Cemented Tailings Fill for Mining Excavations

Résidus aux Ciments Utilisés à Remblayer des Excavations Minières

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SYNOPSIS *The hydraulic filling of stopes in deep gold mines with pumped ore tailings is an attractive proposition as a means of controlling convergence of the stopes and absorbing energy released from the surrounding rock.*

The paper reports on an investigation of the strength and deformation properties of pumpable tailings slurries with water contents of up to 55 per cent. The slurries were stabilized with the equivalent of 10 per cent of cement. This results in a material that, initially, is a pumpable slurry, but which solidifies to a low strength solid soon after placing. If the solidified material is compressed at a rate slow enough to allow of consolidation, useful strengths are developed, the compressed material behaving as if purely frictional.

In practice, the cement stabilized slurry will be pumped into mined-out stopes to form slabs of filling. Tests on geometrically similar model slabs showed that triaxial constraint caused by friction on the upper and lower surfaces of the slab is sufficiently large to enable the model slabs to support a vertical stress of more than 70 MPa (equivalent to an overburden of 3 000 m of rock). The compression and energy absorption of the material under this stress compares favourably with that of a compacted rock fill.

Prototype full-scale stope fillings have been successfully pumped into place underground (at a depth of 1 900 m below surface) and these appear to function as predicted from the model tests.

INTRODUCTION

In the deep South African gold mines the gold bearing reef occurs as a thin sheet or table of rock which is often no more than 75 to 100 mm thick and may dip at any angle between 0° and 90°. The ore is mined by driving headings or gullies into the country rock in the direction of the reef and then cross-connecting the gullies by means of tabular excavations or stopes which remove all of the gold-bearing ore. The type of excavation which results is illustrated diagrammatically in Figure 1. The initial height of the stopes is kept to the absolute minimum necessary to provide working space and is usually about 1 m.

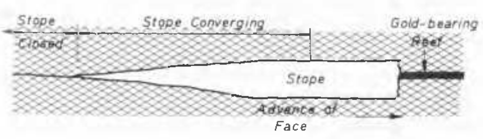

Figure 1: Diagram of tabular mining excavation (horizontal scale compressed).

As mining progresses in the direction of the reef, the stopes converge under the tremendous rock overburden pressures (up to 100 MPa in mines with workings at a depth of 3 500 m); a typical stope closure rate being 100 mm/month.

Closure of stopes has traditionally been controlled by means of timber grillage supports or 'mat packs' which are progressively compressed as the stope closes. The use of timber for this purpose has many disadvantages:

(i) An excessive amount of labour is required to handle the timber and its transport occupies valuable shaft time and causes congestion of haulages and crosscuts.

(ii) The large quantities of timber left in place underground constitute a fire hazard.

(iii) Ventilation of the underground working space is difficult to control because of the large open spaces between the packs.

(iv) Timber is a valuable natural product which can be better used for other purposes.

The hydraulic filling of mines using pumped ore tailings has been adopted elsewhere in the world during the past quarter century and various authors (Espley et al.(1970) Thomas (1971), Waterfield (1973), Johnson and Gisler and Worotnicki et al. (1975)), describe the benefits (all applicable to South African conditions) of using this method of support:

(i) Labour requirements are reduced as the slurry can be pumped to the workings from a central mixing and pumping plant.
(ii) Fire hazards are reduced.
(iii) Ventilation control is facilitated.
(iv) Morale is improved as a hydraulically filled stope looks and is safer than one supported by timber. The hanging wall is more uniformly supported and stress concentrations are reduced.
(v) Expensive timber requirements are reduced.
(vi) Large quantities of mining waste are disposed of underground.

An additional advantage not mentioned above, is that compression of the fill absorbs energy released from the rock in the vicinity of the filled stope.

Hydraulic filling has not been used in South African mines until now. The reasons for this appear to be:

(a) Gold mine tailings are extremely fine (see Table 1) and slow draining c_v = 20 to 40 m^2/month). Hence it has been assumed that pumped tailings would not solidify before stope convergence began to apply pressure to the fill. This assumption appears correct, but a cementing agent can be used to partially solidify the slurry without any drainage occurring.
(b) Because of the need to maintain communication past filled stopes, fill must be retained while in a liquid state. This has not been considered feasible.
(c) There has been a fear of "mud-rushes" should retained fill break away while still liquid or if re-liquified by vibration from blasting or seismic shock.

A close examination of these objections revealed that most of them could be overcome and this paper will describe the methods and materials to do this.

2. CHARACTERISTICS REQUIRED OF FILL IN UNDERGROUND EXCAVATIONS

When an unsupported excavation is made in a mass of stressed rock, energy is released from the destressed rock surrounding the excavation and, if the excavation does not fail, the released energy is redistributed and stored as strain energy in highly stressed zones at the perimeter of the excavation. If, however, partial failure occurs, part of the released energy continues to be stored as strain energy in the unfailed rock and part is consumed as energy of fracture. Figure 2a illustrates the energy balance diagrammatically. σ_v is the average virgin rock stress and V_o is the volumetric convergence of the excavation. U_R is the energy released by the excavation and U_S is the energy stored in the surrounding rock. If no fracture occurs around the excavation, $U_S = U_R$. If fracture does occur, the stored energy is reduced by U_F, the energy of fracture. In the case of a catastrophic failure of the excavation the entire stored energy is converted into fracture energy and $U_F = U_R$.

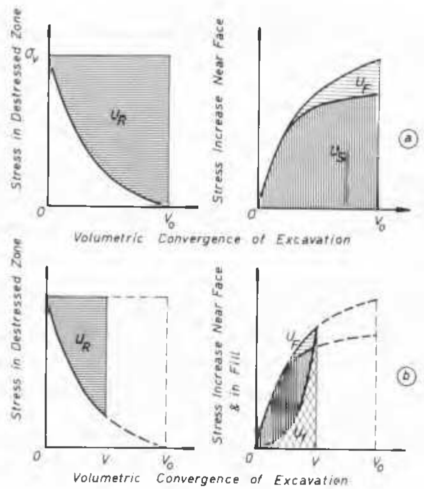

Figure 2: (a) Energy balance for an unfilled mining excavation.
(b) Energy balance for a filled mining excavation.

If the excavation is filled with a compressible medium, part of the released energy is absorbed in compressing the fill. The energy absorbed by the fill is represented by U_f in Figure 2b and for conservation of energy, $U_R = U_S+U_f+U_F$. Because filling reduces the volumetric convergence of the excavation from V_o to V, the released, stored and fracture energies are less for a filled excavation and the potential for catastrophic failure is reduced. It is obvious from Figure 2b that the more incompressible the fill, the smaller will be V, the larger will be U_f and the more favourable will be the support conditions achieved. The best practicable fill would appear to be one of broken rock either hand packed or mechanically compacted into place to give a dense incompressible fill. Such an ideal fill suffers from the disadvantage of high placement cost.

In the present study, it was decided to investigate the use of a pumped slurry. The advantages of this approach are that:

(i) Little labour is required to transport the fill and place it.

(ii) A cementing agent must be used to produce initial solidification of the fill: the cement is not relied on to provide structural strength but only to gel the fill while it consolidates and gains strength as the excavation converges. Hence low percentages of a cheap cement can be used.

To offset these advantages there are the following disadvantages:

(i) Temporary structures must be provided to retain the liquid slurry.

(ii) Volumetric convergence of the excavation is relatively large (the theoretical maximum convergence is equal to the porosity of the slurry).

As the results of the investigation will show, cemented slurry fills perform surprisingly well, even in comparison with materials such as broken rock.

3. CEMENTING AGENTS

The monthly tonnage milled by a typical large gold mine is about 200 000 tonnes of ore. This tonnage would occupy a solid rock volume of 75 000 m^3. The mass of dry solids to provide this volume is about 75 000 tonnes which, at a cement content of 10 per cent, would require about 7 500 tonnes of cement per month. This represents $1\frac{1}{4}$ per cent of South Africa's current total monthly production of Portland cement. It is therefore obvious that the adoption of slurry filling on a large scale, could place a strain on the cement industry. To reduce the demand for cement the use of cement-flyash (i.e. pulverised fuel ash), lime-flyash and gypsum-lime-flyash mixtures has been investigated. Flyash and gypsum are both waste products in plentiful supply and their use can considerably relieve the strain on available supplies of Portland cement and building lime. As the paper will show, these cheap cementing agents prove quite adequate in providing the initial strength required in a slurry fill.

4. SHEAR STRENGTH PROPERTIES OF CEMENTED SLURRIES

Two typical gold mine tailings were selected for the present study. The particle size analyses for these two materials (tailings 1 and 2) are summarized in Table 1.

For tailings 1 a water content of 55 per cent was required to give a pumpable slurry,

TABLE 1

Particle Size Distribution of Tailings

	Mass Per Cent Finer	
Particle Size (mm)	Tailings 1	Tailings 2
0,2	99	91
0,06	67	25
0,02	41	10
0,006	20	4
0,002	9	2

while for tailings 2 the water content requirement was 35 per cent. These water contents correspond to theoretical maximum stope convergences of 59 per cent for tailings 1 and 48 per cent for tailings 2.

Basic shear strength properties were measured by means of drained triaxial shear tests on 38 mm diameter specimens of cemented slurry. Shearing was started after a period of 7 days of curing at a constant water content. A subsidiary investigation showed that curing for longer than 7 days had a negligible effect on strength properties. At 7 days the specimens could be handled but were very weak. Unstabilized specimens, however, remained liquid after a similar period. The results of a selection of these tests are shown in Figure 3 and a tabular comparison of the shear properties of cemented slurries is given in Table 2.

It appears from this comparison that:

(a) both tailings behave as if highly frictional when cemented and show little or no cohesion;

(b) the coarser material (tailings 2) at a lower water content is considerably superior to the finer, higher water content tailings 1; and

(c) cementing agents consisting of cement: flyash mixtures can give results comparable to those produced by ordinary Portland cement;

(d) increasing the content of cementing agent (e.g. material C) can considerably improve the properties of a cemented slurry.

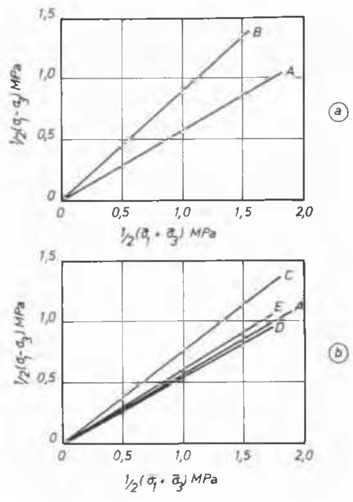

Figure 3: *(a) Shear strength characteristics of materials A and B-see Table 2.*
(b) Shear strength characteristics of materials A, C, D and E - see Table 2.

TABLE 2

Comparison of Results of Drained Triaxial Shear Tests on Cemented Slurries

Tailings	Initial Water Content	Proportions of Solids by mass	Strength Parameters $\bar{c}$	$\bar{\phi}$	Material
1	55%	1:10 cement:tailings	0	35°	A
		1:3:15 cement:flyash: tailings	0	49°	C
		1:2:15 lime:flyash: tailings	0	33°	D
		0,2:0,8:2:15 gypsum:lime: flyash:tailings	0	38°	E
2	35%	1:10 cement:tailings	0	62°	B

5. TESTS ON MODEL STOPE FILLINGS

The behaviour of cemented slurry fills in tabular excavations was simulated in the laboratory by compressing flat slabs of material having initial dimensions of 180 mm square in plan and 30 mm in thickness. These dimensions are geometrically similar to the proportions of a typical stope. Slabs having other proportions were also tested (eg 90mm x 180mm x 30mm). The results of these tests were similar to those reported here.

The slabs were compressed between parallel platens lined with layers of filter paper to provide top and bottom drainage and the rate of compression was kept sufficiently slow to ensure fully drained conditions in the compressed slab. The edges of the slab were completely unconfined.

Figure 4 shows the load-compression characteristics of slabs of materials A, B, C, D and E (Table 2). As a standard of comparison, Figures 4a and 4b each include a curve (S)* for the compression of a model fill consisting of broken rock particles. The compression curves for the model slabs retain the same relative positions as the corresponding strength curves in Figure 3, showing that the resistance of the slabs to compression is directly related to their shear strength. As Figure 4c shows there is an inverse relationship between tan $\bar{\phi}$ for Tailings 1 and the convergence at a particular stress. However the resistance of the slabs to compression is apparently not a function of shear strength only but depends also on other variables such as volume compressibility. A limited series of tests showed that placement water content has an important influence on the compression characteristics of slabs.

* This curve is similar to one quoted by Jaeger and Cook (1969).

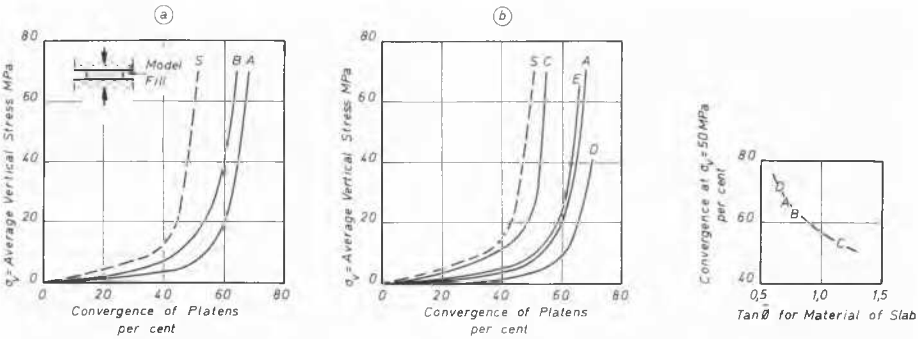

Figure 4: (a) Stress-convergence curves for model fills of broken rock (S) and materials A and B.
(b) Stress-convergence curves for model fills of broken rock (S) and materials A, C, D and E.
(c) Relationship between stress-convergence characteristics and tan $\bar{\phi}$ for materials A, C, D and E.

The model test results represented by Figure 4 indicate that the compression resistance of full scale fills of cemented slurry should compare favourably with that of fills of broken rock, especially if the content of cementing agent is as high as about 25% (eg Material C). Flyash is not used as a pozzolan in South Africa at present, and can be obtained for the cost of its transport. This means that a 1:3:15, cement:flyash: tailings slurry (C) should cost no more than a 1:10 cement:tailings slurry (A), yet will have a considerably better compression characteristic.

6. THE EFFECT OF LATERAL CONFINEMENT ON LOAD-COMPRESSION CHARACTERISTICS OF SLABS

A lateral spreading of the loaded material occurs during compression of a model fill and it is obvious that any means of confining the lateral spread will enhance the load-compression characteristics of the fill*. For this reason a number of tests were performed to explore the effects of lateral confinement

Virtually complete confinement was achieved by casting the slabs in moulds made of a continuous strip of 1 mm thick mild steel. The slabs were compressed by means of a plunger that neatly fitted the internal dimensions of the mould. During compression, strains in the steel strip were monitored by means of electric resistance strain gauges. The strains in the strip proved to

*The lateral spread of the slabs accounts for the fact that actual maximum convergences shown in Figure 4 exceed the theoretical maxima mentioned in Section 4.

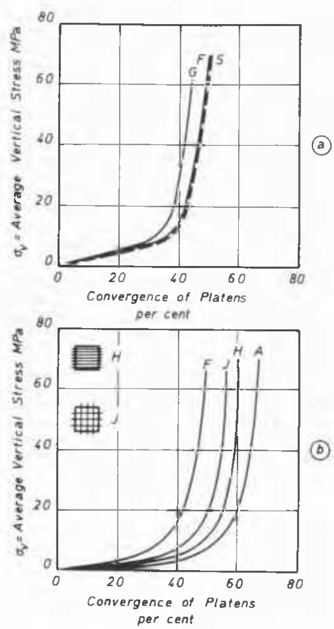

Figure 5: (a) Stress-convergence curves for confined model fills of materials A and B (curves F and G)and unconfined broken rock fill. (b) Stress-convergence curves for reinforced model fills of material A(curves J and H), unconfined fill of A (curve A) and confined fill of A (curve F).

be consistently one hundredth of the vertical compression so that for all practical purposes the slabs were completely laterally confined. The load-compression curves for these tests are shown in Figure 5a. Curve F corresponds to a confined slab of material A and Curve G to one of material B. The compression characteristics of the two confined slabs are compared with curve S (broken rock fill) of Figure 4. It will be seen that complete confinement results in characteristics that can be superior to those of an unconfined broken rock fill. The superiority of tailings 2 over tailings 1 is again evident.

The mild steel confining strips yielded at a convergence of about 10 per cent and thereafter the lateral confining stress must have remained virtually constant. An approximate calculation shows that the lateral confining stress once the strip had yielded was about 3 MPa. This is only a small proportion of the vertical stress, but nevertheless an impossibly large confining stress to achieve in practice on the perimeter of a full-scale fill. A condition of complete confinement would, of course, obtain over most of the area of a fill of large area extent.

Less complete but effective confinement can be induced by reinforcing the fill by means of steel rods or cables running parallel to the median plane of the slab. Figure 5b shows the effect of reinforcing model slabs of material A with 1,65 mm diameter mild steel wires. For curve H the wires were aligned in one direction only to give a reinforcing area of 0,24 per cent of the original cross-sectional area of the slab. For curve J the wires were aligned in two directions at right angles to give a reinforcing area of 0,12 per cent in each direction. The slabs were tested with unconfined edges so that the improvement in load-compression characteristics is entirely due to the confining effect of the reinforcing. As Figure 5b shows, even this small proportion of reinforcing was sufficient, significantly to improve the load compression characteristics of the slabs. It is also clear that two-way reinforcing is considerably more effective than one-way reinforcing. In practice it would be possible to reinforce slurry fills by lacing scrap wire rope through the area to be filled prior to filling.

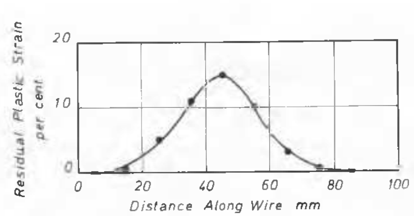

Figure 5(c) Distribution of residual plastic strain in a reinforcing wire.

It is interesting to note that in a compression test on a reinforced slab, sufficient bond stress is developed to yield the reinforcing. Figure 5c, for instance shows the distribution of residual plastic strain along a wire used to reinforce a slab measuring 180 mm x 90 mm in plan. (The wire ran in the 90 mm direction). This strain distribution also gives some idea of the complex distribution of stress in the model slabs. It is worth noting that the bond length required to develop yield in the wires appears to be less than 10 mm or 6 diameters.

7. A COMPARISON OF ENERGY ABSORBED BY FILLS OF VARIOUS MATERIALS

The energy absorbed by each of the model fills (S and A to J) up to a convergence of 50 per cent is shown in Table 3 both in absolute terms as well as relative to the performance of slab S. The information given in Table 3 quantifies the qualitative assessment of the relative merits of the various fills given in sections 5, 6 and 7 of this paper.

Accordingly to Cook et al. (1972) the energy released from the rock surrounding an idealized longwall stope at a depth of 1 500 m after a convergence of 500 mm is 18 MJ/m^3 for a stoping width of 1 m. Hence for an excavation with an initial height of 1 m, a broken rock fill will absorb only 25% of the energy released. It would obviously be advantageous to increase this percentage and research presently in hand is aimed at achieving this.

TABLE 3

Comparison of Energy Absorbed by Various Fills up to a Convergence of 50 per cent

Fill of Material	Energy Absorbed MJ/m^3	Energy Absorbed as % of Absorption by Fill S
S	4,45	100
A	0,85	19
B	2,10	47
C	3,50	79
D	0,60	13
E	1,60	36
F	6,10	137
G	9,35	210
H	1,80	40
J	2,30	52

8. THE POSSIBILITY OF LIQUIFACTION OF CEMENTED SLURRIES

In the introduction, reference was made to the possibility of "mud rushes" should the cemented fill become liquified after placing. Even if the fill did re-liquify, there would be no danger of a mud rush provided the structure used to retain the slurry during placing remained intact as convergence of the stopes progressed. This can easily be ensured by using a highly flexible retaining structure.

The propensity of a cemented slurry to liquify was investigated by means of a limited series of cyclic undrained triaxial shear tests. In a typical test of this series, specimens of materials A and B were consolidated to an effective stress of 0,5 MPa and then subjected to an undrained cyclic shear stress equal to half the static shear strength of the material. The decrease in effective stress as the number of shear stress applications was increased is shown in Figure 6. Even though only 20 cycles of shearing were applied, it is clear from the results that under the conditions of these tests material A could be expected to liquify after about 100 cycles of shearing, while material B appeared unlikely to liquify. This comparison again highlights the desirability of using as coarse a fill as possible, thus keeping water contents to a minimum.

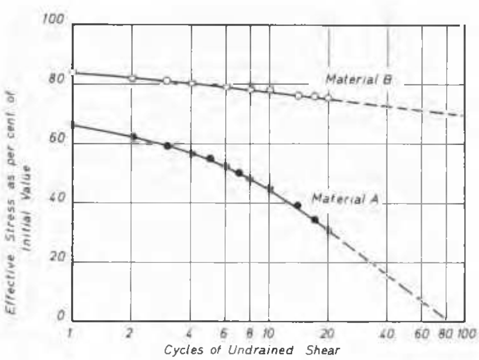

Figure 6: Effect of undrained cyclic shear on materials A and B.

9. AN EXPERIMENTAL FILLED STOPE

To prove the possibility of using a pumped cemented slurry as underground fill, a prototype experimental fill was pumped into place in a stope at a depth of 1 900 m below surface. The retaining structure was made of a pervious woven polypropylene cloth glued to the footwall and hanging of the stope. The polypropylene cloth was further supported by means of wire fencing mesh spanning between vertical wooden poles at 1 m centres. As the depth of slurry to be retained was only 1 m, it was probably unnecessary to use the fencing mesh. When the fill was placed the working face was 4 m from the fill. In order to study the worst conditions likely to occur in practice the enclosure was filled with material A.

The prototype fill was inspected 6 weeks after placing at which time a convergence of 10 per cent had taken place. At this time the working face was 8 m from the fill and blasting had produced no visible effect. Vane shear tests made horizontally into the fill showed that the vertical stress in the cemented slurry was of the order of 0,4 MPa. Figure 7, a photograph of the prototype fill, taken after 3 months at a convergence of 33% shows the retaining mesh intact even though the edges of the fill have developed a considerable bulge. The face was 25 m away from the fill at this stage.

10. CONCLUSIONS

The laboratory investigation and the subsequent prototype field test have shown that pumped cemented slurries can be successfully used as fill for mining excavations. The following important conclusions have emerged from the investigation:

(i) As coarse a material as possible should be used as fill. Coarse material requires less water to form a pumpable slurry and, when cemented, has superior shear strength characteristics.

(ii) Cementing agents consisting of cement:flyash and gypsum:lime: flyash mixtures can give results equal to or superior to those produced by more expensive ordinary Portland cement.

(iii) If sufficient cementing agent is used, a pumped cemented slurry fill can be almost as effective as a hand-placed broken rock fill.

(iv) Lateral confinement of a fill considerably improves its load-compression characteristics. Two-way reinforcement of fills using wire rope scrap appears to offer a feasible way of providing lateral confinement in practice.

(v) If reliquifaction of a cemented fill is likely to cause problems, coarser materials have been shown to be less susceptible to liquifaction than fine materials.

Figure 7: Appearance of prototype filled stope at convergence of 33 per cent.

11. ACKNOWLEDGEMENTS

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