PROPERTIES OF WEAKLY CEMENTED SLURRIES

OF GOLD MINE SLIMES

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DECLARATION BY CANDIDATE

I, Derek Luigi Avalle, hereby declare that the work presented in this dissertation is my own and that it has not been submitted for a degree of another university.

March 1976

ABSTRACT

The problem investigated relates to the application of stabilised slimes as a load-bearing material in mining stopes. Literature on overseas research, practice and experience was consulted. Various methods and types of applications of pumped cemented and uncemented hydraulic fill are used overseas, and their research programs were reviewed.

The major test program concerned itself with strength development properties of the material under compression. Two types of slimes were tested, but more attention was paid to the finer silty slimes which proved to be a less favourable material than the coarser more sandy slimes.

Ordinary Portland cement was adopted as a standard additive and in a standard proportion with the slimes. Seeing that the material will be pumped to its final position, the moisture contents used were the estimated minimum proportion of water required for pumpability. Cement-flyash, lime-flyash and gypsum-lime-flyash mixes were also tested as cementing agents.

Shear strength envelopes were plotted for the various mixes. Compression tests modelling stope conditions were conducted on unreinforced slabs of material, slabs with wire reinforcement and mould-restrained slabs. The effects on strength development of different additives, moisture content, particle size distribution and partial and full lateral restraint were investigated. Cyclic loading triaxial tests were conducted to investigate the possibility of the occurrence of liquefaction of the material due to vibrations caused by blasting.

The results indicate the benefit of the coarser material : it requires a lower moisture content for pumping, it exhibits improved shear properties and liquefaction failure is less likely to occur. Cementing agents were shown to improve shear strength and strength development properties, even in the case of a fully-restrained slab. Cement-flyash and gypsum-lime-flyash as additives appear to give favourable and economic results.

Lateral restraint is important to strength development, and the inclusion of even small area proportions of reinforcement show markedly improved strength development properties. Full lateral restraint produces pronounced strength improvements, but theoretical considerations show lateral pressure development to be substantial.

The practical application of weakly cemented hydraulic backfill to South African gold mines appears to be feasible and has many advantages including the economical and useful mass disposal of waste products.

ACKNOWLEDGEMENTS

I wish to thank the Management of Stilfontein Gold Mine for permission to publish the results of tests conducted on their behalf; in particular, I wish to thank Mr. R. More O'Farrell for the interest he showed throughout the project. Thanks are due to Messrs. Rodio (S.A.)(Pty) Ltd. for providing field test results.

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1. INTRODUCTION

1.1 Hydraulic Fill Practice Overseas

The practice of pumping cemented and uncemented hydraulic fill into mine workings to form a permanent support has been adopted in a number of overseas countries, including Canada and Australia. The technology appears to have originated in Canada about twenty-five years ago[1], and cement stabilised hydraulic fill has been used at Mount Isa, Australia, for about twelve years[2].

Various authors [1,2,3,4] describe the practical benefits to be derived from the use of pumped cemented or un-cemented hydraulic fill:

a) the traditional expensive timber requirements are reduced;

b) provision is made for underground disposal of large quantities of mining waste product;

c) roof and wall failures in stopes are minimised as the fill resists the forces causing movement;

d) induced stresses in the abutments are reduced by the resistance of the fill to loads transferred by wall closure;

e) ventilation control is facilitated;

f) productivity is increased by allowing higher mechanisation;

g) morale is improved through increased safety, for example improved control of rock bursts and subsidence, and the reduction of fire hazard;

h) fill can be deposited concurrently with mining operations;

i) costs are reduced and ore extraction is speedier because of the ready availability of the material at the mine site, the low cost of the product, and the use of cheap methods of placement in the stopes.

Johnson and Gisler[4] describe three important disadvantages resulting from the large amounts of water required for pumping the fill:

a) there is an increased volume of water to be pumped out of the mine;

b) fill material that might be washed or slushed into haulage ways or ditches can cause problems;

c) if the water-placed material does not drain adequately, due to poor percolation rates or permeability, or through lack of drainage facilities, it might retain the nature of a liquid for a long period after placing.

1.2 Findings and Research on Cemented Fill

Espley, Beattie and Pasieka[1] describe how, in Canada, cemented hydraulic backfill, consisting of normal Portland cement and classified (de-slimed) mill tailings, is mixed in various proportions to form a high-density slurry which is transferred underground through a gravity system of boreholes and pipes. Moisture contents are maintained at between 39% and 47% during transfer. The backfill is allowed to consolidate and the water is drained off. Without detailing figures and results, they state that: strength characteristics are primarily dependent on cement content, moisture content and age; particle size distribution influences strength; chemical and physical properties of different cements have only minor effects on strength characteristics; and acid mine water appears to have no harmful effect on this type of cemented backfill.

Thomas[2] describes the use of hydraulic fill, cemented and uncemented, in various Australian Mines. He also describes recent research on cemented fill, the main objective of this research being to produce a cemented fill at reduced cost by reducing the amount of Portland cement used in the mix. Attempts were made to use locally available materials, either alone or in combination with one another or Portland cement. The test program was designed to determine trends of strength development with curing time and cement content.

Moisture contents and void ratios were measured, as strength development was expected to improve with the reduction in both. Thomas' results are summarised in Fig. 1. The curves show the relationship between compressive strength and moisture content (Fig. 1a), and between compressive strength and void ratio (Fig. 1b), after a 7 day curing period. These results emphasize that strength is very dependent on moisture content and void ratio, and that every effort must be made to reduce placement moisture contents in hydraulic fill to a minimum. Regarding stabilising agents, favourable results were obtained using power station flyash (PFA) with Portland cement: when moist PFA (or any moist pozzolanic material) is mixed with Portland cement (or any source of free lime), it reacts with the free lime produced by hydration of the cement to form secondary cementitious compounds; the mixture is strengthened by these secondary cements, and also by the removal of the weakening effect of free calcium hydroxide. The use of PFA with Portland cement allows a reduction in cement content for equivalent strengths and reduces the quantities and rates of production of heat of hydration. Laboratory test work concluded that 20% by mass of Portland cement could be replaced by PFA, giving a net saving of 10% on costs. Thomas also reported that copper reverberatory furnace slag (CRFS), a waste product of the copper smelting operation, can result in major cost reductions by replacing Portland cement either partially or fully.

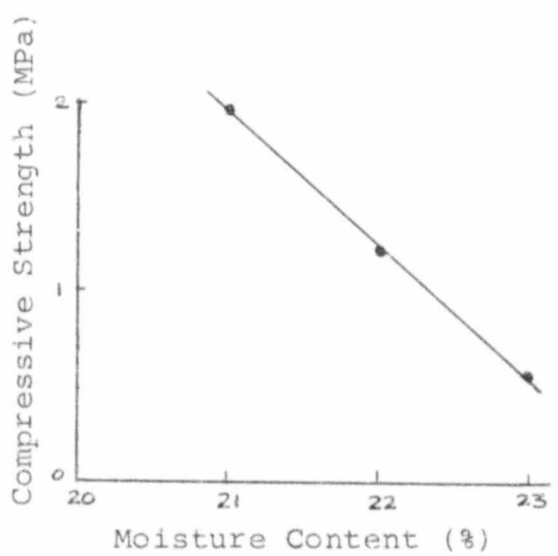


Fig. 1a   Relationship with Moisture Content

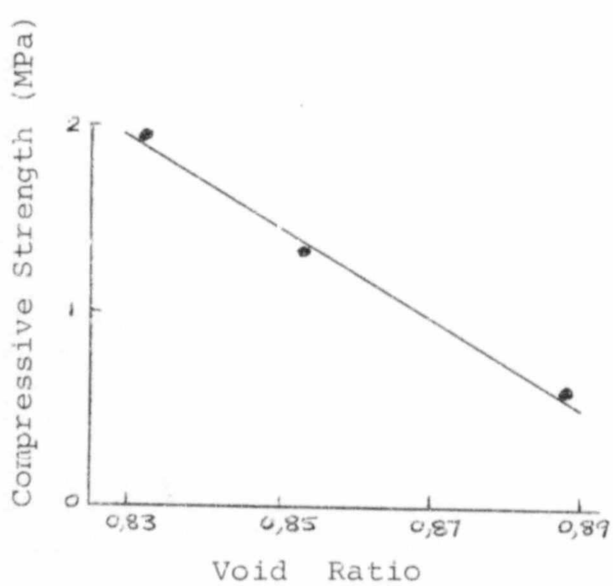


Fig. 1b   Relationship with Void Ratio

Fig. 1   Compressive Strength Relationships with Moisture Content and Void Ratio[2]

Waterfield[3] describes the use in Canada of cyclones for the classification of mine tailings, mainly to improve permeability. He notes that classified hydraulic tailings fill can be prepared, delivered and placed underground at lower cost than any other comparable fill material, but is unable to support its own weight over considerable "unsupported heights". The term "unsupported heights" is not very clearly defined but it appears to refer to the stable slope height of dumped material. Stabilisation of the fill using small percentages of Portland cement (around 5% by mass of tailings) proved to be an economical procedure for providing stability and the stable "unsupported heights" improve about two-fold to about 35 m. Moisture contents should be kept as low as possible, and values of between 43% and 54% were found to be satisfactory. Waterfield calls for research to assess the feasibility of using cheaper cementing agents, especially lime.

Weaver and Luka[5] discuss laboratory studies on cement-stabilised mine tailings. Test data was collected over about ten years, during which time the technology was introduced at many Canadian mines. The investigation covered numerous conditions and variables affecting cement-stabilised tailings, such as curing time, pulp density (ratio of solids to total mass), ratio of cement to tailings, cement fineness, cement type, incorporation of flyash, the grading of the tailings, use of flocculants, effects of minewater, durability, effects of sulphides, moisture content of stabilised backfill and curing temperature. Conclusions from their research were as follows:

a) Cement-stabilised backfill achieves a compressive strength resistance which increased with time. Fig. 2 shows the effects of the mix ratio and of curing time on compressive strength, and it can be seen that the lower the cement content the less is strength development affected by curing time;

b) Substantial strength increases were recorded for high pulp densities, as shown in Fig. 3. Another benefit of increased pulp density is the smaller amount of water draining from the fill which in turn can result in less fines and cement being washed into the drainage system;

c) The higher the cement content, the higher the strength. This is seen in Fig. 2, and the rising curve of compressive strength versus cement content is shown in Fig. 4;

d) The fineness of the cement can affect the strength. Strengths were found to decrease with finer cements, due to fine particles being carried off in suspension, as well as with coarser

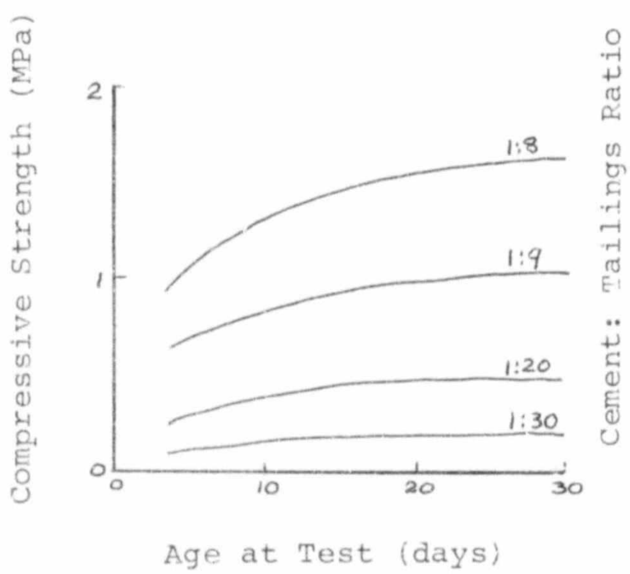


Fig. 2 Effect of Cement Content and Curing Time on Strength[5]

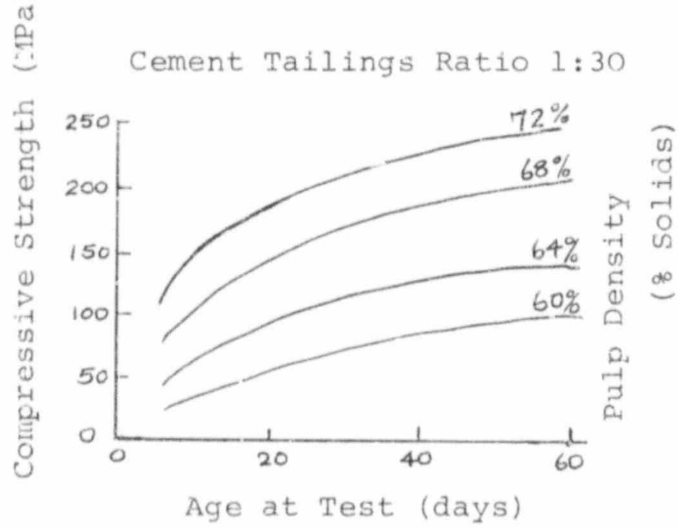


Fig. 3 Effect of Pulp Density on Strength[5]

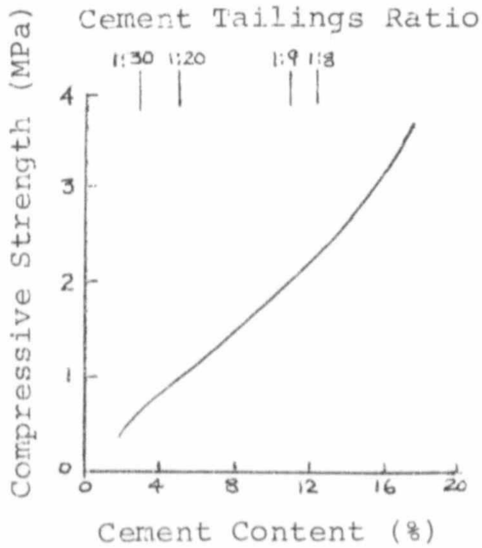
cements, due to the coarse particles being slow to hydrate. An optimum cement fineness with respect to strength was reported to be in the range of 2 500 to 3 500 cm^2/g as measured by the Blaine apparatus;

e) Different cement types only show pronounced effects on strength in mixes with high cement contents. Very little effect was found on a 1:20 cement:tailings mix;

f) Local flyash, being readily available at low cost, was investigated as a pozzolan for partial replacement of cement. Mixes were made with 10% and 20% of the cement replaced with flyash, intermixed or interground. Intergrinding was found to give slight strength advantages over intermixing. Mixes with smaller percentages of additive (1:20 and 1:30 additive:tailings mixes) were found to give a serious loss of strength at early ages (14 to 28 days) even with only 10% flyash, and this strength loss is not recovered at later stages. In mixes with a larger additive content (1:8 additive:tailings) good strengths were achieved even with 20% flyash;

g) Tests were carried out on tailings samples of different size gradations, the difference obtained by classification of either or both the fine and the coarse fractions. Fig. 5 shows the test results, and it is seen that the best strengths are obtained from the material with the fines fraction removed;

h) The use of flocculants was found to assist in reducing the amount of fine material carried off by the water. The effect on compressive strength was not substantial and was largely dependent on agitation times. Percolation rates were improved in all tests;



68% Pulp Density

Fig. 4 Effect of Cement Content on Strength[5]

1. Unclassified
2. Coarse fraction removed
3. Coarse and fine fractions removed
4. Fine fractions removed

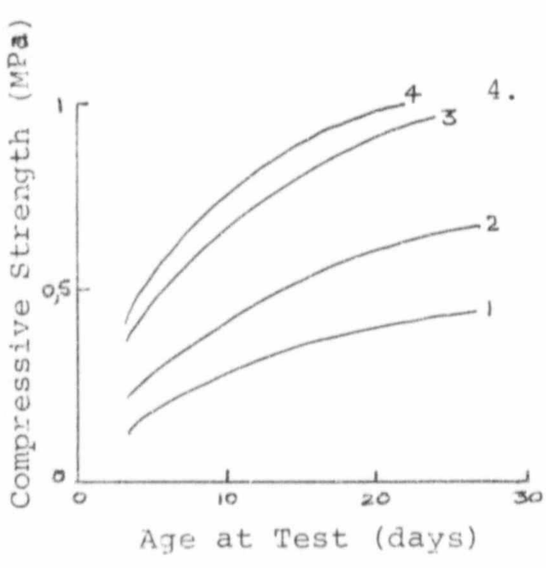


Fig. 5 Effect of Particle Size Distribution on Strength[5]

i) Mine water having a pH of 10,1 gave higher strengths than neutral mixing water when used in 1:6 and 1:20 mixes. However, testing the effects of alkaline mine water is recommended for each practical application;

j) The leaching effect of acid mine water on a 1:30 cement:tailings mix was found to reduce strengths very slightly. Mixes with higher cement contents exposed for up to 21 months to water with variations in pH from 4,4 to 8,6 and sulphate contents from 800 to 12 500 ppm showed excellent durability;

k) Triaxial tests were conducted on two types of tailings with varying cement contents and curing times. Cohesive strength was found to increase with cement content and age. No definite relationship was observed for the angle of shearing resistance;

l) The free moisture remaining in the specimens after curing was found to have direct bearing on compressive strength. Proper moist-curing at high humidity was ceased after 85 days, and for an additional 5 days specimens were cured under different humidity conditions to achieve lower moisture contents at the time of the test. Results of triaxial tests on the samples at various cell pressures are shown in Fig. 6 and it can be seen that compressive strength gradually increases with decreasing moisture content;

m) a curing temperature of 10°C was found to give the best strengths at all ages compared with 23°C and 30°C for mixes of 1:20 cement:tailings ratio. Although this phenomenon is described as "consistent with concrete technology", it does not appear to be consistent with the concept of concrete maturity* which shows that concrete strengths increase with increasing ambient temperatures.

McDowell[6] discusses stabilisation with lime and lime-flyash, outlining the history of the process and briefly describing its effects on the physical characteristics of soils. He states that the treatment of granular soils not reacting well with lime alone can be enhanced by the addition of flyash.

* A.M. Neville. Properties of Concrete, pp.249 and 258

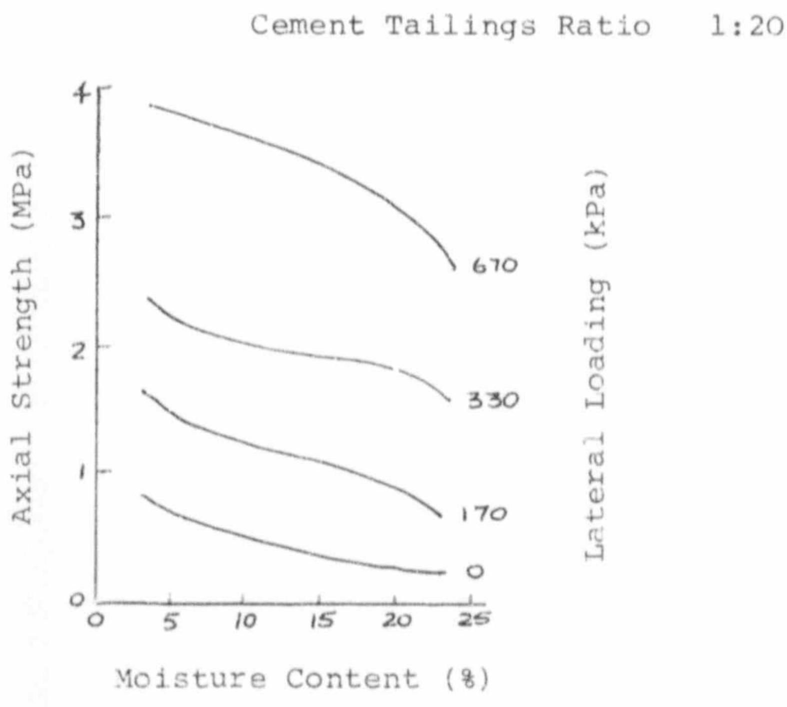


Fig. 6 Effect of Moisture Content on Strength[5]

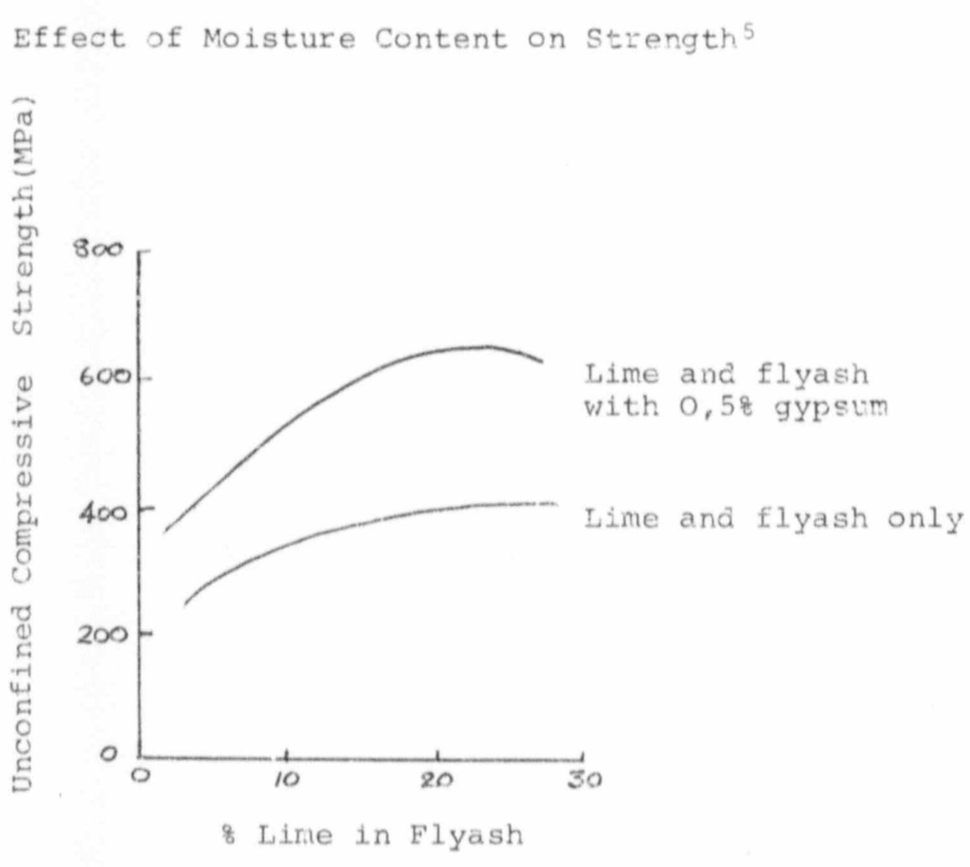
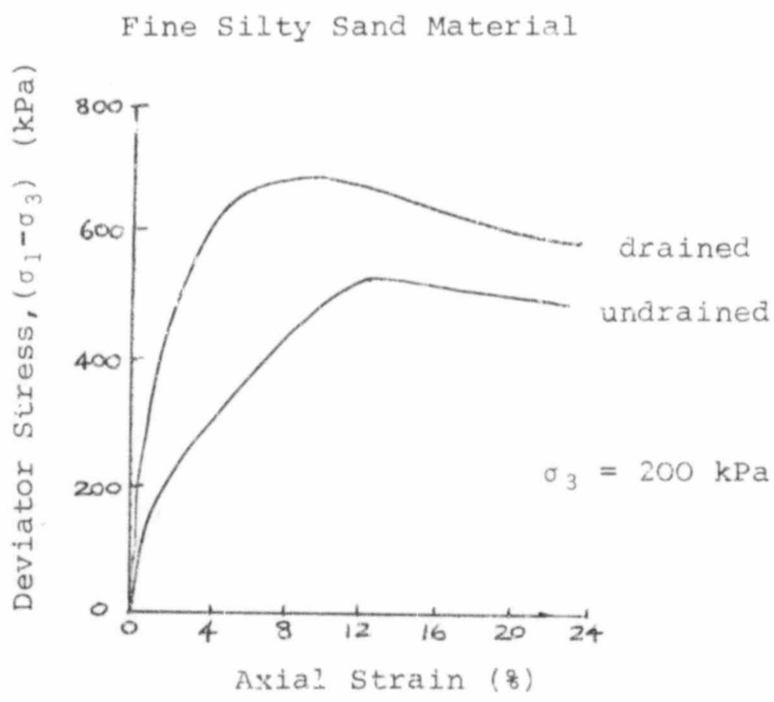


Fig. 7 Effect of Gypsum on Lime-Flyash Mixes[7]

Beckwith and Schnuir[7] conducted unconfined compressive tests on samples of flyash stabilised with various percentages (by mass) of lime. They repeated these tests with the inclusion of 0,5% of phospho-gypsum and their results are shown in Fig. 7. Remarkable strength increases are evident with the inclusion of a small amount of gypsum.

1 3. Liquefaction of Soils under Cyclic Loading

The triaxial testing of soils from an hydraulic fill dam in Canada is described by Lee et al[8]. Drained and undrained triaxial tests were conducted on isotropically consolidated samples in order to determine the properties of the hydraulic fill. The specimens exhibited a dilation tendency at failure, as can be seen in Fig. 8. Strengths under cyclic loading (which could result, for example, from earthquakes) were measured using cyclic triaxial tests, the results of which were corrected to correlate the uniform laboratory cycling with a typical erratic earthquake shear stress history. The cyclic tests produced liquefaction failures which were contrary to the dilation tendency observed in the earlier tests. This was accounted for by the large peaks of excess pore water pressure which actually cause liquefaction failure under cyclic loading.



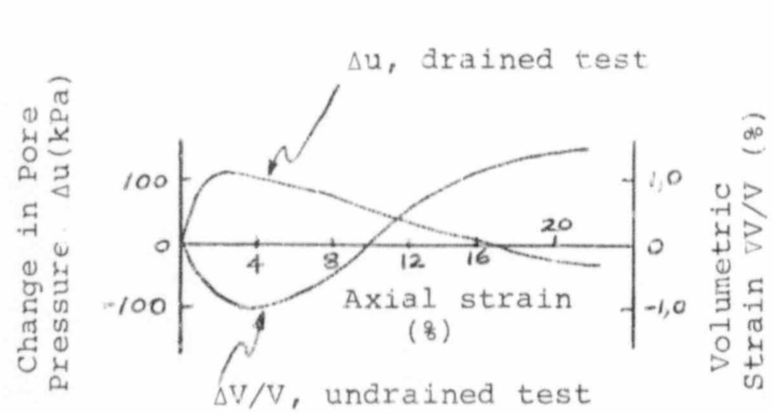


Fig. 8 Typical Stress-Strain Curves from Triaxial Tests on Hydraulic Fill[8]

Knight and Blight[9] describe the use of cyclic triaxial tests to investigate the application and release of shear stress by repeated loading on soils in road bases. Positive pore-pressure increments produced on loading are dissipated on release of load resulting in densification of the soil and increases in strength.

Martin, Finn and Seed[10] investigate the mechanism underlying liquefaction of saturated sands subjected to cyclic loading such as that produced by earthquakes. When drainage is prevented, the tendency for volume reduction during cyclic loading results in corresponding progressive increases of pore water pressure. If this pressure builds up to equal the confining pressure, the sand loses its strength and is said to have liquefied. This may only be a temporary state. The authors describe volume change characteristics under drained cyclic loading, and a relationship is developed between these and the pore water pressure increases in undrained tests. The key to the practical application of this relationship lies in the fact that volumetric strains during drained cyclic tests were found to be independent of vertical stress. To enable this theory to be simply stated, the following assumptions were made:

ε_{vd} = the net volumetric strain corresponding to the decrease in volume occurring during cyclic loading in simple shear on saturated sand under drained conditions. ε_{vd} has been shown to be primarily a function of shear strain amplitude and may be envisaged as being due to slip at grain contacts. If loading, having the same shear strain amplitude, is applied under undrained conditions, it is known from experimental data that for small shear strain magnitudes, the magnitude of cyclic pore water pressure fluctuation is small. By assuming the magnitude of residual pore water pressure increase occurring during a cycle to be relatively small compared with initial pore water pressure, it is reasonable to assume that the intergranular contact forces induced during the cycle are similar to those induced during a drained cycle. Thus, slip at grain contacts must again occur resulting in the volumetric strain ε_{vd}.

ε_{vr} = the recoverable volumetric strain stored by elastic deformation at grain contacts. The slip deformation must transfer some vertical stress previously carried by intergranular forces to the more incompressible water. The pore water pressure increase corresponding to a reduction in vertical effective stress results in the release of recoverable volumetric strain, ε_{vr}.

The simplest form of the theory thus implies that if a sample of saturated sand loaded to an initial vertical effective stress σ'_{vo} has a recoverable volumetric strain ε_{vr}, then liquefaction will occur under an applied cyclic strain history that produces a volumetric strain

$$\varepsilon_{vd} = \varepsilon_{vr}$$

under drained conditions.

1.4 Proposed Application in South African Gold Mines

The proposal in South Africa is to pump a slurry mix of gold mine slimes, a waste product, and some cementing agent into the mining stopes to provide support for the hanging wall. The slurry will have to be pumped into some type of temporary retaining structure or dam to retain the fluid material until solidification takes place with the hydration of the cementing agent.

The backfill method just described is different to the overseas applications described in the previous sections. The difference is that backfill practice overseas has been in well-confined areas such as shafts, whereas the proposed application is in the unconfined areas of a stope. 'Corridors' of stabilised fill will have to be utilised to allow haulage ways and drainage ditches to remain open and to allow ventilation. Fig. 9 gives an impression of the support mechanism as envisaged.

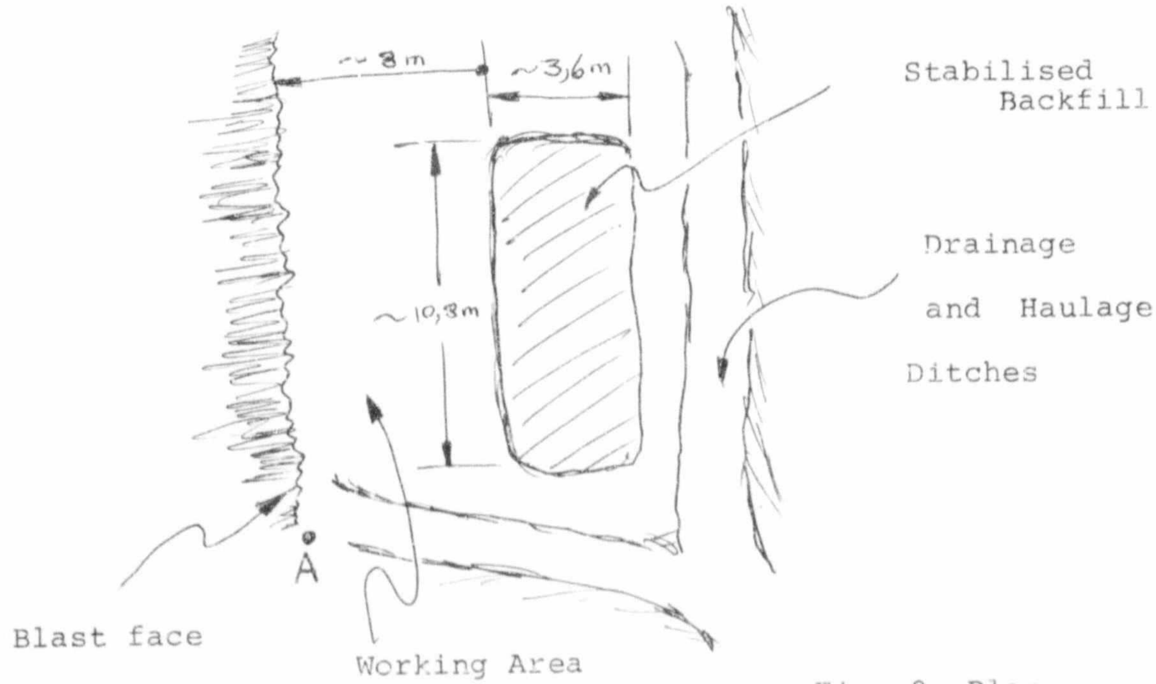


Fig. 9 Plan

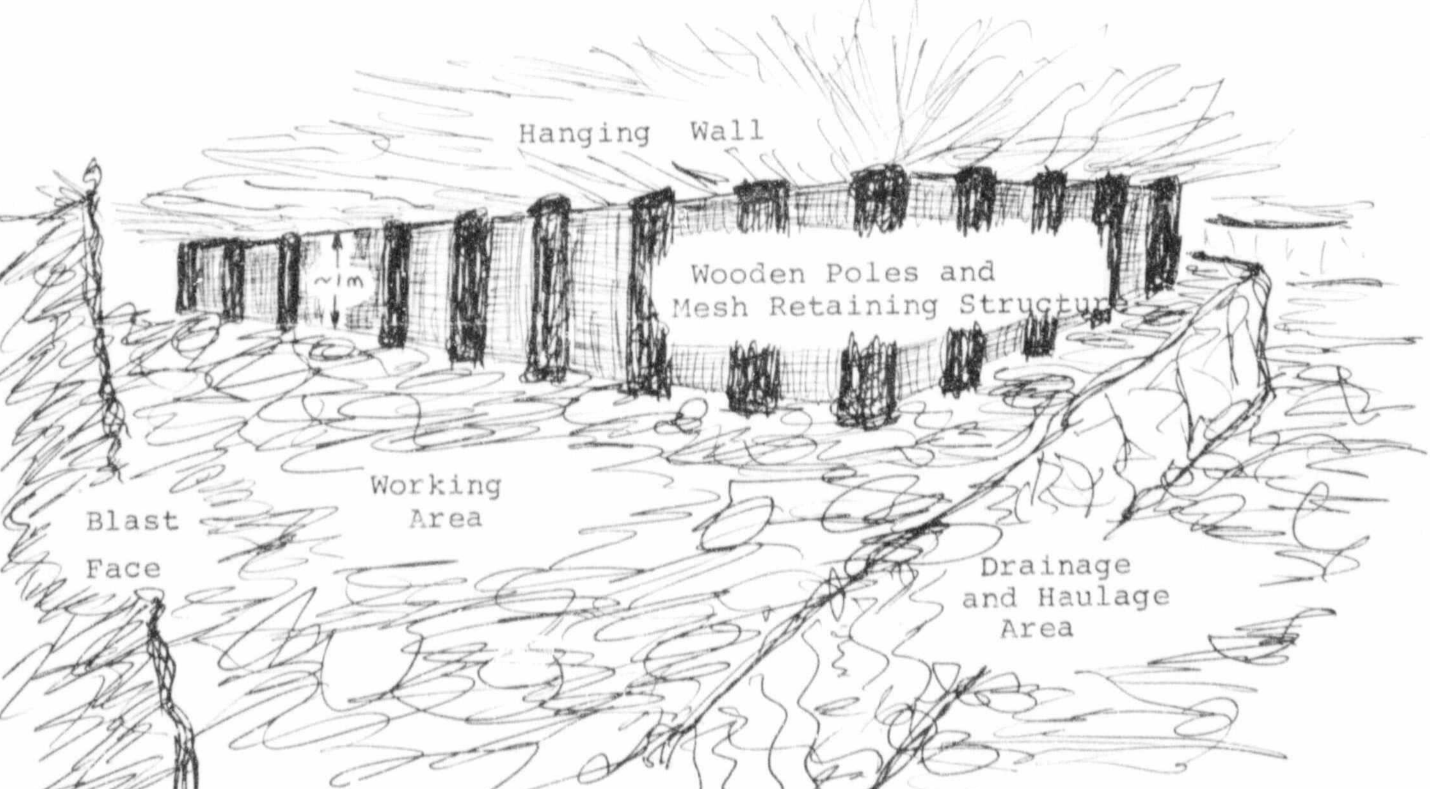


Fig. 9b View from Point A

Fig. 9 Impression at Stope-Support Mechanism

The use overseas of classified or deslimed tailings as backfill material in preference to unclassified tailings has been shown to have distinct advantages[5] (see Fig. 4). However, the use of unclassified slimes has an economic advantage in the saving on classification costs, and the proposal is to use the slimes in an unclassified state.

As regards cementing agents, Portland cement has proved to be the most used additive. However, it has been shown possible to reduce or replace the cement with various less costly additives [2,5], and it is hoped that similar cost savings can be made in South African applications.

The retaining structure will have to be of a nature which allows drainage of the run-off water during consolidation of the fill material but can still retain the slurry. A woven plastic material has been suggested which, possibly with a wire mesh backing, will be attached to hanging wall and floor and to wooden poles. In this state, the retaining structure will not be expected to provide any lateral restraint apart from retaining the fluid material. A further suggestion is to string old wire cables internally across the retaining structure between the wooden poles. The reason for doing this would be to provide some lateral restraint or reinforcement to the fill material.

1.4.1 Research Program

In devising methods for assessing and testing the relevant properties of cemented slimes slurries, attention was paid to overseas experience as well as to local requirements.

Two types of slimes having different particle size gradations were obtained for testing. Preliminary sieve grading, specific gravity and pH tests were conducted in order to observe the differences in the two materials. It was necessary to establish a standard mixture in order to make valid comparisons. Standard moisture contents and additive type and content were thus determined, and a standard method of preparing and curing specimens for testing was decided on.

Triaxial tests were conducted to investigate the shear strength properties of the slimes types with the various additives and additive combinations. The information provided about the shear strength parameters is of significance in later considerations.

The strength development of the stabilised slimes material under compression loading was tested using slabs of the material to model the underground situation. The slabs were tested unrestrained, reinforced with wires and restrained in moulds, and consideration was given to the relationship between the model slabs and the practical conditions.

The reaction of the material to vibrations caused by blasting and possible resulting liquefaction was investigated using cyclic loading triaxial tests.

2 MATERIALS AND TEST SPECIMENS

2.1 Types of Slimes

The main test series was conducted on fine grey slimes (SGM slimes) provided directly from the reduction filters at Stilfontein Gold Mine. Some tests were repeated on coarser yellowish slimes (ROD slimes) sampled from the side of a slimes dam at Stilfontein.

2.1.1 Grading Analyses

The particle size distribution curves in Fig. 10 show the essential difference between the two types of slimes. The SGM slimes is seen to be a silt with about 30% of fine sand, while the ROD slimes is a fine sand with about 25% of silt.

2.1.2 Specific Gravity

The standard test method was utilised to determine the specific gravity (SG) of each type of slimes in the unstabilised state. Five tests on each provided average results as follows:

	SG
SGM Slimes	2,61
ROD Slimes	2,66

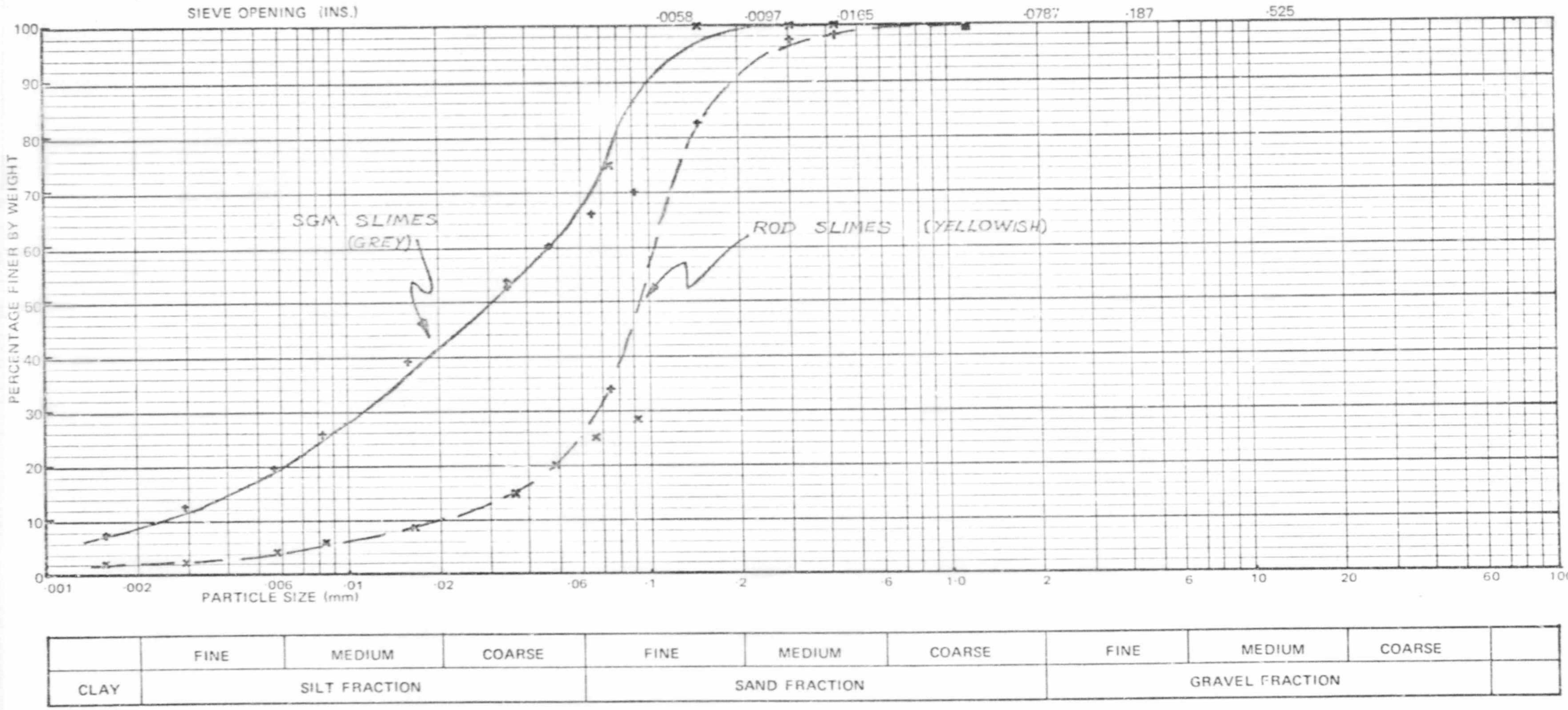


Fig. 10 Particle Size Distribution Curves

2.1.3 pH of Slimes

The pH of the unstabilised slimes was determined using a C.S.I.R.O. pH indicator set for soils. The results were as follows:

	pH
SGM Slimes	> 10
ROD Slimes	∿ 4

Although the pH value might influence pumpability, all mixes containing cementing agents showed pH values exceeding 10.

2.2 Moisture Contents

"Moisture content" is defined as the ratio

$$w = \frac{\text{mass of water}}{\text{mass of solids}}$$

In the literature, an equivalent term "pulp density" is often used which is

$$\gamma_p = \frac{\text{mass of solids}}{\text{total mass}}$$

The relationship between the two is:

$$\text{Moisture Content} = \frac{1 - \text{Pulp Density}}{\text{Pulp Density}}$$

or

$$w = \frac{1-\gamma_p}{\gamma_p}$$

where the ratios are given as fractions.

Seeing that the material will be pumped into position in the stope and that water will be the pumping agent, the moisture contents are expected to be high. Rodio (S.A.) (Pty) Ltd. conducted pumpability tests on unstabilised ROD slimes, and reported a 35% minimum content requirement for pumpability.

In order to arrive at standard values of moisture content to be used for testing, a measure of the flow characteristics of the unstabilised slimes was sought. Samples of SGM and ROD slimes with varying amounts of water were tested in the standard liquid limit device. The standard ASTM grooving tool was used, and the number of blows required to close the groove at a series of moisture contents was determined. The number of blows versus moisture content is plotted in Fig. 11.

For the ROD slimes with $w = 35\%$, the groove would just not remain open. For SGM slimes with $w \approx 54\%$, the groove would also not remain open and the consistency of this mix was similar to that of ROD slimes with $w = 35\%$. The standard moisture contents for the test series were taken as

$w = 54\%$ for SGM slimes

and $w = 35\%$ for ROD slimes.

The increased water requirement for flow of the SGM slimes over that for the ROD slimes would be expected from the grading curves in Fig. 8. The coarser ROD slimes has a smaller specific surface area than the finer SGM slimes

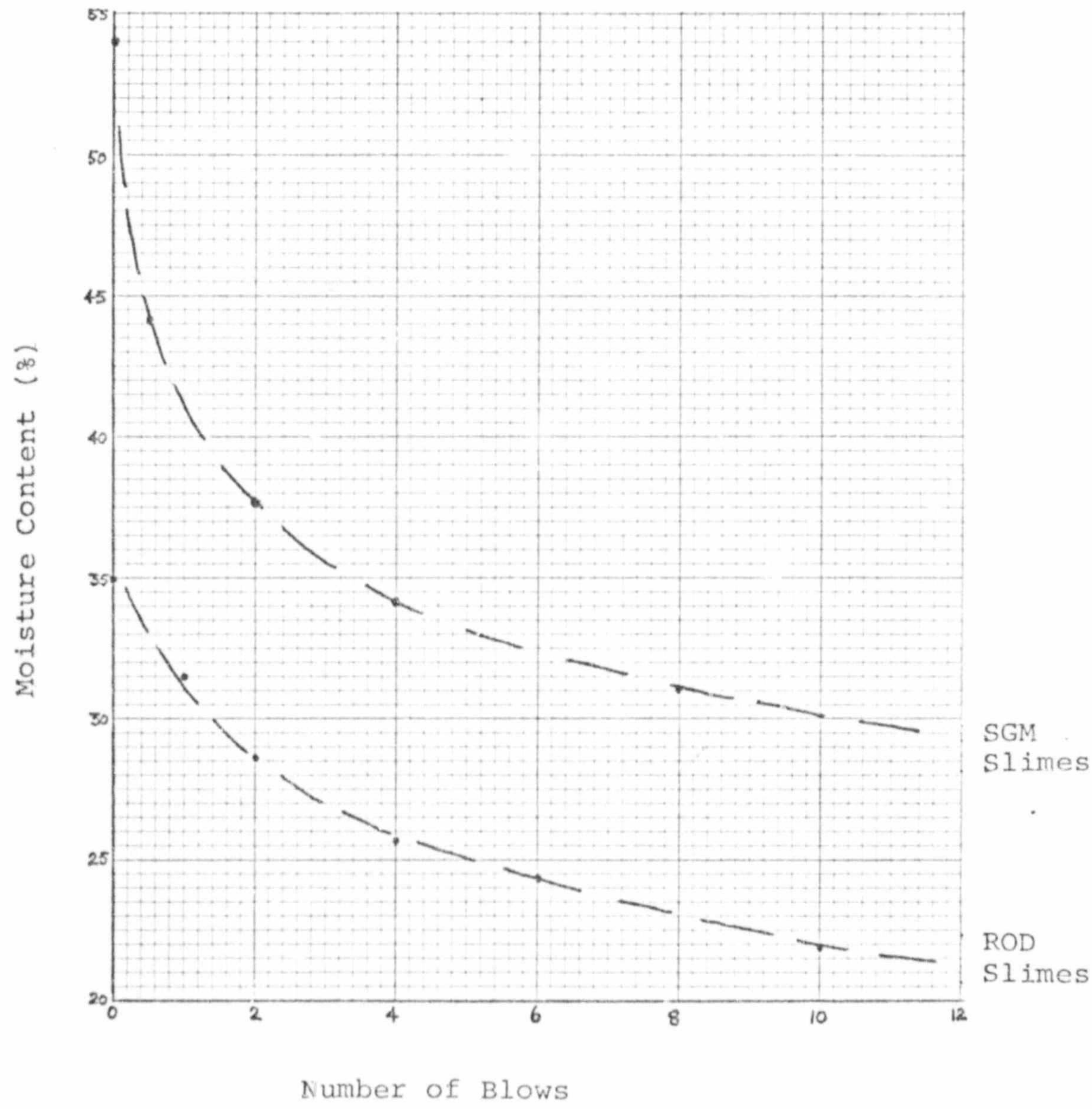


Fig.11 Flow characteristics

and the SGM slimes thus requires more wetting to achieve a similar workability.

2.3 Specimens of Unstabilised Slimes

It was not possible to conduct triaxial and unconfined slab tests on unstabilised slimes due to the low unconfined strength of the unstabilised material. Neither cylindrical nor slab samples would retain their shape when demoulded.

In an attempt to achieve higher unconfined strengths, various percentages of Bentonite (2%, 4% and 6% by mass of solids) were mixed with SGM slimes and cylindrical specimens were cast. After 3 days these specimens could still not be successfully demoulded.

The only tests that could be successfully conducted on unstabilised slimes were compression tests on slabs retained in their moulds. These tests are reported in Chapter 4.

2.4 Additives

Proportions of additives were measured by dry mass of solids.

Ordinary Portland cement was adopted as a standard additive in the ratio 1:10 of cement:slimes. The evidence of previous research and application[1,2,3] has shown that using cement in this ratio can lead to an economical hydraulic backfill material. The effect of variations in the proportions of cement, as well as a reduced moisture content, were investigated for SGM slimes.

Power station flyash has been found useful[2,5] in reducing the cement requirement while maintaining strengths. Flyash obtained from Kelvin Power Station was thus used in various proportions with cement and SGM slimes. The flyash, being a low cost material, was not merely substituted for small amounts of cement as done by Thomas[2] and Weaver and Luka[5], but cement contents were more drastically reduced and larger proportions of flyash were used.

The use of lime has been suggested[3] as an alternative stabilising agent to cement. The usefulness as a cementing additive of hydrated road lime was thus investigated. In the ratio 1:10 of lime: SGM slimes, samples could not be demoulded due to low unconfined strengths. However, lime with flyash has been used as a stabilising agent in road works for many years[6], and it was found that mixing flyash with the lime and slimes yielded suitable specimens. A mix ratio of 1:2:15 lime:flyash:slimes tested for comparison with mixes containing cement and cement-flyash.

The addition of small amounts of gypsum to lime-flyash mixes has been shown to be beneficial to unconfined strengths[7]. Phospho-gypsum, obtained from the Triomf fertilizer factory at Modderfontein, was substituted for part of the lime in some of the lime-flyash-slimes mixes.

2.5 Preparation of Specimens

Cylindrical samples for triaxial testing were cast in 38 mm internal diameter, open-ended rigid plastic tubes, approximately 100 mm long. The tubes were sealed at each end with rubber stoppers thus preventing loss of moisture by evaporation during the curing period.

Slab samples for compression testing were cast in 30 mm high galvanised sheet steel moulds. The plan dimensions were varied as reported in Chapter 4. Evaporation of moisture from the slabs was prevented by capping the moulds with greased glass sheets for the duration of the curing period.

The curing of all specimens took place at between 15°C and 18°C. A standard curing period of 7 days was aimed for although specimens cured for up to 28 days showed insignificant strength improvements over specimens cured for 7 days.

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