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Erosion losses from the surfaces of gold-tailings dams

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SYNOPSIS

Rates of erosion have been measured for the slopes and top surfaces of a number of gold-tailings dams in the Germiston-Johannesburg-Roodepoort area of the Transvaal. Preliminary results were given in an earlier paper. The present paper gives results for a four-year period of observation, and identifies the major factors affecting the rates of erosion from the surfaces of gold-tailings dams.

SAMEVATTING

Erosietempos is vir die hellings en bokante van 'n aantal gouduitskotdamme in die Germiston-Johannesburg-Roodepoort gebied van Transvaal gemeet. Die voorlopige resultate is in 'n vroeëre referaat verstrek. Hierdie referaat gee die resultate vir 'n waarnemingstydperk van vier jaar en identifiseer die belangrikste faktore wat die erosietempo van die oppervlakke van gouduitskotdamme bepaal.

Introduction

Ways and means of preventing surface erosion from gold-tailings dams and the difficulties of doing so were described in two papers by Blight *et al.*[2] and Blight and Caldwell[3]. Those papers describe various defences that were devised to reduce erosion losses and the problems that arise with their implementation. At that time it became clear that not enough was known regarding the rate at which material can be removed by erosion, or the relative importance of wind and water erosion. The distribution of erosion losses over the slopes and top surfaces of tailings dams was also not known. There was an impression, gained from the observation of dust clouds emanating from tailings dams during windy weather, that wind erosion affected mainly the top surfaces of tailings dams and water erosion the slopes. This impression was reinforced by the observation that the slopes of gold-tailings dams are usually hard and crusted, and are apparently impervious to the effects of wind, whereas there are often pockets and areas of loose material lying on the top surfaces of dams. Finally, the efficacy of various measures proposed to reduce erosion losses was not known.

In 1984 the writer, with the assistance of the Chamber of Mines of South Africa, initiated a programme to measure erosion losses from the slopes of gold-tailings dams in the Transvaal. The programme was subsequently extended to include measurements of erosion losses from the top surfaces of dams, and the rates of accretion of material lost from slopes and caught in erosion catch-paddocks. The preliminary results of these observations were published after two years by Dorren and Blight[1] and by Blight[4].

The purpose of the present paper is to give the results of four years of observations. Whereas the previous two papers described only the rates of loss from the unprotected slopes of tailings dams, this paper also describes the rates of loss from top surfaces and grassed slopes. It also discusses the efficacy of some measures that have been proposed to reduce erosion losses.

The Measurement Programme

The two previous papers[1,4] summarized the theoretical mechanics of erosion by water and wind, and the reader is referred to those papers and others[5-9]. In brief, the variables under the control of the engineer that, according to theory and empirical knowledge, affect the rate of erosion of a soil are as follows:

- the strength of the soil surface,
- the length of a slope, and
- the slope angle or inclination of the surface.

The surface roughness or micro-relief is also known to affect rates of erosion (e.g. Jennings and Jarrett[10]).

Two means have been used to measure the strength of tailings surfaces.

ETCOM Penetration Resistance

The ETCOM instrument directs a jet of water 0,8 mm in diameter to impinge normally on the tailings surface. The pressure behind the jet is increased until the surface is penetrated, and the pressure in kilopascals at which penetration occurs is used as an index of erosivity. At first, correlations were made with values of ETCOM measured on initially dry tailings surfaces. Later, ETCOM values were also measured on surfaces that had been prewetted by having water poured over them and had then been allowed to drain of free water before measurement of the index. This was to eliminate capillary stresses that may falsely have enhanced the strength of the surfaces.

When the ETCOM instrument was developed, it was expected that the erosion resistance of a surface would be directly related to the ETCOM reading, and that erosion loss would decrease as the ETCOM reading increased. However, it has since been found that high ETCOM readings correspond to high erosion losses, and *vice versa*. The reasons for this apparently anomalous result were

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analysed by Dorren and Blight[1].

Vane Shear Strength

A hand-held 'Soil Test' shear vane was used to measure the shear strength of surfaces wetted as described above. The blades of the vane penetrate to a depth of 5 mm and thus measure the shear strength of the surface skin of material that is directly affected by erosion forces.

Details of the Measurements

Measurements of the rates of erosion were made in the field at ten different sites. At many of these, the measurements were made on more than one slope or surface. This was because it was thought initially that the aspect of the slope with respect to the direction of the sun and prevailing winds might be important. However, in only one case was such an influence detected.

The experimental measurement plots were each 9 m by 9 m in plan, and consisted of a grid of steel pegs 1 m long and 8 mm in diameter. These were driven in normal to the surface at 3 m intervals to give a 4 × 4 array of 16 pegs.

Initially, 250 mm of each peg was left protruding from the ground but, as this made the pegs obvious and invited vandalism, the protrusion was later reduced to 50 mm. The erosion loss (or gain) could then be gauged simply from measurements taken at successive times of the distance from the tip of each peg to the tailings surface.

The erosion-measurement plots on slopes were positioned approximately in the middle of the slope length. All the pegs were driven in in an exact grid. Thus, some were located in erosion rills, some on ridges between rills, and others in intermediate positions. The results are reported as average values for the whole of each plot. However, observations on individual pegs confirmed the expectation that rates of erosion tend to be progressively higher from the top to the bottom of a slope, and also higher in rills, where the quantity of runoff is larger. In each case, a crest wall was present at the crest of the slope to ensure that no water cascaded down the slope from the top of the dam and that any measured erosion was thus the effect only of water precipitated directly onto the slope.

Originally, each test area was equipped with a rain gauge. However, these were all vandalized within a few weeks of installation, and information from the nearest official meteorological stations at Rand and Jan Smuts Airports was therefore relied on for rainfall data.

Both ETCOM and vane-shear measurements were made adjacent to every peg, and the results are reported as the average for each test plot.

For the first year of the experiment, April 1984 to March 1985, the rainfall was 20 per cent less than the local 30-year average of 750 mm. For the second year up to March 1986, the rainfall was almost equal to the 30-year average. For the final two years, from April 1986 to May 1988, the rainfall was 11 per cent and 29 per cent above the 30-year average. For this reason, most of the results are reported in terms of 1-year, 2-year, and 4-year averages.

Distribution of Erosion between Seasons

Fig. 1 shows the distribution of erosion loss from tailings slopes observed over the first year of the experiment. Most of the rainfall occurs in summer, but there are usually at least one or two precipitation events during winter. These account for about 10 per cent of the annual precipitation. In Fig. 1, the erosion loss, quoted in terms of retreat of the slope in millimetres per season, and tons lost per hectare per season, was plotted against the ETCOM index measured on dry surfaces. As the diagram shows, the erosion loss during the winter amounted to about 80 per cent of the loss during the summer. For individual plots, the winter erosion was measured as between 40 and 140 per cent of the summer erosion. This shows that there is a large component of wind erosion in the total annual erosion loss. The visual impression referred to earlier is thus erroneous, and the slopes of tailings dams are indeed subject to considerable erosion by wind.

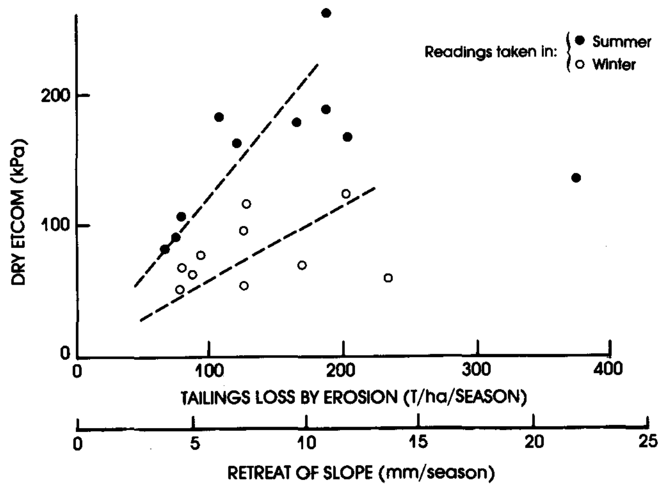

Fig. 1—Correlation between ETCOM erosion index and tailings loss by erosion

Fig. 1 also shows that erosion losses are very considerable, whether reported in terms of slope retreat or tons per hectare per year. Annual erosion losses from agricultural fields rarely exceed 10 to 15 t/ha, whereas annual losses from the slopes of tailings dams are measured in hundreds of tons per hectare.

ETCOM Index and Erosion Loss

Fig. 2 shows the relationships between dry ETCOM index and erosion loss for 1-, 2-, and 4-year periods, and the wet ETCOM index over the 4-year period. For the 1- and 2-year periods, there seems to be a reasonably good correlation between the average dry ETCOM index and the erosion loss. However, over the 4-year period, the erosion loss seems to be quite independent of both wet and dry ETCOM indices. This is a very disappointing result since it means that the ETCOM index cannot be used as a reliable indicator of the erosion potential of a surface.

The 4-year data are plotted against the wet ETCOM index measured at 3 years and the dry ETCOM averaged for years 1 and 3. It will be noted that, whereas the maximum dry ETCOM for year 1 was as high as 210 kPa, the maximum average of dry ETCOM over years 1 and 3 was only 110 kPa. The position of the 4-year dry ETCOM line on Fig. 2 shows that dry ETCOM values measured in year

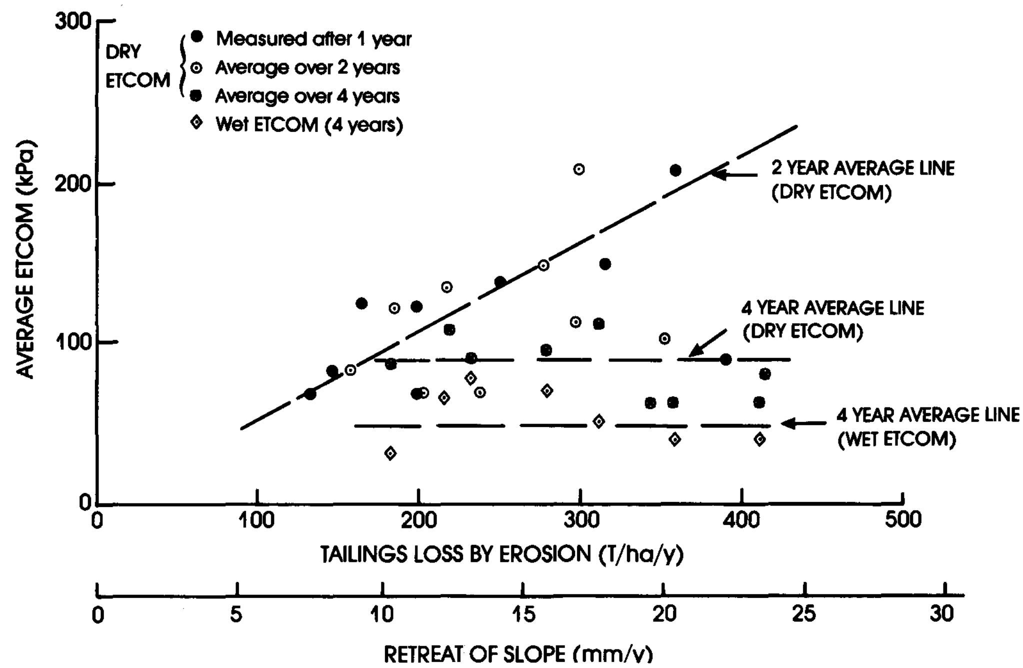

Fig. 2—Correlation between average summer and winter ETCOM erosion index and annual tailings loss by erosion

3 had much lower maximum values, but also higher minimum values, than those measured in year 1. The reason for this effect is not clear. It is probably because the slope surfaces were not as dry in year 3 as they were in year 1, and were therefore generally not as resistant to penetration by the water jet. Whatever the reason, the change in ETCOM values converted correlation to independence for these data.

Surface Shear Strength and Erosion Loss

The correlation between surface shear strength and erosion loss is shown in Fig. 3.

The surface shear strength was measured at the end of each summer and winter period, and the values represent a running average over 1, 2, or 4 years as the case may be. The data show a similar trend to that for dry ETCOM, i.e. shear strength shows a progressive decrease with time.

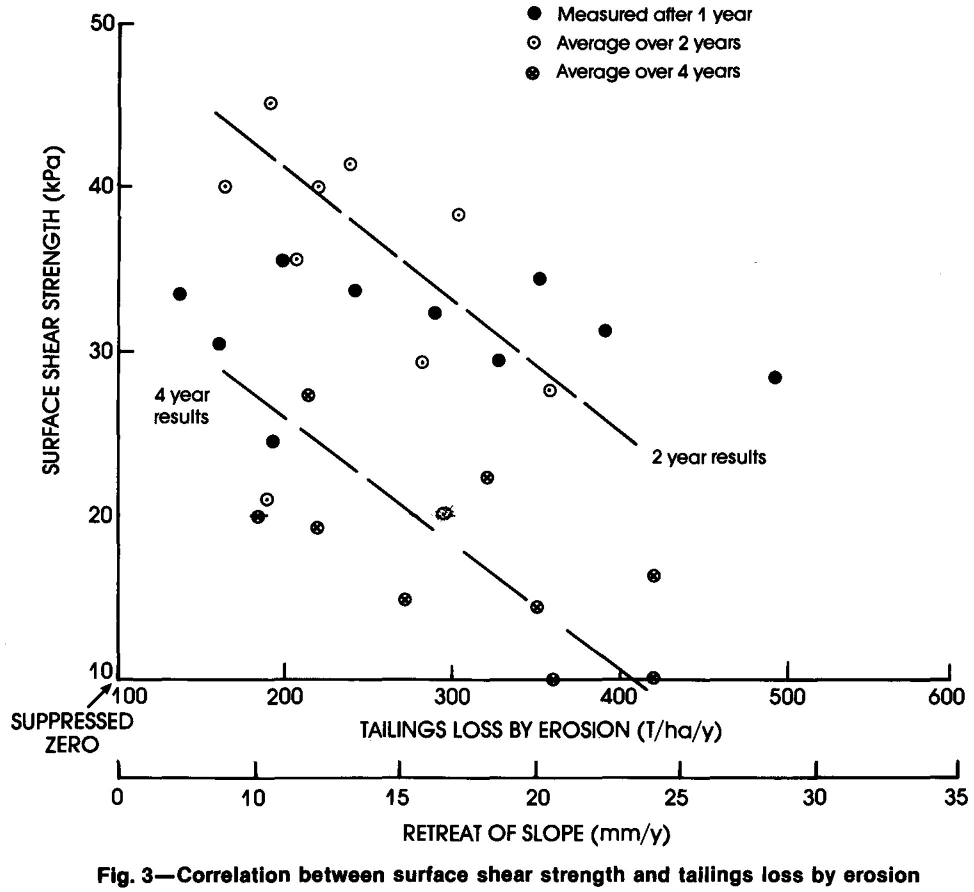

Fig. 3—Correlation between surface shear strength and tailings loss by erosion

However, the weak negative correlation with erosion loss persists, although it changed over the 4-year period of the experiment.

Slope Length and Erosion Loss

Bare Slopes

Depending on how the data shown in Fig. 4 are viewed, they can either be interpreted as showing a zone of correlation and another of no correlation (as indicated in Fig. 4) or as showing no correlation at all. There is agreement that, for the erosion of agricultural lands, soil loss is roughly proportional to slope length. The Universal Soil Loss Equation[6] (USLE) gives the soil loss E as

$$E = ARKLSCP,$$

in which LS is a topographic factor to account for the combined effect of slope length, L, and slope angle, S, and A, R, K, C, and P are factors accounting for other effects[6]. Because the slopes of agricultural land are generally flat, the USLE is not regarded as being valid for slopes steeper than 25 per cent (about 14 degrees).

The portion of Fig. 4 that indicates no correlation between slope length and erosion loss is believed to arise because of the stronger influence of other factors such as surface shear strength or slope angle. It may also arise because certain of the test plots were too small to adequately represent average erosion over the length of some of the slopes, or simply because certain slopes were subjected to more precipitation and therefore eroded more than others.

Some of the uncertainties in the correlation of erosion losses with slope length are illustrated in Fig. 5. This shows the distribution of slope retreat over 4 years down the length of three of the test plots. Data for two of the slopes, those 51 m and 23 m in length, fall on the positive correlation between slope length and erosion loss. Data for the slope 28 m in length do not. The downslope distribution of slope retreat for the slopes 28 m and 51 m in length is what would be expected from the USLE, i.e. the rate of erosion increases downslope. However, that for the slope 23 m in length is quite irregular.

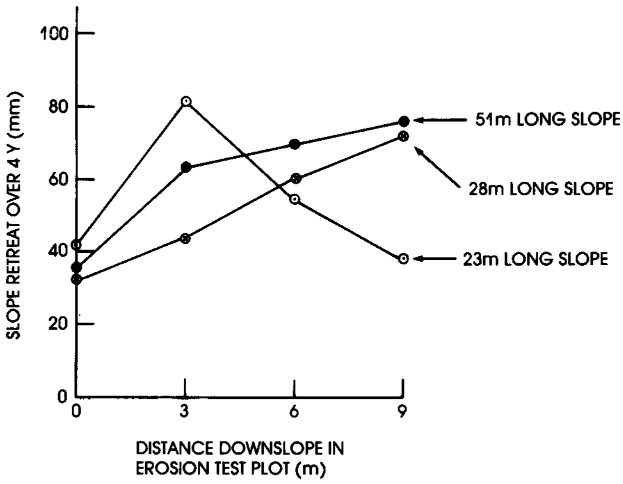

Fig. 5—Distribution of slope retreat over the length of three erosion test plots

With hindsight, it is probable that better correlation would have been obtained if the test pegs had been

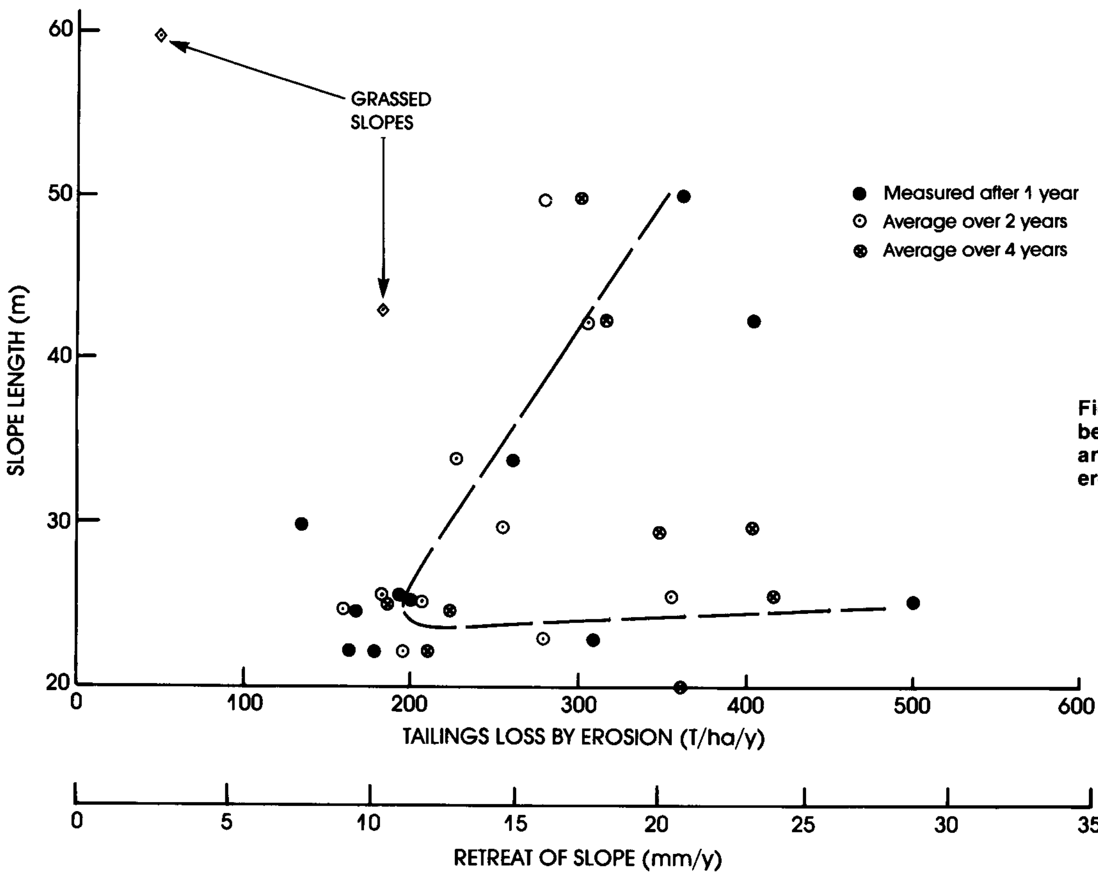

Fig. 4—Correlation between slope length and tailings loss by erosion

distributed over the entire length of each slope, instead of being located at midslope.

Grassed Slopes

Three grassed slopes were included in the programme. Fig. 4 shows 2-year average results for the erosion of two of those slopes, a west- and a south-facing slope. The results lie well to the left of the data for untreated slopes. The result for the third slope, north-facing, is not shown because it is not eroding but is accreting at an annual rate of 35 t/ha (2 mm). Material blown off the other slopes of the dam is apparently trapped by the grass on the north face, and the rate of erosion by water is insufficient to remove this entrapped material. The maximum observed accretion rate for this slope during the winter was 90 t/ha per year (or 5 mm per year).

Slope Angle and Erosion Loss

Bare Slopes

All the available data relating erosion loss to slope angle are shown in Fig. 6. Once again, the data can be regarded as showing no correlation at all, or they can be regarded as showing the two-branched relationship indicated in the diagram. As pointed out earlier, the USLE indicates that a positive correlation can be expected between slope angle and erosion loss. A qualitative two-branched correlation between slope angle and erosion loss was previously noted by Renner[11], who observed that very little erosion occurs on natural slopes steeper than 80 per cent (39 degrees) or flatter than 5 per cent (3 degrees).

Terraced Slopes

Blight *et al.*[2] and Blight and Caldwell[3] suggested that the erosion of a slope can be reduced if it is terraced in a series of steps with vertical and sub-horizontal surfaces, as illustrated in Fig. 7. Each sub-horizontal surface slopes back towards the vertical step above, and is hydrologically designed to retain precipitation on it without spilling down to the next step. The erosion of two terraced slopes was observed as part of this programme.

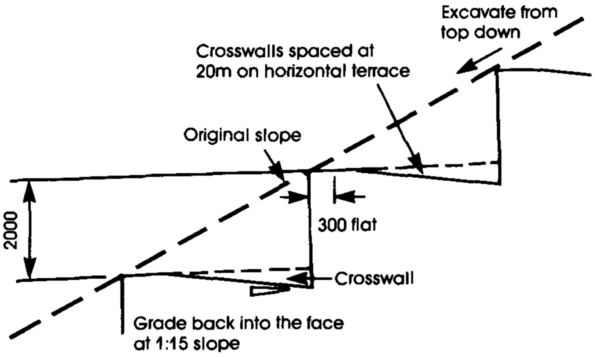

Fig. 7—Design section for a terraced slope

The results of the measurements, shown in Fig. 6, confirm that erosion losses from terraced slopes are relatively

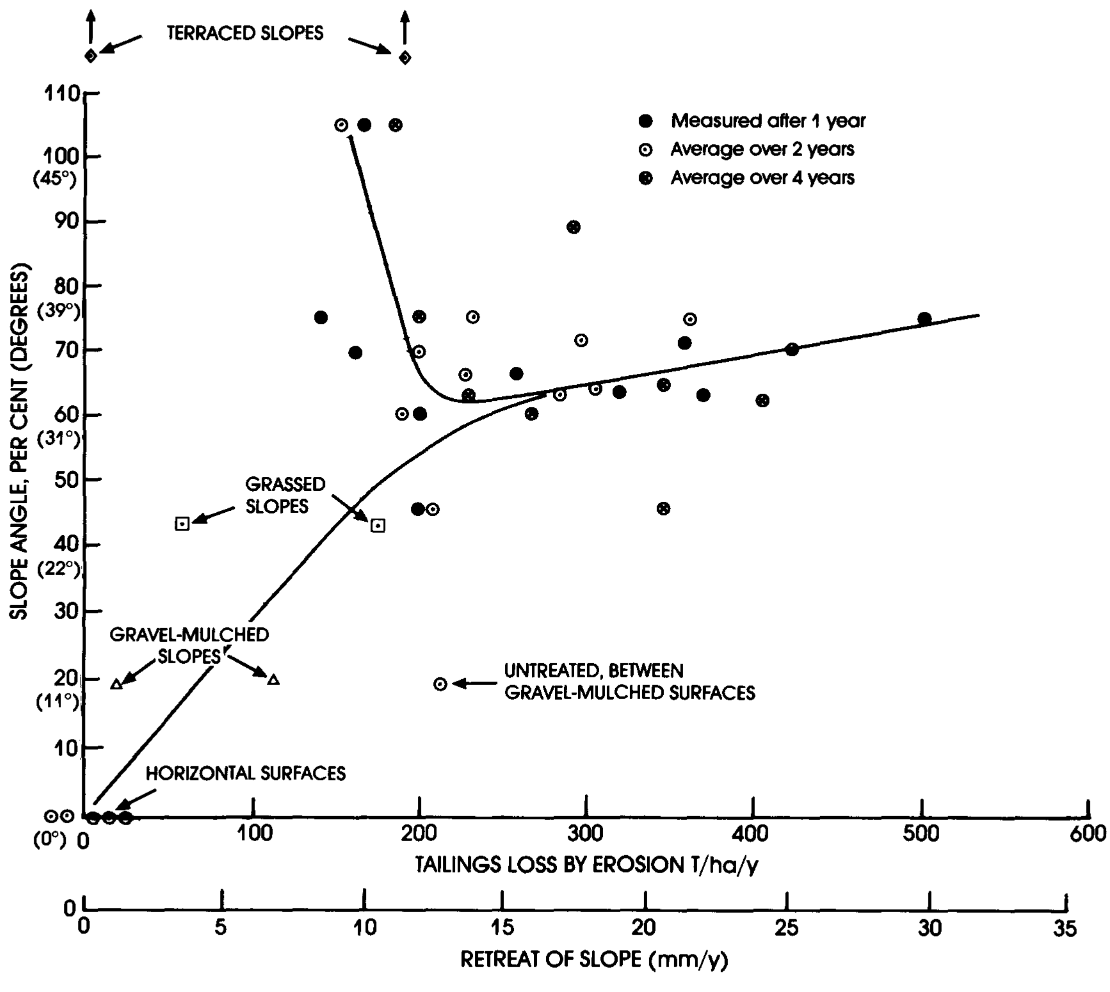

Fig. 6—Correlation between slope angle and tailings loss by erosion

small. These measurements represent an average over 4 years.

Horizontal Surfaces

Five tests plots were established on the untreated horizontal top surfaces of dams. The results of these measurements are also given in Fig. 6, and show that there is little or no erosion loss from untreated top surfaces. In some cases, a small accretion occurred. These measurements represent an average over years 3 and 4 of the experiment.

These results, taken with those shown in Fig. 1, appear to indicate that the major losses from tailings dams due to wind and water erosion take place from the slopes, and not from the flat top surfaces. The dust clouds that appear to emanate from the top surfaces are in reality blown off the windward slope and other slopes that are subjected to a component of wind shear.

Grassed Slopes

The data for grassed slopes are also shown in Fig. 6. There, the losses for the west- and south-facing slopes do not appear to be unusually low when compared with the trend of the other data.

However, the north-facing grassed slope is the only non-horizontal slope for which an accretion was recorded during this investigation.

Gravel-mulched Surfaces

Two sets of measurements are available for the rates of erosion of gently sloping surfaces (11 degrees) that were covered by a layer one particle thick of 16 mm crushed rock. As shown in Fig. 6, the gravel-mulched surfaces eroded considerably less than the untreated adjacent control plot. However, the position of the data in relation to that for other slopes suggests that the control plot was unusually erosive, rather than that the gravel mulch was very effective in preventing erosion. However, there is evidence[12] in the literature that surface obstructions such as closely spaced gravel particles and clods decrease the rates of erosion of soil surfaces by reducing the kinetic energy of runoff passing over the surface.

Other Data from the Programme

Other results from the programme of measurements are as follows.

Effect of Stabilizing Dam Top Surfaces

Blight *et al.*[2] and Blight and Caldwell[3] had reported on the experimental stabilization of the horizontal surface of a tailings dam with Portland cement and road lime. Erosion-measuring plots were set up on those surfaces and on an intervening untreated surface. Measurements over years 3 and 4 gave the result that the cement-stabilized surface is eroding at a rate of 18 t/ha per year (a rate of retreat of slightly more than 1 mm per year). The lime-stabilized surface is eroding at a rate of 3 t/ha per year, and the adjacent untreated surface is accreting at 6 t/ha per year. This set of measurements has therefore simply confirmed the conclusion reached above that near-horizontal surfaces are relatively unaffected by erosion.

Accretion in Erosion Catch-paddocks

Rates of accretion were measured in a number of erosion catch-paddocks at the toes of tailings-dam slopes. The measured rates varied from 70 to 150 mm per year. These accretion rates could not be reconciled with, and generally appeared to be greater than, the losses from the slopes above the paddocks. This is presumably because more material is eroded from near the toe of a slope than from the mid-length area. Again, with hindsight, it would have been better to have measured erosion losses over the full length of the slopes.

Retreat of Crest Walls

The top surfaces of crest walls made of compacted unstabilized tailings decreased in height by up to 200 mm per year. The rate of height reduction of crest walls with cement-stabilized (5 per cent nominal concrete content) crests is only about 1 mm per year. Cement stabilization of the tops of crest walls therefore appears to be well worth while.

Conclusions

The main conclusions drawn from this study are as follows.

(1) Both wind and water are major agents in eroding the slopes of gold-tailings dams.
(2) The horizontal top surfaces of gold-tailings dams are relatively little affected by erosion.
(3) There appears to be no reliable correlation between the ETCOM erosion index and the rate of erosion of slopes of gold-tailings dams.
(4) There is a weak negative correlation between the shear strength of the surface of a gold-tailings-dam slope and the rate of erosion of the slope.
(5) There is a weak positive correlation between the length of a slope and the rate of erosion. This correlation would probably be better if erosion losses were measured over the entire lengths of a series of slopes.
(6) A two-branched correlation exists between the slope angles of gold-tailings dams and the rate of erosion. Very flat slopes and very steep slopes erode less than slopes of intermediate angle. At the limits of slope, the horizontal and vertical surfaces erode very little.
(7) The grassing of slopes appears to be very effective as a means of reducing the rate of erosion.

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References

1. Dorren, D.I., and Blight, G.E., Erosion of the slopes of gold-residue dams on the Transvaal Highveld—preliminary results. *J. S. Afr. Inst. Min. Metall.* vol. 86, no. 12. 1986. pp. 475–480.
2. Blight, G.E., Rea, C.E., Caldwell, J.A., and Davidson, K.W. Environmental protection of abandoned tailings dams. *Proceedings, 10th International Conference on Soil Mechanics and Foundation Engineering, Stockholm,* vol. 2. 1981. pp. 303–308.
3. Blight, G.E., and Caldwell, J.A. The abatement of pollution from abandoned gold-residue dams. *J. S. Afr. Inst. Min. Metall.,* vol. 84, no. 1. 1984. pp. 1–9.