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A Field Study of Evaporation and Shrinkage of Slurried Mine Waste

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Summary Due to high clay contents, some slurried mine wastes can be quite compressible and of low permeability which can present long term handling difficulties. Drying of this material under the effects of evaporation increases the volume reduction that occurs from self-weight consolidation and enables rehabilitation to occur more quickly. During the drying process large shrinkage cracks can develop which may contribute to the overall evaporation rate. This field study has investigated both the evaporation behaviour and the development of shrinkage cracks and their propagation. The study was conducted on a shallow drying pond filled with predominantly kaolinitic material from the mineral sands industry. Measurements were made of evaporation directly from the soil surface using lysimetric methods. Evaporation data was collected from a Class 'A' evaporation pan and this was used to correlate the observed evaporation behaviour with the atmospheric conditions.

1. INTRODUCTION

Large volumes of fine grained mineral wastes, in dilute slurry form, are produced annually by mining operations. Hydraulic disposal of these materials requires the construction of large storage impoundments. The ability to predict the magnitude and rate of consolidation of these materials is important for the design and management of the impoundments. The long term settlement, shear strength profile and the required size of the disposal area are all factors that depend on the consolidation behaviour of the impounded material.

Slurried mine wastes are generally deposited sub-aerially in Western Australia, to allow desiccation and desaturation to reduce both the moisture content and compressibility of the material, whilst increasing the density and shear strength. This method is quite efficient due to the high net evaporative potential (2-3 m/year) that occurs in the mining regions. It is therefore possible to derive benefits from the high evaporation rates, by disposing of slurry in thin layers, which are then allowed to consolidate under the effect of evaporation before further filling takes place.

The evaporation rate from a saturated soil surface can be close to the potential evaporation (and is thus controlled by the climatic conditions). Once desaturation of the surface occurs this rate of evaporation falls rapidly. Desiccation of the surface layers of fine grained soils during this drying process can also lead to large shrinkage cracks developing. Some cracks have been observed in coal mine tailings deposits with depths of 0.5m and spacings of 1m (Morris et al., 1992). Despite the possible reduction in surface evaporation that may occur, further evaporation can continue from the walls of these shrinkage cracks, which will still contribute to the overall drying of the soil mass.

During this study, the emphasis has been placed on the effects of shrinkage cracking on the drying behaviour of slurried mine waste. Estimates of the contribution of the cracks to the drying process have been made by observing the behaviour of individual cracks and by quantifying crack widths, depths and their spatial distribution.

2. FIELD STUDY

2.1 Study Site Description

The study was located at the Yoganup North mine site, 200km south of Perth on the coastal plain of Western Australian. This mine is operated by Westralian Sands Ltd. for the recovery of mineral sands. The region has a Mediterranean climate, with an annual rainfall of 500mm and a net annual evaporation of 1.5 to 2m/year. Strip mining is used to recover the ore and extraction of the heavy minerals is by gravity and magnetic separation. The fine and coarse tailings fractions are separated during this process and subsequently used as backfill. Prior to this the fines or 'slimes' are hydraulically placed in large shallow drying ponds, to reduce their moisture content. The water used for processing is fresh.

During the study, a drying pond (approximately 2-3m deep and 5Ha in plan area) was filled with slimes over a period of 8-10 weeks and monitored over an eight month period, from May 1995. The pond had no provision for base drainage and the foundation material is essentially impermeable. Measurements made include suction, moisture content, shear strength, soil temperature and vertical settlements for the soil profile. Rates of evaporation were monitored using micro-lysimetry and a Class 'A' evaporation pan.

2.2 Material Description

The particle size distribution of the material shows a poorly graded material with approximately 75% finer than 2μm (generally taken as being the division between clay and silt sizes). Classification tests show that the slimes has a liquid limit of 96% and a plastic limit of 35%. Thus this is a highly plastic clay. The shrinkage limit was found to be 19%. The specific gravity (G_s) of the solids was 2.70. Analysis of the slimes using x-ray diffraction indicates 80% kaolinite, 10% quartz and 10% goethite. The initial moisture content of the slimes pumped into the pond is approximately 1000-1200%, which sediments to a moisture content of 400% in approximately 4-5 days.

2.3 Micro-lysimeter Technique

Lysimetric methods are used to determine rates of evaporation directly from the soil surface. The technique involves isolating a body of soil hydrologically from the surrounding soil and determining the loss of water due to evaporation by weighing. The validity of the method is dependant on whether the evaporation from such an isolated body essentially remains the same as that of the surrounding soil. The solution to this problem is usually the adoption of large dimensions for the lysimeter. Alternatively, small lysimeters can be used for a short enough period to ensure that the disturbed base boundary condition does not affect the soil evaporation.

A 'micro' lysimeter method was proposed by Boast and Robertson (1982). This involves pushing a thin walled cylinder (of 76mm diameter and 70mm long) into the ground and removing it filled with soil. The cylinder is sealed at the base (to make it water tight) and its mass is determined. Then the cylinder is replaced in the soil, with the top surface level with the surrounding soil. The lysimeter is then left exposed for 24 hours and re-weighed to determine the loss of water from evaporation.

3. FIELD OBSERVATIONS

3.1 Geotechnical Behaviour

Figure 1 shows the undrained shear strength profile with depth for the pond. The results indicate that prior to September 1995 there was very little strength developed in the slimes (less than 5kPa). Between September and December a reasonable strength was developed at the surface (60kPa) but this reduced rapidly to only 10kPa at 40cm depth. Thus a relatively thin stiff crust had developed on the surface of the slimes at this stage.

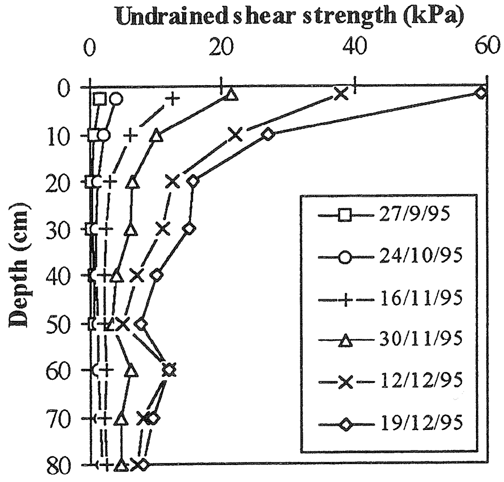

Figure 1. Undrained shear strength with depth

In Figure 2 the variation in the moisture content with depth is shown. This shows that the slimes had dried considerably during this period (from 250% to 40% moisture content), but still remained saturated.

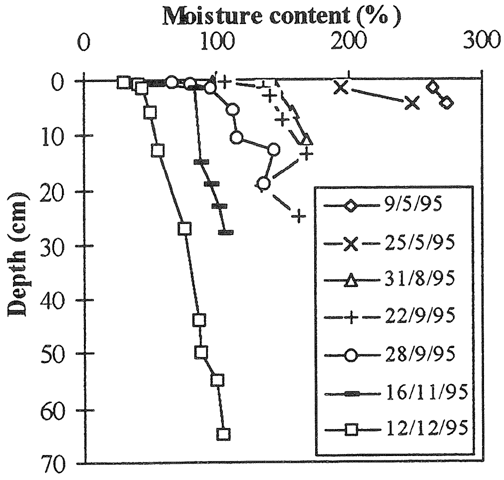

Figure 2. Moisture content with depth

The moisture content gradient at shallow depths, indicates that the zone between 0 and 20mm below the slimes surface is considerably drier than the underlying material.

The vertical settlement behaviour of the pond is shown in Figure 3. Initially, between points O and A the rate of settling is much greater than the pan evaporation rate. This rate decreases between points A and B, whilst the evaporation rate remains fairly constant. Thus between O and B it appears that the evaporative demand is being satisfied by the supply of water to the surface (due to consolidation) and the material is essentially settling under self weight consolidation only (since there is no base drainage).

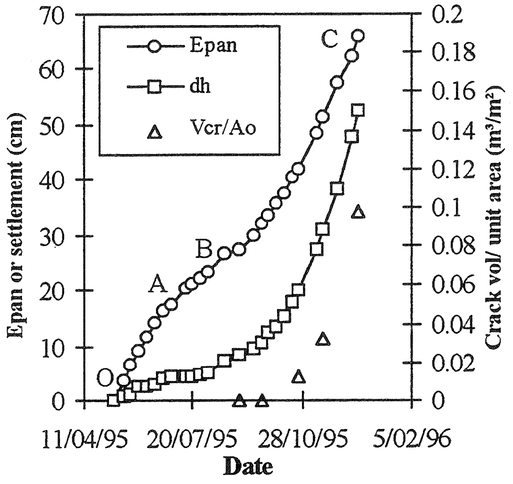

Figure 3. Settlement and evaporation behaviour

From point B to C, there is a sudden increase in the pan evaporation and an increase in the rate of settlement. However, the rate of increase of evaporation is less than the settlement and thus the evaporative demand is not being fully satisfied, leading to the surface desaturating. Another possible contribution to the overall settlement, is the development of surface shrinkage cracks that begins at point B. The estimated crack volume per unit area has been plotted with the settlement and this has increased rapidly to 0.1 m^3/m^2 by December. Despite the increase in the potential evaporative area between B and C, the rate of settlement is still less than the evaporation rate.

3.2 Evaporation Behaviour

It is evident from studies conducted previously (Seneviratne et al., 1995; Abu-Hejleh and Znidarcic, 1995), that the role of evaporation is very significant. The actual rate of evaporation from the soil surface (E_s) can vary from close to that of the potential evaporation (stage I drying) to almost zero (stage III drying), for desaturated soils (Wilson et al., 1994). Stage I drying is controlled mostly by the climatic conditions and is applicable to soil conditions at or near saturation. Stage II and III drying occurs once the soil has begun to desaturate and leads to a rapid decrease in the evaporation rate. Both the climatic conditions and soil properties control the evaporation rate during this phase.

The evaporation rate from a Class 'A' evaporation pan may be assumed to be equal to the maximum potential rate E_P, i.e. the rate dictated by the environmental (climatic) conditions. This rate can therefore be used as a benchmark against which to evaluate the effects of surface drying on the evaporation rate from the slimes. Figure 4 shows data on evaporation from saturated slimes surfaces, E_s (measured with a micro-lysimeter) plotted against the potential rate E_P (measured with a Class 'A' evaporation pan).

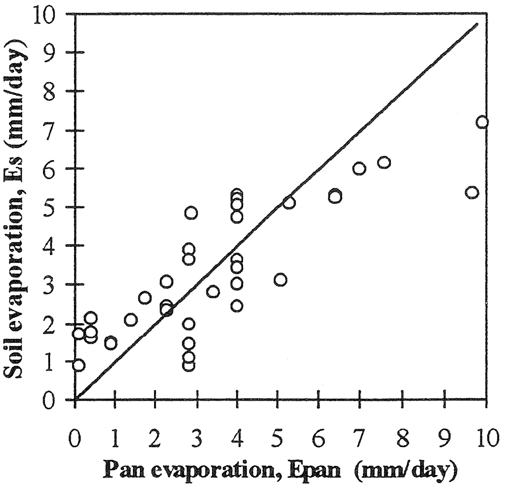

Figure 4. Actual v. potential evaporation

The data have been plotted in such a way that soil evaporation at the 'potential rate of evaporation' would lie on the E_s=E_P line. For this material, the data plot close to the line of equality, i.e. the actual rate is practically equal to the potential rate. It has been found that the actual rate of evaporation from saturated saline tailings is between 60 and 20% of potential evaporation (Newson et al., 1996a). This is due to the reduction of the saturation vapour pressure and the presence of a thin salt crust on the soil surface.

The actual rate of evaporation would be expected to fall below the potential evaporation rate as the surface desaturates and stage II and III drying begins to occur. However, the measured evaporation rates from the surface of the slimes material have continued to be close to those of the evaporation pan throughout the study. The surface moisture contents shown in Figure 2 are still above the plastic limit for this material; thus the material remains saturated and stage I evaporation (E_s=E_P) is still occurring.

3.3 Shrinkage Crack Behaviour

The shrinkage cracks developed in the drying pond are shown in Figure 5. Detailed observations have and slimes surface should be experiencing stage I drying and the climatic effects are nominally the same for both, we need to consider the possible reasons for this decrease in actual evaporation.

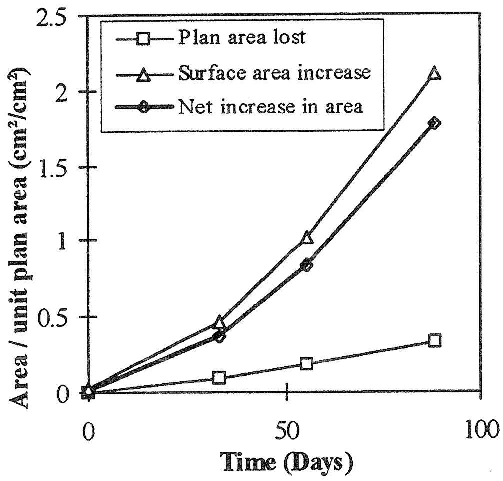

Figure 7. Changes in potential evaporation areas

Like the surface of the deposit, the evaporation from shrinkage cracks is partially dependent on the movement of turbulent air, which is a function of wind speed across the top of the crack. This air movement will decrease with crack depth and therefore saturated humid air will remain in the region at the base of the crack inhibiting further evaporation. Additionally, apart from the period of the day around noon, the majority of the crack will be in shadow and thus the temperature of the crack face will be less than that at the surface, which will also tend to inhibit evaporation.

Therefore only a certain proportion of this additional evaporating surface will be removing moisture at the potential rate. So we can define an *equivalent evaporation area* (A_{ee}) which will indicate the actual ability of the cracks to increase drying.

$$A_{ee} = (A_o - A_{pcr}) + A_{scr} * \alpha \qquad (1)$$

The initial evaporation area (prior to any shrinkage crack development) is A_o. The plan area of the cracks that develop is A_{pcr}. The constant α proportions the crack surface area A_{scr} according to its ability to remove moisture from the soil at the potential rate of evaporation. Figure 8 shows the A_{ee} for various values of α from 0.2 to 1.0. The results of Figure 6 would indicate that a value of α=0.3 would be appropriate and this suggests that by December the cracks would be increasing the evaporation from the surface of the slimes by 30%.

Equation (1) would need to be modified to allow for desaturation of various portions of the soil profile and the accompanying reductions in the evaporation rates during stage II and III drying. Although this is not the case in this field study, it is possible for the surface material of the soil columns to have begun to desaturate (which may only involve a shallow depth of soil), whilst the material in the faces of the shrinkage cracks may still be saturated. The desaturation of the surface layers could effectively seal the underlying zone from further significant drying. However, as the size of the shrinkage cracks increases, the contribution they make to the overall evaporation could become more significant.

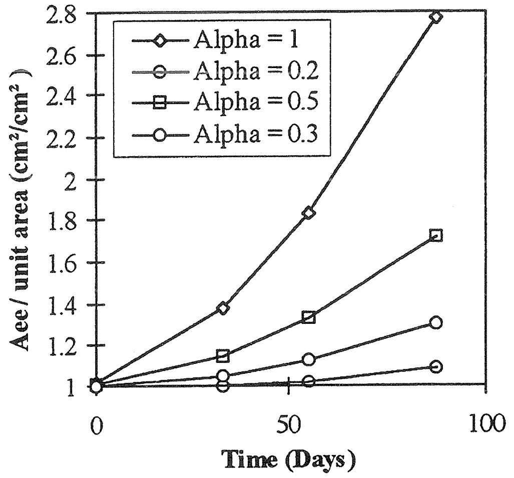

Figure 8. Estimates of the increase in evaporation due to shrinkage cracks

It is intended that this data will be used to further refine a large strain consolidation model (MinTaCo) that has been developed at the University of Western Australia (Seneviratne et al., 1996). The eventual aim is to use this model to providing a method of predicting optimum deposition rates for slurried mine wastes based on a knowledge of the water quality, mineralogy, clay content and evaporative flux at a given site. Since the majority of numerical methods adopted for this purpose rely on one dimensional approaches, the concept of an equivalent evaporation area may be one method of accounting for the effects of cracking. Since the crack depths may be directly related to suctions and shear strengths (Morris et al., 1992), the crack volumes should be easily predicted. With knowledge of the crack spacing (related to mineralogy, evaporation rate, salinity, etc..) the crack volume per unit area could be calculated and thus the equivalent evaporation area could be found. It would only remain for the effect of the additional drying to be accounted for (allowing for the cracked upper layers to shrinkage three dimensionally) to incorporate this into an one dimensional algorithm.

5. CONCLUSIONS

A field study has been initiated to provide more detailed information on the evaporation behaviour of mineral sands slimes. The study consists of observations of slimes drying ponds situated at a been made of crack depths, widths, patterns and spacings over a defined 5m x 5m area of the pond.

Figure 5. Shrinkage cracks in slimes surfaces

It is evident that an orthogonal desiccation pattern has developed, with a network of more or less regularly spaced cracks. Observations by Lachenbruch (1962) indicate that crack spacing is related to crack depth. However, it has also been found from numerical modelling that evaporation rates have an effect on crack spacing (Abu-Hejleh and Znidarcic, 1995).

At high evaporation rates a strong thin surface crust is developed, overlying a softer zone, while at lower evaporation rates a thicker, weaker crust is developed. The thicker crust will lead to deeper more widely spaced cracks, whilst the thinner crust will lead to a shallower, highly fractured crust. It is also evident from observations of a number of tailings deposits in Western Australia that the spacing and depth of cracks is also related to the percentage of clay in the material, clay mineralogy, salinity of pore water, water table position and depth of fill layers (which may be quite shallow if rotation of deposition areas occurs).

As shrinkage cracks developed in the slimes material, shear vane measurements were made vertically into the slimes and horizontally into the sides of the shrinkage cracks. This work is described in detail elsewhere (Newson et al., 1996b) and will only be covered briefly here. These data show that initially the strengths in the vertical direction and horizontal direction (at the mid-depth of the crack) were very similar. Later measurements of shear strength show a large increase in the vertical direction, particularly in the upper 200 to 300 mm. Whilst in the horizontal direction two sets of measurements were made. These results showed very little increase in shear strength towards the crack base, whilst there was a significant increase further up the crack.

The increase in the shear strength (and a reduction in moisture content) within the upper region of the crack is due to some evaporation occurring from this region. Micro-lysimeters were used to estimate the variation in evaporation that occurs at different depths in the cracks. Figure 6 shows a plot of the ratio of surface evaporation (E_s) to crack face evaporation (E_{cr}) against normalised depth into the cracks (D/Z_{cr}).

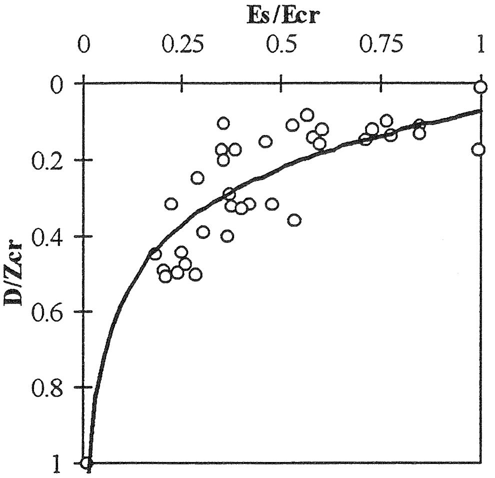

Figure 6. Evaporation with depth into cracks

This shows that the majority of the evaporation occurs in the upper 50% of the crack, with values of E_{cr} dropping to only 20% of the surface evaporation half way down the crack. Observations of cracks have shown that the width of the crack is approximately proportional to the depth, thus any bias due to variations in crack volume can be ignored.

4. DISCUSSION

If the soil contains a high percentage of clay, then there is the potential for the development of large shrinkage crack volumes during drying. The data presented in the previous section indicates that the cracks are contributing to the overall evaporation from the upper layers of the soil. In order to include the effects of this crack evaporation in modelling, the spatial distribution of the cracks needs to be quantified. Figure 7 shows the changes in the evaporation surface areas that have occurred since cracking has initiated. The net increase in potential evaporation surface area is the sum of the increase in surface area due to the cracks minus the loss in plan area (on the surface of the deposit) due to the presence of the cracks. The figure shows that after 90 days of cracking that there was a potential evaporation surface increase of 200% in the drying pond.

However, the results shown in Figure 6 show that the evaporation from the crack surfaces decreases with depth in the crack. Since both the crack faces mine site in Western Australia. The effects of shrinkage cracking on the drying behaviour were observed. The following conclusions were reached based on the findings of this study:

- the deposit appears to have remained saturated over the study period, with stage I drying continuing at the surface
- a large network of regularly spaced shrinkage cracks have developed on the surface of the slimes
- significant additional drying from these cracks was measured, particularly from the upper regions of the cracks
- the data indicates that the cracks are currently increasing the drying of the upper layers of the slimes by approximately 30%

6. ACKNOWLEDGEMENTS

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