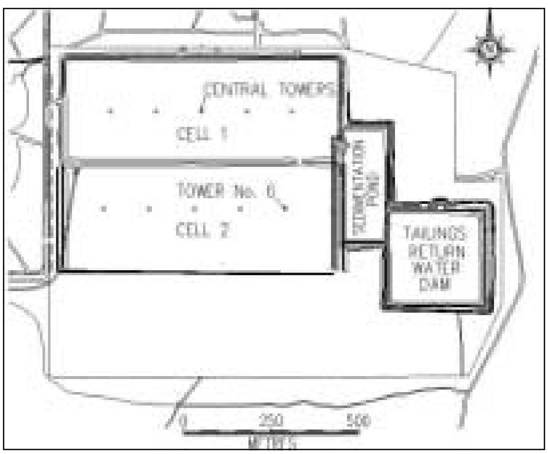

Figure 1: Site Layout.

Additionally, the influence of beach depth on the drying rate of tailings was investigated by drying tests carried out in cylinders. Four different beach depths were considered namely 150, 300, 600 and 900 mm.

2. Material properties of the tailings

Foundation indicator tests were carried out by the mine and a commercial soil laboratory to determine the basic properties of the tailings. These were carried out in accordance with the procedures laid out in the ASTM (2002) standards. Figure 2 shows the particle size distribution of the tailings. The specific gravity (G_s) was found to be 2.76. In terms of the unified soils classification system (USCS), the tailings are classified as an inorganic silt.

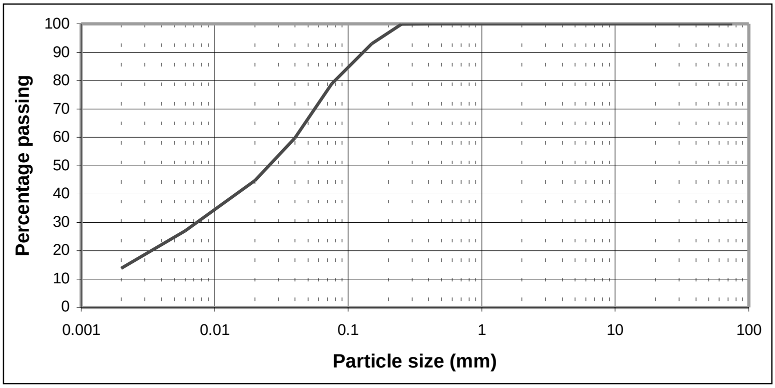

Figure 2: Particle size distribution of the tailings.

3. Monitoring

Daily measurements of the gravimetric moisture content and suction pressure were taken every 5m where the slope exceeds 5° and every 10 m elsewhere. Chainages were recorded relative to the discharge point (tower). Monitoring took place over a period of 90 days. Precipitation occurred on three occasions namely Days 2, 20 and 22.

3.1. Instrumentation

The dry density of the tailings was measured by the mine, using the sand replacement technique (ASTM, 1982). Measurements were made at three points along the beach: at the discharge point (0 m), in the middle of the beach (22.5 m) and at the toe (55 m).

Gravimetric moisture content ($\omega = M_w/M_s$) was measured at seven points along the beach. Tests were carried out in accordance with BS 1377: Part 2 (1990). Since the tailings facility is located outside of the plant area where the laboratory is housed, moisture loss through evaporation could occur in the period between sampling and weighing of the samples. In order to reduce errors arising from evaporation, the wet samples were weighed immediately after sampling. An Ohaus HH120 handheld balance with a 120 g capacity and 0.1 g accuracy was used.

A quick draw tensiometer (Soil Moisture Equipment Corporation) was employed to measure the suction pressure of the tailings. The instrument measures the negative pore water pressure i.e. matric suction of the soil. It consists of a porous filter and pressure measuring device that is separated from each other by means of a water reservoir (Ridley, Patel and Marsland, 1998). The suction manifests itself as a tensile stress in the water reservoir that is measured by the measuring device. The suction range of the tensiometer is influenced by the length of tube (reservoir) required for measurement. A correction in the order of 10kPa/m tubing is required (Ridley and Wray, 1996). In order to compensate for this inadequacy as well as changes in the internal characteristics of the gauge with time, the instrument is equipped with an adjustable zero reading. Provided that the instrument is fully saturated, the suction range of tensiometers is normally in the order of 0 to 90 kPa. Beyond this value cavitation occurs. Cavitation is the formation and collapse of vapour bubbles in a liquid (Chadwick and Morfet, 1993). It is associated with a sudden drop in suction pressure that can in no way be related to the true suction of the soil. Cavitation pressure is a function of the height above sea level and temperature. Bulyanhulu mine is located at an elevation of 1,200m above sea level and has an average tailings temperature of 24.7°C. The air entry value (AEV) of the probe is thus reduced to 74 kPa.

3.2. Dry Density

The dry density of the tailings was measured on four occasions during the monitoring period (Figure 3). The first measurement was made 29 days after deposition ceased. The rate of increase in dry density of the tailings decreased with time. Measurements at the three locations appear to approach each other and may reach some common value with time.

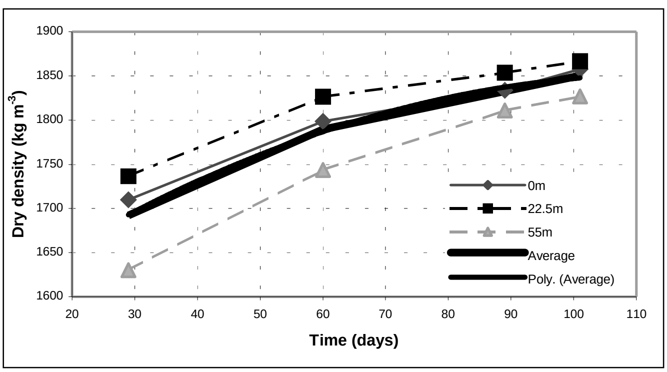

Figure 3: Change in dry density of the tailings with time.

3.3. Gravimetric Moisture Content

The gravimetric moisture content of the tailings was measured with distance from the discharge point as well as depth. Figure 4 shows the recorded gravimetric profile of the tailings at the surface with distance from the discharge point. The broken vertical lines indicate precipitation events.

The surface moisture contents at the discharge point (0 m) varied considerably during the period from Days 11 to 30. None of the other measurement locations displayed similar behaviour and hence discharge measurements were disregarded. Distance from the discharge had no influence on the surface gravimetric moisture content profile of the tailings. Measurements fell within a narrow band (indicated by the broken lines) that decreases with time.

Initially the rate of decrease of the gravimetric moisture content is large, but decreases with time until finally, the decrease is small. It appears as though moisture content behaviour converges to some point which is similar to the bulk density behaviour. Precipitation events had no influence on the surface moisture measurements indicating that infiltration was not significant.

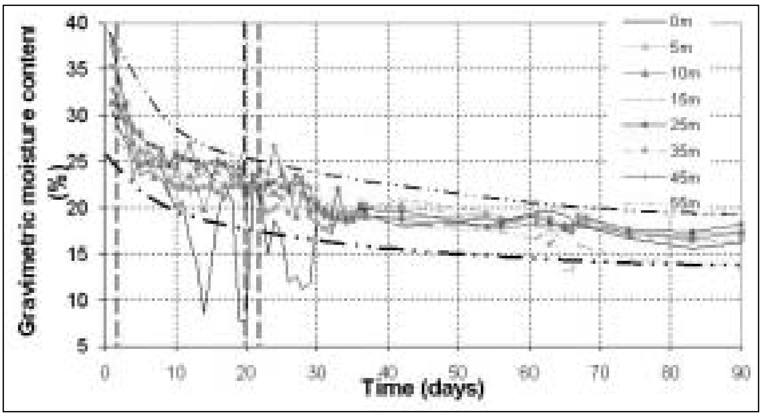

Figure 4: Gravimetric moisture content profile.

The gravimetric moisture content profile with depth was measured at three points along the beach namely at the discharge point (0 m), toe (55 m) and midway (22.5 m). Samples were obtained from 15 cm and 30 cm below the surface using a hand auger. The moisture content 30 cm below the surface at the toe was not measured, as the beach depth was less than 30 cm.

Figure 5 shows the average gravimetric moisture content of the tailings at the surface, 15 and 30 cm below the surface. The gravimetric moisture content of the tailings below the surface is indicated by solid lines while that of the surface, by a broken line. Initially the gravimetric moisture content of the tailings at different depths is similar but after some time the decrease in the moisture content of the tailings at the surface and 15 cm below the surface is greater than that of the tailings 30 cm below the surface. The difference in moisture content between the three depths appears to decrease with time. Once again, precipitation events (indicated by the broken vertical lines) had little influence on the measurements.

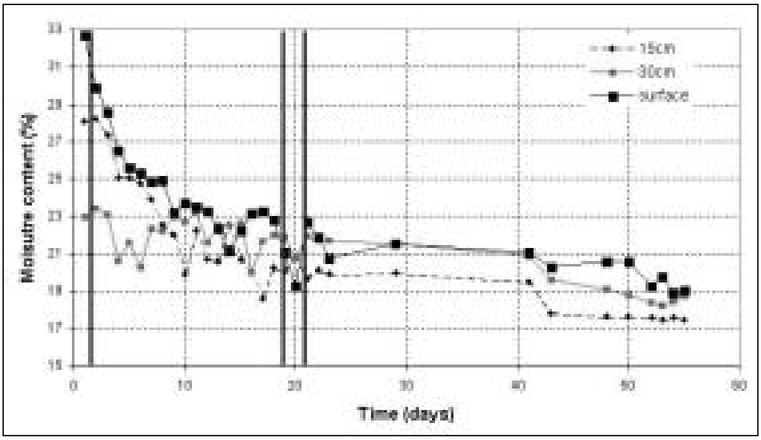

Figure 5: Average gravimetric moisture content with depth.

3.4. Suction Pressure

The suction pressure was measured at regular intervals along the tailings beach. Figure 6 shows the measured suction over a period of 90 days. Negative pore pressures were only measured after Day 9. As expected, the suction pressures increased with time. Measurements remained below the cavitation pressure of 74 kPa. The variation in suction measurements is large and could be attributed to difficulties in saturating the tensiometer. Measurements appear to be unaffected by distance from the discharge point as well as by precipitation events.

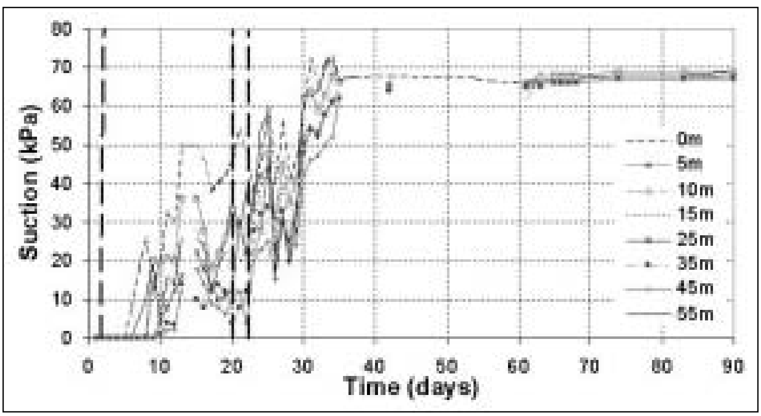

Figure 6: Suction pressure with time.

4. Drying tests

The influence of beach depth on the drying rate of the tailings was estimated by means of experimental steel cylinders. The weight and decrease in height of the tailings was monitored on a daily basis. The decrease in height was measured at three points on the sample and the average value was adopted. Monitoring ceased once measurements reached an asymptote.

The shrinkage limit for each beach depth as well as the time required to do so was determined. The shrinkage limit is defined as that moisture content where the volume of the soil mass ceases to change (Das, 1995). Figure 7 shows relationship between shrinkage of the samples, expressed as a percentage of the initial sample height, and gravimetric moisture content. As expected, the gradient of the two is not constant, but reduces as the constant shrinkage is approached.

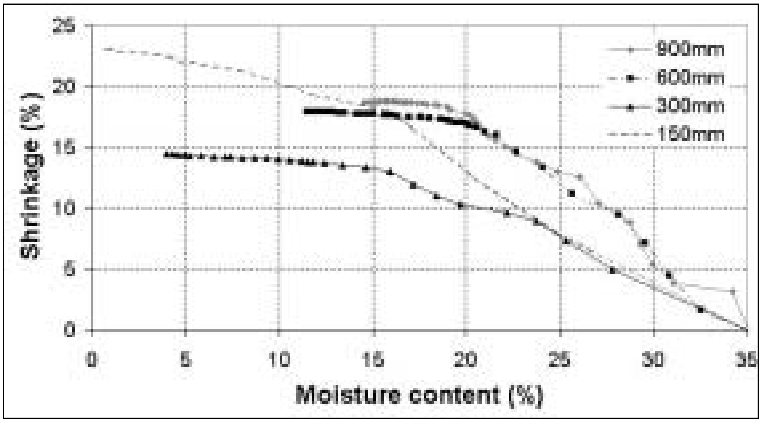

Figure 7: Relationship between shrinkage and moisture content.

Table 1 summarises the drying test results. The time required to reach the shrinkage limit decreased with beach depth. The shrinkage limit of the tailings is not a constant value. It is not sure why the shrinkage of the 150 and 300 mm cylinders differs from the rest.

Cylinder height	Shrinkage limit	Shrinkage	Time
mm	%	%	%
900	15	19	40
600	13	18	33
300	4	15	29
150	1	23	22

Table 1: Drying test results.

5. Discussion

The gravimetric moisture content of the tailings decreased with time. Initially the rate of decrease in moisture content is large, but decreases with time. Moisture content is independent of the distance from the discharge point.

The shrinkage limit of soil is defined as the moisture content (in percentage) at which the volume of soil mass ceases to change (Das, 1995). The shrinkage limit of the tailings was determined by a commercial laboratory as 16%. Field measurements were made to an average gravimetric moisture content of 17%. It is anticipated that the measured dry density would start to decrease once the shrinkage limit is reached. Unfortunately, the data were insufficient and hence the influence of further drying below the shrinkage limit on the dry density could not be assessed.

The soil moisture characteristic curve (SWCC) of soil is a function of the initial moisture content, dry density, stress history and state. It can be used to establish both the air entry value and residual water content of the tailings (water content where large suction pressures are required to remove additional water from the soil) (Figure 8). The air entry value is defined as the matric suction at which air starts to enter the largest pores. In general, this value will fall within the following range (e.g. Kovacs, 1981; Aubertin et al. 1998):

Coarse sand	2 to 10 cm of water
Medium sand	10 to 35 cm of water
Fine sand	35 to 70 cm of water
Silts	70 to 250 cm of water
Clays	Greater than 250 cm of water

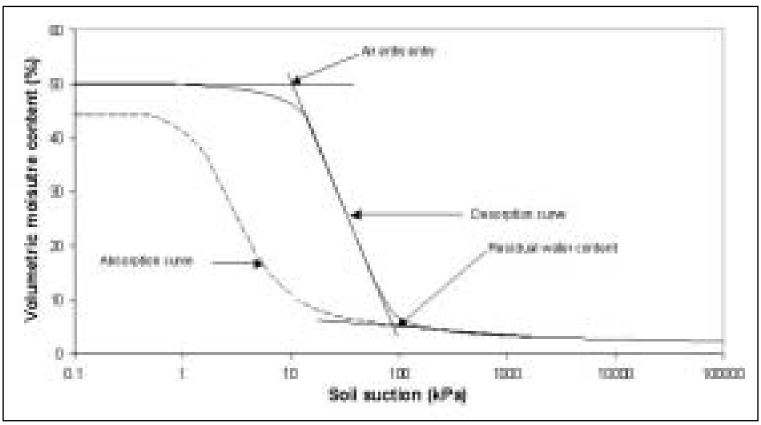

Figure 8: Typical desorption and absorption curve for silty soils.

As mentioned previously, the tailings classify as silt. Adopting the above guidelines, the air entry value of the tailings would be reached between 7 and 25 kPa suction pressure. The SWCC of the tailings was estimated by employing the gravimetric moisture content and suction pressures (Figure 9). The air entry value of the tailings estimated from Figure 9, is in the order of 27 kPa. This value falls slightly out of the above range. The residual water content could not be determined as measurements ceased prematurely.

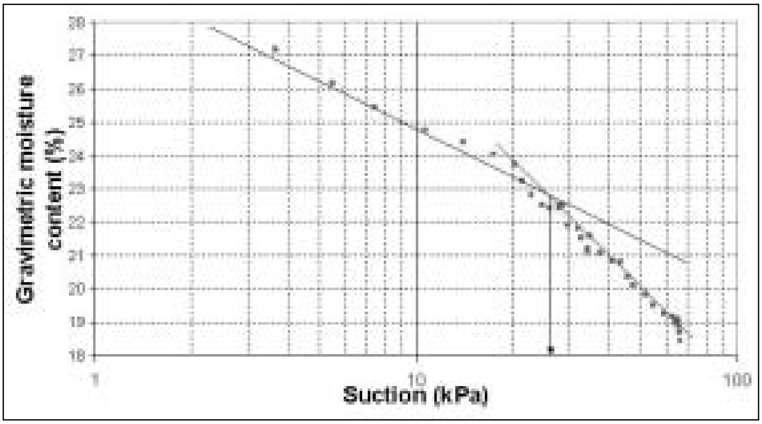

Figure 9: Soil moisture characteristic curve of the tailings.

The decrease in moisture content is greater at the surface and 15 cm (quarter of beach depth) below the tailings surface than 30 cm (half of beach depth) below the surface. This is expected as pore pressure dissipation is a function of the square of the drainage path. If two-dimensional drainage is assumed, the pore pressures (and moisture content) would be the greatest in the middle of the layer. However, as soon as a layer of freshly deposited tailings is placed on top of an existing layer, pore pressure dissipation would take place towards top and bottom of the new layer. The pore pressures of the existing layer would also increase. The pore pressures of the existing layer would also increase.

In order to determine the allowable rate of rise of paste tailings, the change in effective stress with time of the composite tailings need to be established. Measurements should be extended to include the composite tailings layer (i.e. freshly deposited as well as existing layers).

"All measurable effects of change in stress, such as compression, distortion, and a change in shearing resistance, are exclusively due to changes in the effective stress σ_1*',* σ_2*' and* σ_3*'."*

Terzaghi (1936)

- The change in effective stress could thus be monitored by means of the change in pore pressure and volume. Allowable rate of rise can be determined by the time it takes a layer to reach a moisture content at which shrinkage ceases (Wates et al., 1999). Based on the drying test results of the 600 and 900 mm cylinder tests (Table 2), a shrinkage limit of 16 to 19% was assumed. An allowable rate of a freshly deposited layer of tailings of 300 mm and 150 mm thickness would reach their shrinkage limit after 26 and 23 days respectively.

6. Conclusions

The following conclusions can be drawn from the analysed data:

- The gravimetric moisture content profile of the tailings is independent of distance from the discharge point. The average moisture content of the tailings changes with depth i.e. moisture loss in the middle of the layer is less than that of the surface and a quarter into the freshly deposited layer.
- The rate of increase in dry density decreases with time. It appears as though an asymptote may be reached with time. Similar behaviour was noted for the gravimetric moisture content.
- Drying tests of the tailings in cylinders were carried out to determine the influence of beach depth of the drying time. The time required to reach the shrinkage limit is a function of the beach depth i.e. increases with increasing beach depth.
- The soil moisture retention curve of the tailings was derived based on the average matric suction and measured gravimetric moisture content. The derived air entry value obtained from Figure 7 falls within the general range for silty material.
- The allowable rate of rise could be established once the tailings have gained sufficient strength. Allowable rate of rise is also determined by the time it takes a layer to reach a moisture content at which shrinkage ceases (Wates et al., 1999). Drying test results of the 600 and 900 mm cylinders could be used to determine the drying rates for the Bulyanhulu gold tailings paste.

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References

Aubertin, M., Richard, J. and Chapuis, R.P. (1998) A predictive model for the water retention curve: Application to tailings from hard-rock mine. *Canadian Geotechnical Journal*. Vol. 35, pp. 55-69 (with Erratum, 36:401).

ASTM D422-63 (2002) Standard Test Method for Particle-Size Analysis of Soils, ASTM International.

ASTM D-1556 (1982) Standard Test Method for sand cone method, ASTM International.

BS1377: Part 2 (1990) British standard methods of tests for soils of civil engineering, *Technical report*. British Standards Institution, London.

Chadwick, A. and Morfett, J. (1993) *Hydraulics in civil and environmental engineering*. 2nd ed. E & FN Spon, London.

Concoli, N.C. and Sills, G.C. (2000) Soil formation of predictions and field measurements. *Geotechnique*, Vol. 50, No. 1, pp. 25-33.

Das, B.M. (1995) *Principles of geotechnical engineering*. 3rd Ed. PWS Publishing company.

Fredlund, D.G. and Rahardjo, H. (1993) *Soil mechanics for unsaturated soils*.1st ed. John Wiley and Sons Inc.

Kovacs, G. (1981) *Seepage hydraulics*. Elsevier Science Publishers, Amersterdam.

Rassam, D.W. and Williams, D.J. (1999) Unsaturated hydraulic conductivity of mine tailings under wetting and drying conditions. *Geotechnical testing journal*, Vol. 22, No. 2, pp. 144-154.

Ridley, A.M., Patel, A.R. and Marsland, F. (1998) Tensiometers; their use for civil engineering purposes. *Proceedings of the 1st international conference on site characterisation*, Atlanta. Robertson P. K. and Mayne P. W. (Ed), A. A. Balkema, pp. 851-865.

Ridley, A.M. and Wray, W.K. (1996) Suction measurement: A review of current theory and practices. *Proceedings of the 1st international conference on unsaturated soils*, Paris, Alonso A. A. and Delarge P. (Ed), A. A. Balkema, pp. 701-708.

Terzaghi, K. (1936) The shear resistance of saturated soils. *Proceedings of the 1st international conference soil mechanics and foundation engineering*. Vol. 1, pp. 54-56.