Properties of pumped tailings fill

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SYNOPSIS

The mining industry is making increasing use of pumped tailings fills. The properties that affect the performance of tailings fills are described by means of typical examples. They are the particle-size grading for maximum density, the water content for pumpability, settlement after placing, compression and drainage under stress, shear strength, and resistance to shock loading.

SAMEVATTING

Die gebruik van slyk vir vul doeleindes in die mynbedryf neem toe in gewildheid. Die eienskappe wat die werkverrigting van slyk vul beïnvloed word beskryf aan die hand van tipiese voorbeelde. Die eienskappe is die partikelgroote-gradering vir maksimum digtheid, die watergehalte vir pompbaarheid, versakking na plasing, verdigting en dreinering onder spanning, skuifsterkte en weerstand teen skokbelasting.

Introduction

There is a growing world-wide interest in the mining industry in the use of underground fills of tailings material. These may be cemented[1] or uncemented[2]; and may be placed mechanically, pneumatically[3], or hydraulically[1, 2]. The purposes of these fills are numerous. For example, fills are used to

(i) improve the stability of pillars[2],
(ii) provide access to assist in the mining of wide ore-bodies[2, 4],
(iii) reduce surface subsidence in the case of shallow mining, or stabilize the surface in the case of long-abandoned shallow workings,
(iv) act as structural support to stopes in deep mines[1, 2].

In addition to these purely functional uses, the disposal of tailings in the form of underground fill reduces (though only slightly) the pressures on the surface environment[5, 6] by

(a) releasing area at the surface for more productive use than the disposal of tailings, and
(b) reducing problems of air, water, and visual pollution, both in the short and the long term.

Properties of Pumped Tailings Fill

It appears that the following are the properties required of a successful pumped tailings fill.

(1) The tailings should become pumpable at the lowest possible water content. In South Africa's semi-arid to arid climatic conditions, water supply is often a major problem. In addition, much of the water used to place a fill eventually drains out of it and must be handled within the mine. However, the most important reason for seeking pumpability at a low water content is that, the lower the water content at which the slurry is placed, the less compressible the fill subsequently.
(2) During placing, the fill should settle into as dense a state as possible and after that should be as incompressible as possible under applied stress.
(3) The fill should be capable of resisting the effects of shock loading produced by blasting or seismic events.

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†The reader is referred to this work for further details of the well-accepted concepts of soil mechanics discussed in this section.

When the relative merits of a number of possible fill materials are considered, an attempt should be made to maximize the above factors, all of which, as it happens, are compatible with one another.

Fills under Stress

When fills are subjected to stress, their behaviour is governed by the principle of effective stress, which applies to all particulate materials[7]†. This principle states that changes in volume or in strength of a particulate material are governed by changes in effective stress, and that volume and strength can change only if the effective stress in the material changes. The effective stress is defined by the equation

$$\sigma' = \sigma - u, \qquad (1)$$

in which σ is the total or applied stress in the material, u is the pressure in the water contained by the material (the pore-water pressure), and σ' is the effective stress.

Changes in the volume of a fill are governed by the equation

$$\triangle\epsilon_V = -C\triangle\sigma', \qquad (2)$$

in which $\triangle\epsilon_V$ is the change of volumetric strain corresponding to a change in effective stress of $\triangle\sigma'$, and C is the compressibility of the fill material. Changes of shear strength are controlled by the equation

$$\triangle\tau = \tan\phi'\triangle\sigma', \qquad (3)$$

where $\triangle\tau$ is the change in shear strength corresponding to a change in the effective stress of $\triangle\sigma'$, and $\tan\phi'$ is the angle of shearing resistance of the fill material. Integrating equation (3) yields the shear-strength equation

$$\tau = c' + \tan\phi'\,\sigma', \qquad (3a)$$

in which c' is the shear strength when $\sigma'=0$.

Changes of volume, shear strength, and water content are inextricably linked in that the shear strength cannot change without a change of volume, the volume cannot change unless water is expelled from the fill, and the compressibility depends on the shear strength (as compression usually involves internal shearing).

The compressibility C and the angle of shearing resistance ϕ' depend on the density at which the fill is placed and increase with increasing placed density. As the dry density γ_d of a saturated fill is related to the water content w by

$$\gamma_d = \frac{G_S\gamma_w}{1+wG_S} \qquad (4)$$

(in which G_s is the particle specific mass of the fill and γ_w the density of water), low water contents are associated with high dry densities and *vice versa.*

An increment of total stress applied to a fill will result in the expulsion of water via a time-dependent process of consolidation, which is governed by the differential equation

$$\frac{\delta u}{\delta t}=c_v\frac{\delta^2 u}{\delta z^2}. \quad \quad (5)$$

In this equation, t is the time measured from the instant of application of a stress increment, and z is a distance related to the drainage path or distance through which water must percolate in order to escape from the fill; c_v, the coefficient of consolidation, depends on both the permeability and the compressibility of the consolidating material.

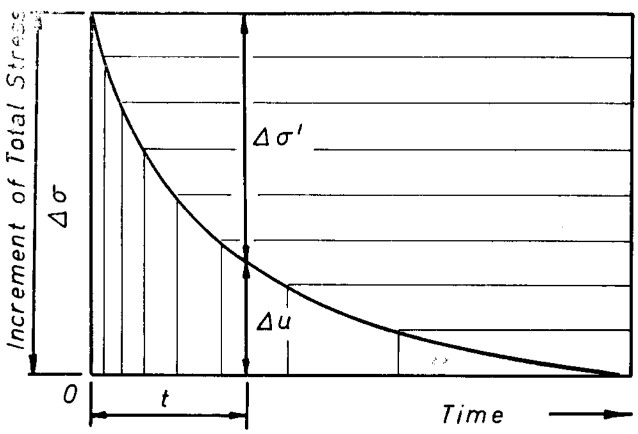

Fig. 1—Interchange between total stress, pore-water pressure, and effective stress during the consolidation process

The interchange between pore pressure, total stress, and effective stress according to equation (5) is shown schematically in Fig. 1: when the increment of total stress is imposed, it is entirely transferred to the pore water, i.e. at time $t=0$, $\triangle u=\triangle\sigma$ and $\triangle\sigma'=0$.

The pore water immediately starts to drain from the fill, and, as it does so, stress is transferred from the pore water to the solids in the fill, i.e. at time $t>0$, $\triangle u+\triangle\sigma'=\triangle\sigma$.

Finally, after the elapse of a period of time that is related to the dimensions and drainage conditions of the fill (z) and the coefficient of consolidation cv, the entire total stress increment is carried by the solids in the fill, i.e. at $t\rightarrow\infty$, $\triangle\sigma'=\triangle\sigma$ and $\triangle u=0$.

Gradings for Maximum Density

The placement density, and hence the compressibility and shear strength, of a fill greatly depend on the grading or particle-size distribution of the material. In what follows, guidance will be given as to what constitutes a satisfactory grading and what factors are more important in ensuring a high placement density.

Grading curves can be idealized to two main types:

(i) uniform or Fuller gradings, for which the grading curve (the relationship between the logarithm of the particle size and the percentage finer than that size) is an inclined straight line, and

(ii) gap gradings, which consist of a series of inclined straight lines joined by horizontal size 'gaps' in which there are no particles present.

Uniform Gradings

Most tailings materials include a relatively narrow range of particle sizes (see, for example, Fig. 8) and can be approximated by a straight-line grading curve. The two main variables in a straight-line grading curve are the slope (or ratio of maximum to minimum particle size) and position (size of the largest particle present).

Fig. 2a shows a series of straight-line or Fuller gradings in which the ratio d_1/d_0 of the largest to the smallest particle size present ranges from 8 to 128 (gradings F0 to F4). Fig. 2b shows the effect of these gradings on the settled densities of aggregates made up from two different source materials. The same compactive effort was used for each material. Fig. 3a shows a series of parallel straight-line gradings F0, F5, F6, and F7, and Fig. 3b compares the settled densities of aggregates having these gradings.

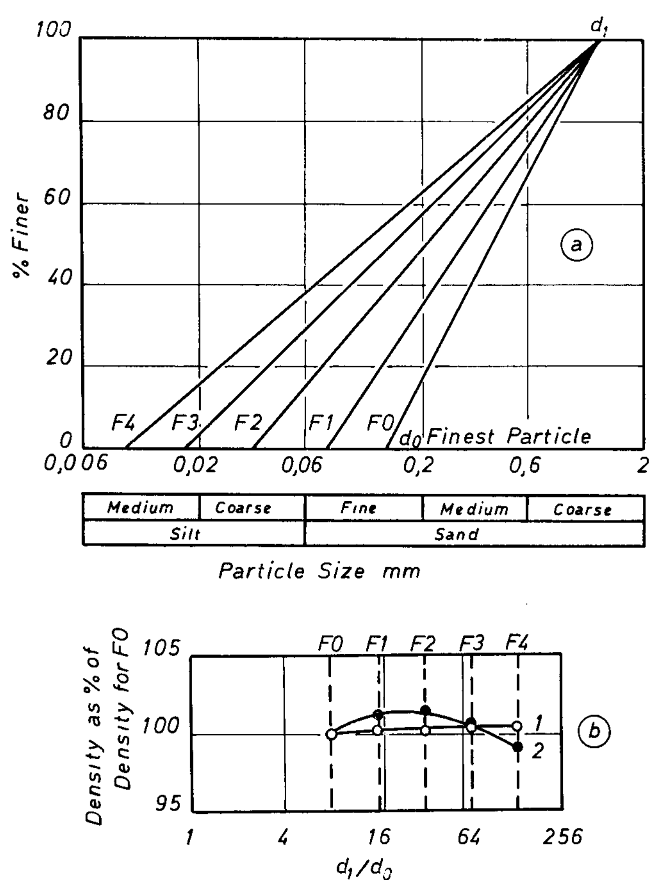

Fig. 2—(a) Series of continuous gradings F0, F1, F2, F3, F4
(b) Settled densities of two materials made up in gradings F0 to F4

It is clear from Figs. 2 and 3 that the slope of a uniform grading curve has a relatively minor effect on the settled density but that the position of the curve has a greater effect. For the same slope of grading curve, the density may decrease by up to 8 per cent when the maximum particle size is decreased by a factor of 4.

Gap Gradings

Fig. 3a also shows a series of gap gradings G0 to G3 in which the gap bridges between the uniform gradings

F0 and F5. The settled densities corresponding to the various gap gradings are shown in Fig. 4 (for the same two basic source materials). A comparison of Fig. 4 with Figs. 2b and 3b shows that a far greater range of densities is obtainable via a gap grading than via a uniform grading. For example, the addition of about 20 per cent fines to a material with grading F0 can cause the settled density to increase by 4 per cent, whereas the density of the fines alone would be 5 per cent less than the density obtainable with grading F0.

The experimental results presented in Figs. 2 to 4 do not provide a set of rules for producing the greatest possible settled density, but do provide a framework for experimenting with a combination of available materials to produce a satisfactory high settled density, and hence a fill of low compressibility and high strength. It can be concluded that, in order of increasing importance, the slope of a uniform grading curve, the size of the maximum particle present, and the percentage of fines in a gap grading all have an effect on the attainable settled density of a pumped fill.

Water Content for Pumpability

One of the first requirements in any programme of testing to ascertain the properties of a potential pumped tailings fill is to estimate the minimum water content at which a slurry of the tailings will become pumpable.

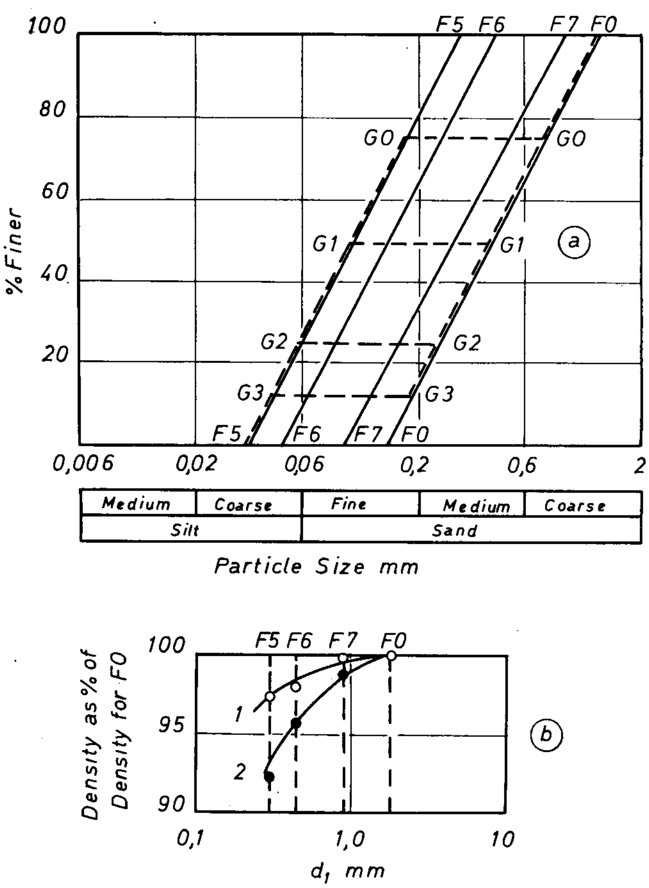

Fig. 3—(a) Series of continuous gradings F0, F5, F6, F7, and gap gradings G0, G1, G2, G3
(b) Settled densities of two materials made up in gradings F0, F5, F6, F7

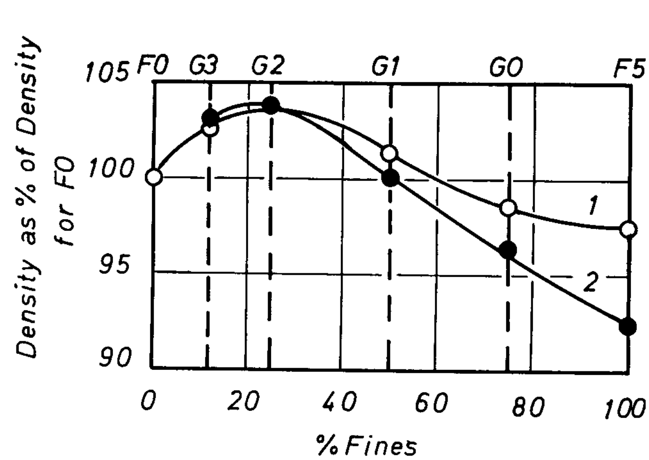

Fig. 4—Settled densities of two materials made up in gradings F0. G0 to G3, and F5

Once this has been established, all the laboratory specimens for further testing are prepared at that water content.

The pumpability of a slurry depends on its viscosity*, which can be measured in a variety of ways. One suitable method is by means of a rotating-cylinder apparatus in which the slurry is contained in the annular space between a pair of co-axial cylinders. The outer cylinder is rotated at a fixed rate, and the torque transferred to the inner cylinder is measured to establish the viscosity of the slurry.

The pumpability characteristics of the slurry can then be investigated via the Hagen–Poiseuille equation, which for viscous flow in a circular pipe or a semicircular open channel flowing full has the form

$$v=\frac{\gamma i D^2}{32\mu} \quad \ldots \quad (6)$$

in which v=the velocity of flow
γ=the density of the slurry (mass per unit volume)
i=the flow gradient or the loss of head per unit length of conduit
D=the diameter of the conduit (pipe or semicircular channel)
μ=the viscosity of the slurry.

The rate of transport of dry solids can be found from

$$Q=vA\rho_d, \quad \ldots \quad (7)$$

in which A=cross-sectional area of conduit
ρ_d=dry specific mass of slurry (mass of dry solids per unit volume of slurry).

It appears that a viscosity of 100 P (poise) or 10 Pa.s represents the upper limit to pumpability, but lower viscosities, and hence higher water contents, may be required, depending on the specific application.

The water content at which a slurry has a viscosity of 100 P can be estimated by means of an adaptation of a simple soil mechanics test, using the liquid-limit apparatus[7]. This consists of a hemispherical cup that can be raised and dropped through a fixed height onto a

*Tailings slurries are here assumed to act as Newtonian fluids. This is probably not strictly true (see reference 8, for example), but is a sufficiently accurate first approximation to their true behaviour.

hard-rubber base by means of a rotating cam. The slurry is placed in the cup, and its surface is levelled and a groove cut in it with a special tool. The water content at which the groove just closes with one blow of the cup on the base corresponds to the water content for a viscosity of 100 P. A typical relationship between viscosity measured by means of the rotating-cylinder test and the number of blows in the liquid-limit test is illustrated in Fig. 5.

The grading or particle-size analysis of the tailings has a considerable influence on the water content required for the 100 P viscosity. For example, a typical gold-mine slimes requires a water content of 55 per cent, whereas a coarser gold-mine sand requires only 33 per cent. The cement content of the slurry also influences the 100 P viscosity water content slightly, e.g. for the same gold-mine sand:

Cement content	100 P water content
0	33%
5	31,9%
10	31,6%.

This effect appears to result from an improvement in the grading of the fill from the addition of the cement fines. The fines convert the approximate straight-line grading of the sand (sand 2 in Fig. 8) to a gap grading that is similar to G3 in Fig. 3a, thus improving its flow properties at a given water content.

Settlement of Slurries after Placing

A pumpable slurry always contains more water than is required to fill the voids in the settled material. If this were not so, interparticle friction and interlock (equation 3a) would prevent the material from flowing. Once the pumped fill is in place, this surplus water drains or bleeds off and must be disposed of. Fig. 6 shows the influence of cement content on two typical sand-cement slurries placed at the 100 P water content. The extent of the problem posed by the disposal of this bleeding water will clearly depend on the volume of the fill being placed, on its rate of placing, and on the configuration of the fill relative to available drainage in the mine. The more bleeding that occurs, the better will the fill ultimately perform, as bleeding is an indication of settlement into a denser state.

The amount of bleeding water is also very dependent on the grading of the fill. In Fig. 6, the increase in bleeding water with increasing cement content also arises because the cement content acts as an addition of fines, thus improving the grading and allowing the particles to settle into a closer packing.

Compression of Fills under Stress

Most of the compression undergone by a pumped fill subjected to stress occurs at low stresses. This is illustrated by Fig. 7, which shows how a typical fill becomes less compressible as the stress increases. Hence, it is the compressibility at low stresses that is all-important — a fill that is incompressible at low stresses will remain incompressible at high stresses and *vice versa*.

It will be noted that the compression curve has been presented in terms of decreasing water content. This

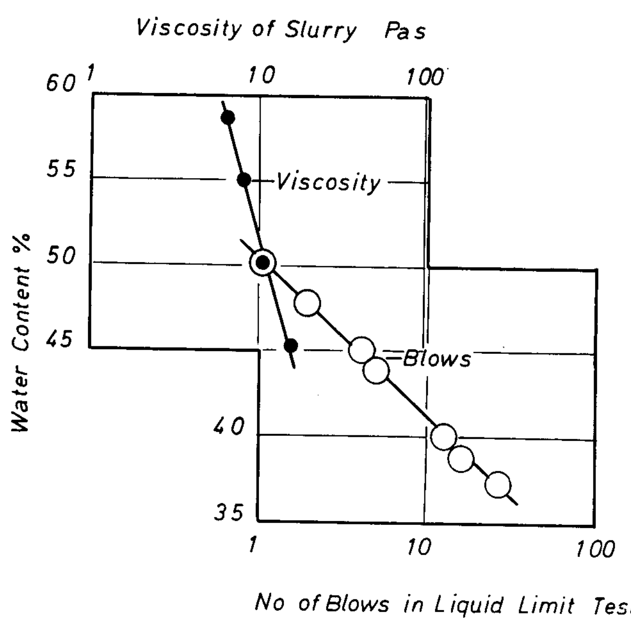

Fig. 5—Relationship between viscosity, blow count in the liquid-limit apparatus, and water content for a typical tailings slurry

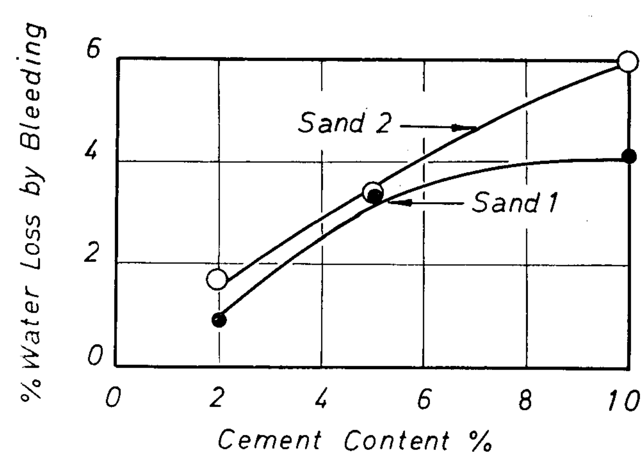

Fig. 6—Relationship between cement content and water lost by bleeding for two cemented sand slurries

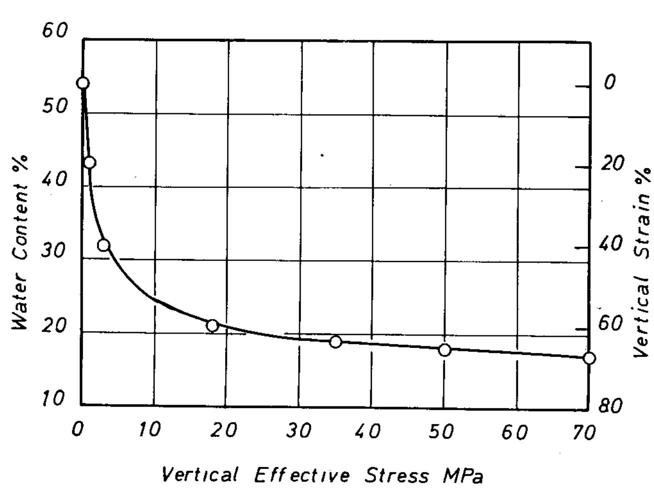

Fig. 7—Compression curve for slimes containing 10 per cent cement and showing that most of the compression occurs at low stresses

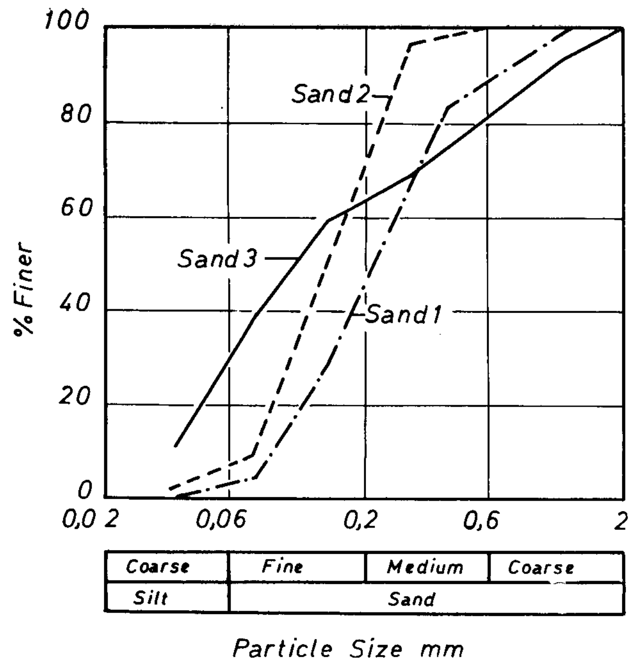

Fig. 8—Grading curves for three typical tailings sands

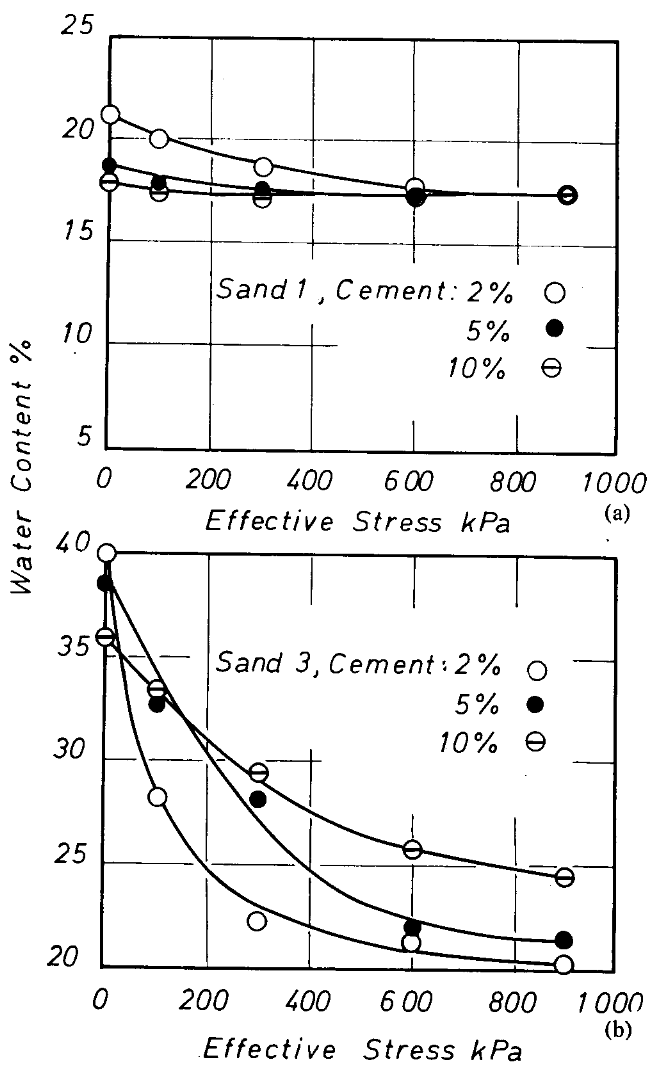

Fig. 9—(a) Compression of sand 1 at three cement contents
(b) Compression of sand 3 at three cement contents

emphasizes the fact that a fill of saturated tailings can compress only as water is expelled from it under increasing stress.

As stated earlier, the compressibility of a fill is highly dependent on its grading, both at small and large stresses. For small stresses, this is illustrated by Figs. 8 and 9: Fig. 8 shows the grading curves for three sands (sands 1 and 2 have been referred to in Fig. 6), while Fig. 9 shows the compression curves, at low stresses, for sands 1 and 3 and the effect on compressibility of added cement fines. (All the specimens were placed at a water content corresponding to 100 P viscosity.)

The water contents at zero effective stress indicate the effect of cement content on bleeding, since all the specimens were placed at the same initial water content. It will be noted that the materials that bled most (lower initial water contents) are also less compressible under applied stress. This conclusion also applies to a comparison of sands 1 and 3: sand 1 had a lower initial water content than sand 3 and proved less compressible under stress.

Apart from altering the grading of the fill, the cement content also decreases the compressibility by developing cohesive bonds between the solid particles of the fill.

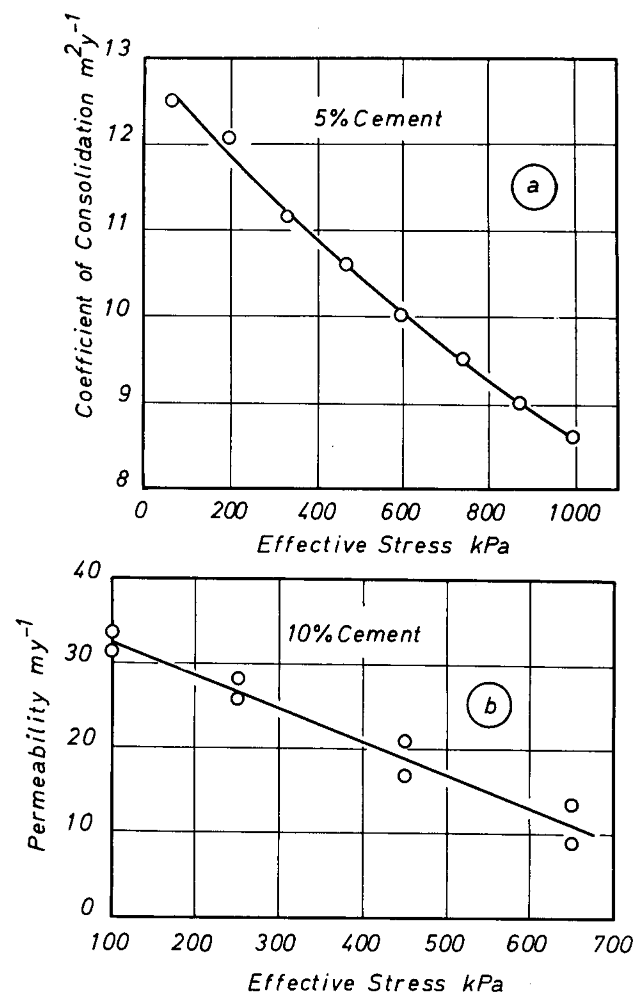

Fig. 10—(a) Variation of coefficient of consolidation with effective stress for a typical tailings fill
(b) Variation of coefficient of permeability with effective stress for a typical tailings fill

However, as will be seen later, at the high water contents and low cement contents used in pumped tailings fills, these bonds are relatively weak and have only a small effect on the compressibility of the fill.

To sum up, Fig. 9 shows that materials that settle into a dense packing on being placed will be less compressible under subsequent loading.

Drainage of Fills

As described earlier, the rate at which fills under compression drain is influenced primarily by the coefficient of consolidation, c_V. Fortunately, most tailings materials are relatively permeable, and values of c_V lie in the range of 10 to 50 m² a year or more (in comparison with clays, which may have c_V values as low as 0,1 m² a year).

The value of c_V is influenced by the effective stress, and decreases with increasing effective stress as shown in Fig. 10a. However, the effect of stress on c_V, and hence on the rate of drainage, is usually relatively minor.

It may also be necessary to estimate the rate of percolation flow through a fill if the fill is being used as a water barrier. In this case, D'Arcy's law,

$$v = ki \quad (8)$$

(where v is the velocity of flow under a gradient of head i, and k is the coefficient of permeability) is applicable. The coefficient of permeability for tailings materials typically falls in the range 1 to 50 m a year, and also decreases with increasing effective stress, typically as shown in Fig. 10b.

Although the figures quoted above are typical, both c_V and k can be drastically reduced by the presence of only a few per cent of clay-sized material in the fill.

Shear Strength of Fills

Typical strength characteristics for cemented-tailings fills are shown in Fig. 11. In these diagrams, the maximum shear stress at failure $\frac{1}{2}(\sigma_1-\sigma_3)_f$ has been plotted against the average principal effective stress $\frac{1}{2}(\sigma_1'+\sigma_3')_f$. The diagrams clearly show the effect on shear strength of an increasing cement content. Increasing cement contents affect both the slope Ψ of the strength lines (Ψ is related to the angle of shearing resistance ϕ' by $\sin\phi'=\tan\Psi$) and the cohesion c' of the material. At higher stresses, the major effect on shear strength results from the increase in ϕ'. For example, for sand 3, when $\frac{1}{2}(\sigma_1'+\sigma_3')_f$ was equal to 3000 kPa, the strength increase as a result of an increase in the cement content from 0 to 10 per cent was 550 kPa, of which 110 kPa resulted from the increase of cohesion and 440 kPa from the increase in ϕ'. This disparity increases progressively with increasing stress.

The effect of cement content on both c' and ϕ' for sands 1, 2, and 3 is summarized in Fig. 12. A comparison of Fig. 12 with Figs. 8 and 9 shows that the least compressible sand (1) has considerably superior strength characteristics to those of sand 3. Sand 2, which has a

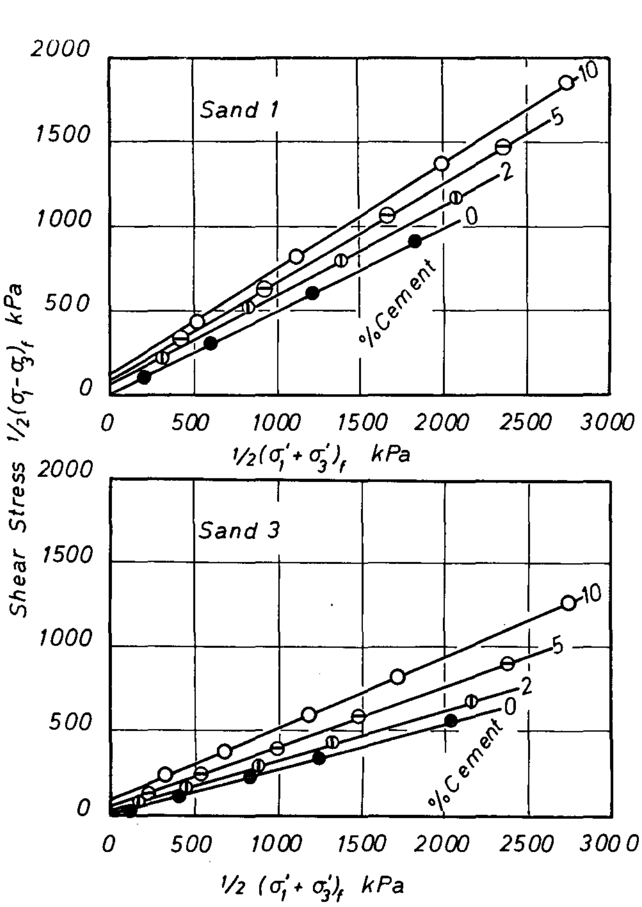

Fig. 11—Failure stress diagrams for triaxial shear tests on two cemented sands

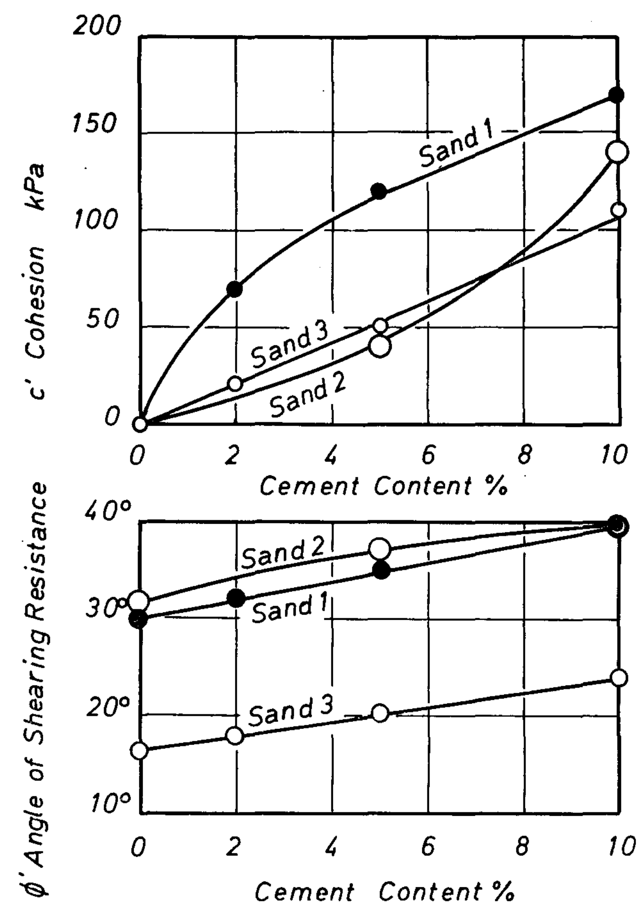

Fig. 12—Relationship between cohesion c', angle of shearing resistance ϕ', and cement content for three cemented sands

compressibility intermediate between that of sands 1 and 3, displays intermediate strength characteristics. One is therefore led to the conclusions that, in relation to strength,

(i) the greater the initial density of the fill, the better its performance; and
(ii) the cementitious bonds developed by any cement that may be added to a fill play a relatively unimportant role in the strength of the material; the effect of the cement on compressibility and frictional strength via its effect on ϕ' is far more important.

This latter effect probably results from improved grading (via higher settled density) rather than any chemical bonding.

Role of Cement in Pumped Fills

In view of earlier remarks, one is led to ask whether cement is necessary in a pumped fill and whether, if the major effect of the cement is to improve the settled density and compressibility of the fill by impoving its grading, some other type of fine material (preferably a waste material obtainable at low cost) would not do almost as well. These are questions that should be explored in each individual case. There are certainly indications, for example, that a mixture of pulverized fuel ash (PFA) and lime added to a tailings fill can produce almost the same effect as cement[9]. PFA is produced in vast quantities in South Africa[2] as a power-station waste product, and PFA from ash dams can be obtained for the cost of loading and transportation. Fig. 13 compares the compression curves for three slurries of gold-mining slimes containing cement and lime–PFA fines. It is evident that the use of lime–PFA mixes warrants further investigation, especially as the addition of this type of fines to a coarser material than gold-mine slimes could be expected to have an even better effect. (The grading of the PFA was not much finer than that of the slimes.)

Effects of Shock Loading

Shock loading as a result of blasting or seismic events has the effect of applying a rapidly alternating shear stress to a fill. Each application of shear stress causes an increment of pore pressure and, because the frequency

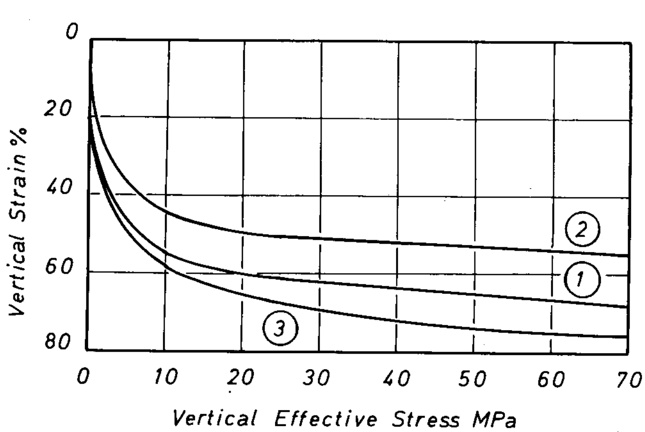

Fig. 13—Compression of gold-mine slimes containing
(1) 10 per cent cement
(2) 5 per cent lime and 16 per cent PFA
(3) 6 per cent lime and 12 per cent PFA

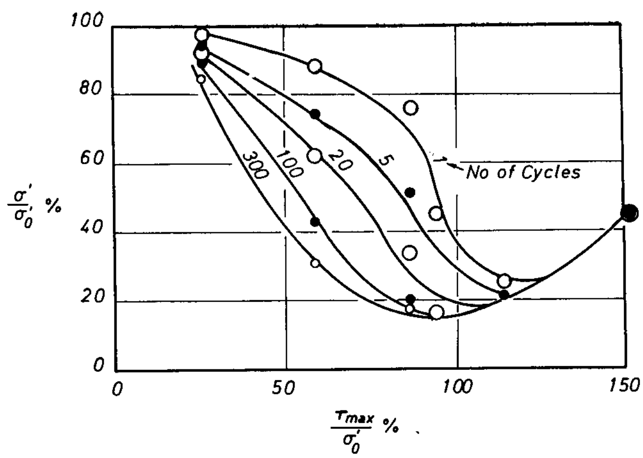

Fig. 14—Results of undrained repeated-load triaxial shear tests on a cemented slimes fill

of the applied shear stresses is relatively large, there is no time for drainage of the fill to allow the shear-induced pore pressure to dissipate. In terms of equation (3),

$$\triangle\tau = \tan\phi'\triangle(\sigma - u); \quad \ldots\ldots\ldots\ldots \quad (3b)$$

σ remains reasonably constant, but u increases with each application of shear stress, the net result being that $\triangle\tau$ is negative, i.e. the shear strength of the fill decreases. In the worst case, $\triangle\tau$ becomes equal to $-\tau$, and the fill loses all its strength and liquefies.

The effect of seismic or blast loading can be simulated in the laboratory by the application of alternating shear stresses under undrained conditions to a specimen of tailings fill in a triaxial test[7].

In tests of this type on specimens of cemented-slimes fill, it has been found that the pore pressure first of all increases (indicating a tendency for the fill particles to move into a denser packing) and then starts to decrease (indicating a tendency for the material to increase in in volume or dilate). A set of results for tests of this type[10] is shown in Fig. 14. On the vertical axis, the ratio σ'/σ_0' represents the effective stress after N cycles of repeated loading as a percentage of the initial effective stress (σ_0') in the fill. On the horizontal axis, the magnitude of the applied repeated shear stress is also expressed as a percentage of the initial effective stress. It will be seen that in this particular case, 100 cycles of a shear stress equal to σ_0' caused the effective stress in the fill to fall to 15 per cent of its initial value. The effective stress (and hence the strength) did not fall to less than this, however, and the fill was in no danger of liquefying.

It is well established that dense particulate materials do not liquefy when subjected to seismic-type loading, but that materials of low density are prone to liquefaction. Tests such as those depicted in Fig. 14 should certainly be undertaken if a fill is likely to be subjected to shock loading, but the best guarantee against liquefaction is to ensure that the grading of the fill is such that the fill will settle into as dense a state as possible on being placed.

Conclusion

The density a fill attains on being placed is very important since it affects the subsequent compressibility, strength, and resistance to shock loading. The density attained by a fill material is very much a function of its grading, and the inclusion of cement fines may improve the grading of a fill material and hence increase its density and strength and decrease its compressibility.

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Professional development seminars

During the 1979-80 academic year McGill University will once again be offering professional development seminars in various aspects of mineral engineering, mineral management, and mineral economics. These seminars have been designed to meet the practical needs of the Canadian mineral industry and of mining organizations in developing countries.

Lectures, discussion groups, case studies, and workshops are conducted by the staff of McGill University with the assistance and co-operation of recognized authorities from government agencies, mining companies, independent consultants, and other universities.

The United Nations Centre for Natural Resources, Energy and Transport and the Canadian international Development Agency help in arranging the participation of personnel from developing countries.

The following seminars are offered:

Principles and practices of ground control, 5th to 17th November, 1979 (Seminar Leader: John E. Udd)

Extractive metallurgy of copper, 12th to 16th November, 1979 (Seminar Leader: W. G. Davenport)

Blasting systems, 19th to 23rd November, 1979 (Seminar Leader: R. R. MacLachlan)

Health and safety aspects of the mine environment, 21st to 25th January, 1980 (Seminar Leader: D. A. Trotter)

Quality of working life in the mineral industry, 28th January to 1st February, 1980 (Seminar Leader: T. E. Hawkins)

Union–management–employee relations in the mineral industry, 4th to 7th February, 1980 (Seminar Leader: T. E. Hawkins)

Geostatistical ore reserve estimation, 11th to 15th February, 1980 (Seminar Leaders: M. David and M. L. Bilodeau

Mineral investment decision techniques, 18th to 29th February, 1980 (Seminar Leader: B. W. Mackenzie)

Organizing for results in the mineral industry, 3rd to 7th March, 1980 (Seminar Leader: T. E. Hawkins)

The financing and implementation of mineral projects, 10th to 14th March, 1980 (Seminar Leader: P. Glenshaw)

The planning and execution of mineral development strategies, 17th to 21st March, 1980 (Seminar leader: P. M. T. White)

Mineral processing systems, 24th March to 3rd April, 1980 (Seminar Leader: J. A. Finch)

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Rock-handling techniques at Sishen iron-ore mine

by B. G. FORDYCE*, B.Sc. (Eng.) (Wits.), M.B.L. (S.A.) and
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SYNOPSIS

A description is given of the methods used in management planning, pit-equipment selection and maintenance-operator training, and formal organization of mining personnel.

SAMEVATTING

Die metodes van bestuursbeplanning, die keuring en instandhouding van groeftoerusting, operateursopleiding en die formele organisasiestruktuur van die mynbouafdeling, word bespreek.

Introduction

The production of iron ore at Sishen Mine began in June 1953, the ore being crushed and screened in a dry state. In 1961 a crushing and wet-screening plant was erected, and in 1963 the first heavy-medium beneficiation plant was commissioned.

The production of iron ore for the Sishen–Saldanha Export Project began in 1976 after considerable expansion of the pit equipment and facilities. An additional, improved heavy-medium beneficiation plant was also built. The maximum total output of these two plants, which supply lumpy and fine ore for domestic and export markets, is rated as 27 million tons per year.

Run-of-mine ore and waste rock are at present being mined at a rate of nearly 80 million tons per year.

Management Planning

Long and Medium-term Planning by the MPS[1]

Heavy reliance is now placed on a powerful computerized mine-planning system, MPS, which has been partially installed at Sishen. The ore-body is modelled as follows: drawn geological sections are digitized and link-point sets between sections are indicated; intermediate sections are interpolated linearly by the system; and hence a three-dimensional model of the ore body is constructed. Any section that is perpendicular to the survey co-ordinate system can be viewed on the graphics terminal or plotted on paper to the desired scale. Once these sections are checked by the geologists, pit design can commence.

Long and Medium-term Pit Planning

The most economic pit design is determined by use of the Lerchs–Grossman dynamic programming algorithm[2] constrained by the marginal volumetric instantaneous stripping ratio, the estimated maximum pit-slope angle, and the surface contours of the area.

This layout is typically unpractical, but, by means of the simplified interactiveness of the system, pit profiles are smoothed and haul roads inserted. The tonnages of ore produced from the final and optimum pit designs are then retrieved from the model of the ore-body. Part of the long-term pit plan is shown in Fig. 1.

*Iscor, P.O. Box 178, Durnacol, Natal.
**Iscor Thabazimbi, Transvaal.
†Maximum curve established by mining the pit level to final pit limits.

Outputs of the MPS

Besides pit plans drawn to desired scales, tonnages of ore and waste rock by level and by area are calculated. One of the most useful outputs is the determination of minimum and maximum† stripping curves[3] (Fig. 2). If the minimum curve is followed, the present value of the cost is minimized, but the pit equipment and service facilities must be continuously expanded. If the maximum curve is followed, the present value of the total production facilities is maximized, with a later redundancy of these facilities. An average stripping policy ensures at least stable production facilities over the life of the pit, which is advantageous to management control.

Roads and Declines (Ramps)

The main pit roads, which are 30 m wide, usually have a slope of 1 in 15, with a maximum slope of 1 in 12 in special circumstances. Safety berms are built by the tipping of waste rock on the cliff side of these roads (see Fig. 7).

Access roads are built for the pit electrical-distribution network and the pit dewatering pipelines.

Declines are normally 50 m wide, with a minimum width of 30 m.

Waste Dumps

The first priority is that the waste dumps must be as close as possible to the pit for minimum haulage distances, waste-rock dump and pit-wall stability and drainage having been taken into account. Dumps are built at present in 20 m slices with a maximum height of 60 m.

Medium-term Planning

Forecasts of ore sales are periodically reviewed, and this information is used in the scheduling of ore and waste-rock production according to the objective of minimizing costs, constrained by the present stripping-ratio policy and the ore specifications, which require blending of the ore from several areas. These decisions are carried over to 1 in 5000 scale plans, where priority areas are indicated and ranked.

Short-term Planning

The object of the short-term planning is to translate the medium-term plan into weekly and daily plans so that the production objectives are realized efficiently