

# Fill support systems for deep-level gold mines

by S. J. PATCHET\*, Ph.D. (Newcastle), M.Sc. (Arizona), B.Sc. Hon. (NMIMT) (Member)

## SYNOPSIS

The use of fill in deep-level gold mining presents the possibility of achieving considerable economic and operational benefits if conventional support can be eliminated. Unfortunately, the combination of the properties of tailings from gold reduction plants and the narrow, flat, tabular reefs being exploited make conventional hydraulic filling very impractical. Laboratory tests indicate that, with careful control of water content, these tailings can provide an adequate fill material. A variety of bonding agents have been investigated, and the most practical seems to be ordinary Portland cement. Even at very low cement contents some cohesion is achieved. The design and layout for a complete fill support system using hydraulic transport, dewatering, and pneumatic placement are discussed, and a surface field trial indicated that the principles involved are correct and that acceptable results can be achieved. This system and material would completely eliminate conventional timber and brick support, and a preliminary economic analysis indicates that filling is cost competitive on a direct replacement basis. All the operations for a full-scale operation are available or have been developed to a stage sufficient to indicate that the system is practical, although certain operations require further refinement.

## SAMEVATTING

Die gebruik van slyk invulling in goudmyne met diep vlakke bied die moontlike geleentheid om aansienlike ekonomiese en operasionele voordele in te hou, indien konvensionele stutting daardeur vervang kan word. Die kombinasie van verskillende eienskappe wat gevind word in die afval van 'n goud aanleg en die smal, plat rif wat ontgin word, maak konvensionele hidroliese invulling uiters onprakties. Laboratorium toetse bewys dat met noukeurige kontrole van die water inhoud, hierdie afval doeltreffend gebruik kan word. 'n Verskeidenheid bindingstowwe is getoets en gewone Portland sement blyk die mees praktiese te wees. Selfs met 'n baie lae sement inhoud word 'n mate van binding gevind. Die ontwerp en uitleg van 'n volledige invul stut stelsel wat gebruik maak van hidroliese vervoer, ontwatering en die plasing deur middel van lugdruk is bespreek. Bopie toetse het bewys dat die betrokke beginsels korrek is en dat aanvaarbare resultate verkry kan word. Hierdie stelsel en materiaal sal die konvensionele hout en sementsteen stutte geheel en al uitskakel. Voorlopige ekonomiese analise dui aan dat 'n direkte oorsakelike na invulling ekonomies kompetender is. Alle apparaat is beskikbaar of is in so 'n mate ontwikkel om dit 'n praktiese stelsel te bewys, alhoewel sekere werkinge verder afronding nodig het.

## Introduction

The use of fill in modern mining is spreading rapidly throughout the world. The reasons for this vary from place to place but are broadly to be found in the need for improved ground control, increased mechanization, and stable if not decreased working costs. Since the early 1950s, an ever-increasing amount of research and field work has been expended in examining this topic and developing practical mining systems that use fill<sup>1</sup>. There is now a very considerable body of literature on this subject, ranging from purely theoretical studies<sup>2</sup>, through field instrumentation programmes<sup>3</sup>, to plant design and operation<sup>4</sup>. For a variety of reasons, the Rock Mechanics Department of the Technical Development Services Organisation of the Anglo American Corporation has been investigating the possible use of fill in the deep-level gold mines of South Africa. This paper describes the philosophical approach taken to this problem, and discusses the results of laboratory and field trials on potential fill materials and systems.

## Background Studies

The initial objectives of the investigation were predicated by the rising cost of timber used in conventional support and the rising cost and shortage of African labour. In addition, it was felt that it would be useful to develop a means of exploiting ore-bodies and reefs that, for a variety of reasons, cannot be extracted by conventional techniques. A literature survey undertaken to relate available techniques to the conditions in deep-level gold mines revealed two primary items of relevance and several lesser ones. The first item of primary importance was that, with a few exceptions, most fill consists of mill

tailings and is placed hydraulically as a slurry. The second was that, again with a few exceptions, most fill is used in mining methods that involve either post-filling or progress vertically (or essentially vertically) upwards<sup>5</sup>. Some of the lesser items include the need to control *in situ* density, percolation rates, cement contents, and so on<sup>6, 7</sup>. It now remained to relate these findings to the South African gold-mining environment and to devise a suitable line of research and development.

First it was necessary to resolve the two primary items mentioned. The use of tailings presented two difficulties since, even at that stage, it was known that tailings from gold reduction plants (RPT) are considerably finer than those generally used, and it seemed difficult to envisage a filling system employing hydraulic placement that could be used for narrow, tabular, relatively flat gold reefs. The next stage of the investigation therefore had much more clearly defined objectives:

1. investigate and establish the material properties of the RPT,
2. investigate and establish if these RPT can provide an adequate fill material,
3. develop a fill system suitable for use in South African gold mines based on the results obtained, and
4. evaluate, on a preliminary basis, the economic viability of such a system.

## Material Properties

A number of samples were taken from the tailings produced by the reduction plant at Western Holdings Limited. In general, the results were very consistent, probably because of the uniform conditions maintained in the reduction process. Table I indicates some typical particle-size distributions obtained from RPT samples taken over a period of several months. See also Fig. 1. It

\*Rock Mechanics Department, Anglo American Corporation, Welkom, O.F.S.

TABLE I

PARTICLE-SIZE DISTRIBUTION OF TAILINGS FROM THE REDUCTION PLANT AT WESTERN HOLDINGS LIMITED

Passing $\mu\text{m}$	Cumulative per cent			
	Sample 1	Sample 2	Sample 3	Sample 4
208	99,6	99,9	99,8	—
147	98,6	98,9	98,8	99,7
104	91,7	92,0	93,1	95,9
74	76,9	76,8	79,1	74,9
41	58,2	70,1	72,7	33,2
31	45,8	50,1	53,6	23,5
21	35,8	39,1	43,1	3,6
14	28,4	31,0	35,1	2,5
10	23,8	24,7	29,0	2,1

Samples 1 to 3 are straight reduction-plant tailings. Sample 4 is cyclone underflow material.

is important to note the extremely fine nature of this material, some 25 per cent by mass being finer than  $10 \mu\text{m}$ . The size distribution is fairly good, as a comparison with a proposed ideal curve<sup>7</sup> shows. However, because of the absolute particle sizes involved, the use of the coefficient of uniformity in comparisons with other fill materials proved to be misleading.

The mineral constituents were analysed, and the RPT were found to consist of about 80 per cent quartz, about 10 per cent pyrophyllite, and just under 5 per cent each of chlorite and sericite. Any naturally occurring bonding agents are insignificant. Predictably, particle-shape analysis indicated that virtually all the particles are angular and acicular. This latter feature is particularly predominant in the fraction between 74 and  $35 \mu\text{m}$ , and this has a considerable influence on sizing results in this region since particles report in the various fractions largely by chance.

The permeability of the RPT was investigated by use of the falling head test described by Rawlings *et al.*<sup>8</sup>. It was found that the RPT as produced were essentially impermeable, typical values being about 1 to  $2 \times 10^{-4} \text{ mm/h}$ . Later discussions held with group personnel who sampled old slimes dams on the East Rand indicated that the centres of these dams were still wet.

In order to improve the permeability, a deslimed material was obtained by the cycloning of regular RPT. The size distribution for this material is also shown on Fig. 1. This material had a more acceptable permeability but gave low-density samples and slumped badly. It was therefore concluded that a reasonable proportion of the material smaller than  $10 \mu\text{m}$  was necessary in order to achieve an adequate fill material. Two other important aspects that arise if the very fine material is removed are the metallurgical problems involved in making a separation in this size range and the economic, practical, and environmental problems associated with the disposal of large quantities of very fine material.

### Strength Properties

The literature survey indicated that adequate strength properties can be obtained from a wide variety of tailings materials provided attention is paid to particle-size distribution, density, and water content. Hence, the strength investigations centred on comparisons with previously accepted norms and on assessments of the magnitude of any deviations from these norms. Because of the depths currently being reached (and eventually to be reached) in South African gold mines, the fill material must be of the highest possible quality consistent with reasonable economic considerations.

Strength tests were conducted at the Portland Cement Institute (Johannesburg), the Advanced Research

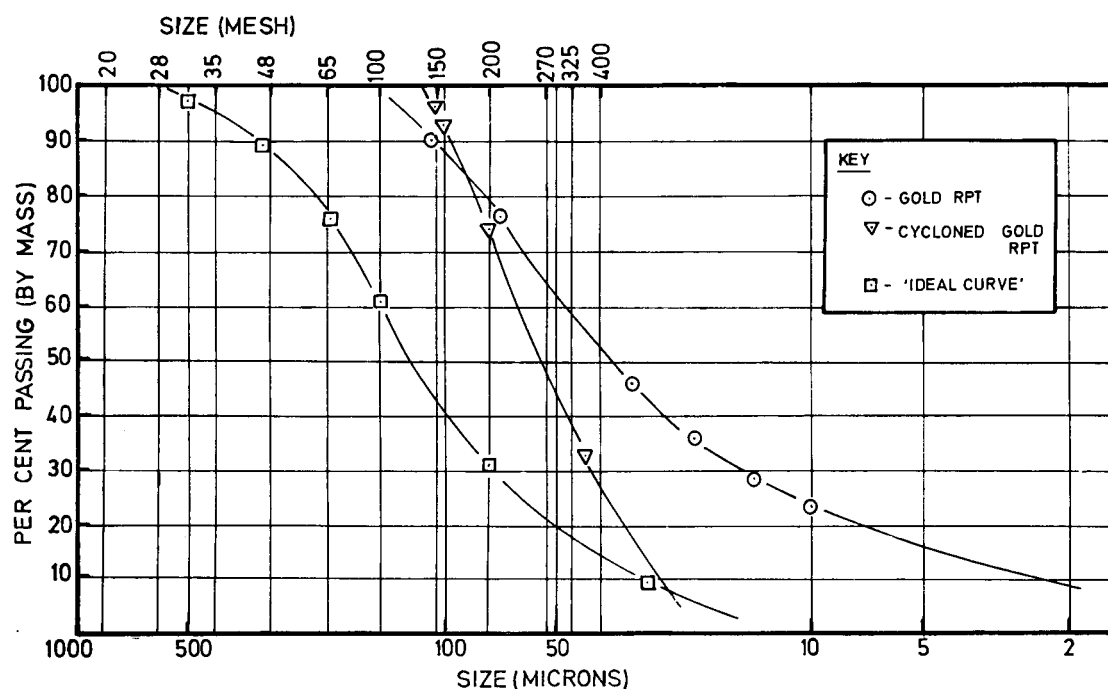


Fig. 1—Particle-size distribution

Laboratory of Joy Manufacturing Company (Galt, Ontario, Canada), and the T.D.S. Rock Mechanics Department Laboratory (Welkom). A variety of testing procedures was used, but in every case the slimes were straight RPT. The results are discussed below. Because

of the differing procedures used, the absolute values vary, but it is encouraging to note that the trends observed were always consistent within the results from each laboratory. All the proportions are by mass unless otherwise stated.

TABLE II

STRENGTHS (MPa) OF CUBE SAMPLES OF TAILINGS: CEMENT MIXES (AVERAGES OF THREE SAMPLES)

Series A 73 per cent solids by mass					
Age d	Ratio of tailings to cement				
	1,75:1	4,5:1	12,75:1	54:1	109:1
1	1,59	0,76	—	—	—
7	7,18	1,87	0,34	0,20	0,14
28	12,55	3,39	0,68	0,24	0,17

Series B 76 per cent solids by mass				
Age d	Ratio of tailings to cement			
	5:1	10:1	20:1	30:1
3	0,83	0,35	0,24	0,12
7	1,66	0,60	0,22	0,14
28	3,55	1,64	0,36	0,23

TABLE III

STRENGTHS (MPa) OF CYLINDRICAL SPECIMENS (WIDTH: HEIGHT = 0,5) OF TAILINGS: CEMENT MIXES (AVERAGES OF 4 SAMPLES)

Series C 74 per cent solids by mass				
Age d	Ratio of tailings to cement			
	5:1	10:1	20:1	30:1
3	3,48	1,17	0,51	0,32
7	5,00	1,79	0,74	0,49
28	6,42	2,18	0,99	0,75

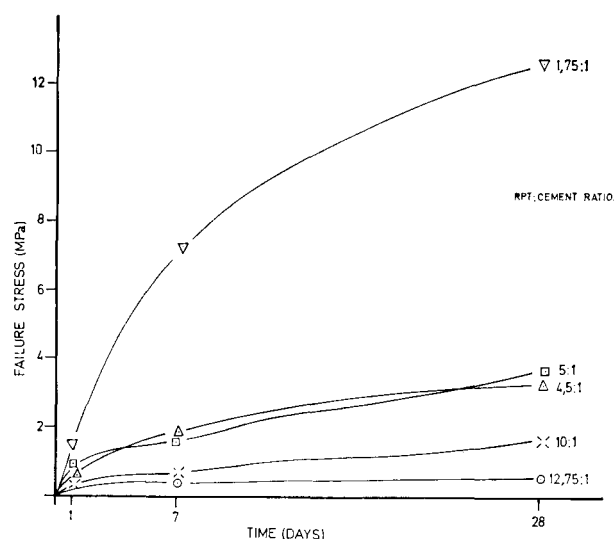


Fig. 2—Cube strengths of RPT-cement mixtures high in cement (averages of three tests)

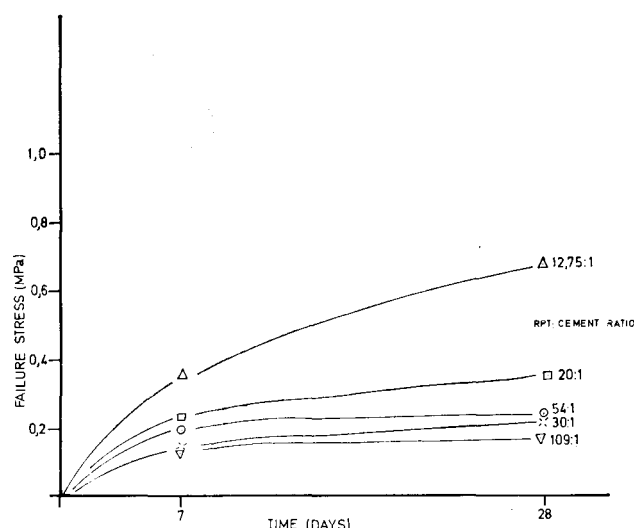


Fig. 3—Cube strengths of RPT-cement mixtures low in cement (averages of three tests)

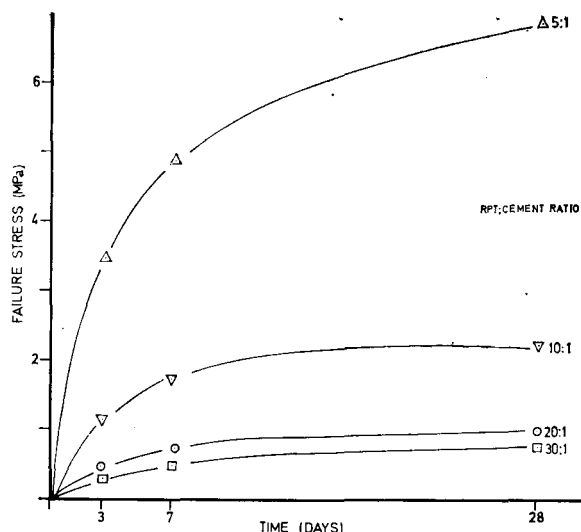


Fig. 4—Cylinder strengths of RPT-cement mixtures (averages of four tests)

It is generally desirable to obtain the maximum amount of strength possible in the shortest period of time. For example, the series B tests indicate that, if the 28-day strength is taken as a base, the build-up of strength is proportional to the cement content. See Fig. 5. The analysis of other results is far less distinct, and the influence of time is probably less important than relatively minor variations in other parameters — solids content, for example. The general patterns from concrete technology with regard to increasing strengths are thus confirmed even at very low cement contents. In general, the 3-day strength can be taken as about 50 per cent and the 7-day strength as 60 to 75 per cent of the 28-day strength over the ratios and solids contents investigated.

### Mixing Time

Under certain conditions, it proved difficult to mix dry cement into damp RPT, and a series of tests was performed on this problem. The solids contents, mixing times, and RPT:cement ratios were varied, and the

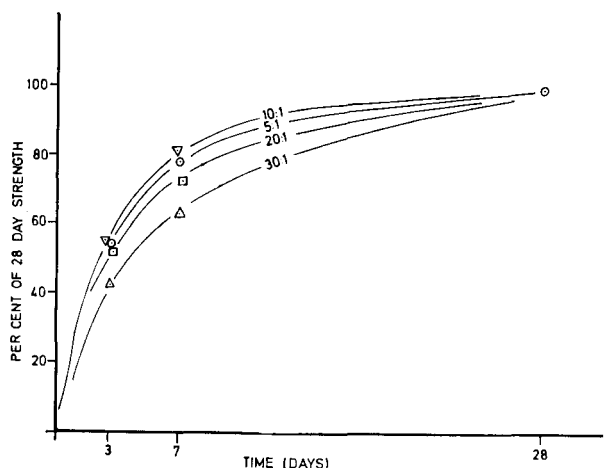


Fig. 5—Strength of RPT-cement mixtures as a function of time

results of cube tests on these materials are shown in Table IV. At the lower solids contents, adequate mixing was achieved without difficulty and the influence of mixing time was at a minimum. At higher solids contents, it proved difficult to mix the materials owing to balling, and a definite improvement in strength occurs with longer mixing times, particularly in the early (1 to 7 day) strengths.

TABLE IV

STRENGTHS (MPa) OF CUBE SAMPLES OF TAILINGS: CEMENT MIXES AT VARIOUS MIX RATIOS, WATER CONTENTS, MIX TIMES, AND CURING CONDITIONS (AVERAGES OF 3 TESTS)

Series D 70 per cent solids by mass 16,8:1 RPT:cement

Age d	Mixing time (minutes)			
	1†	1*	3*	5*
1	0,12	0,09	0,06	0,06
4	0,24	0,12	0,10	0,10
7	0,29	0,13	0,15	0,12
28	0,53	0,20	0,22	0,24

Series E 73 per cent solids by mass 20:1 RPT:cement

Age d	Mixing time (minutes)			
	1†	1*	3*	5*
1	—	0,12	0,12	0,13
4	—	0,17	0,16	0,17
7	—	0,21	0,24	0,27
28	—	0,34	0,36	0,38

Series F 80 per cent solids by mass 30:1 RPT:cement

Age d	Mixing time (minutes)			
	1†	1*	3*	5*
1	0,24	0,24	0,40	0,36
4	0,40	0,29	0,41	0,40
7	0,62	0,32	0,46	0,42
28	1,01	0,52	0,67	0,64

Series G 73 per cent solids by mass 60:1 RPT:cement

Age d	Mixing time (minutes)			
	1†	1*	3*	5*
1	—	0,03	0,05	0,07
4	—	0,09	0,10	0,09
7	—	0,10	0,12	0,10
28	—	0,16	0,17	0,17

†Cured at 22 to 25°C, 90 per cent relative humidity

\*Cured at 22 to 25°C, under water

It seems reasonable to conclude that, at lower solids contents (70 to 75 per cent), the mixing time is relatively unimportant, but, at higher solids contents (75 to 80 per cent), the mixing time is important and should not be less than about 3 minutes. It is also important at higher solids contents to use a vigorous mixing action in order to ensure that the cement is uniformly distributed.

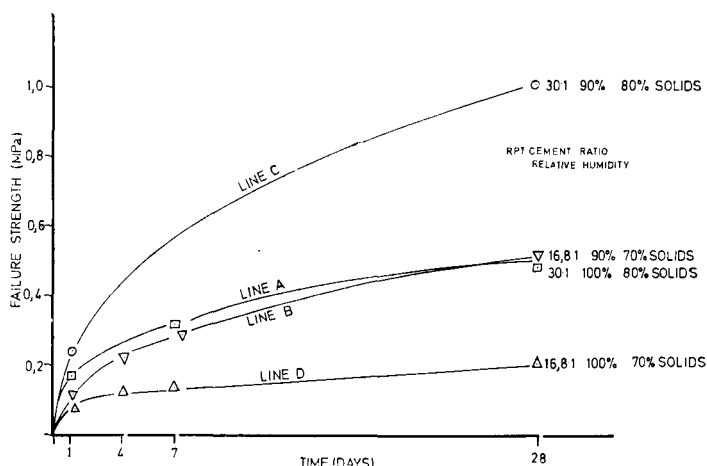


Fig. 6—Cube strengths of RPT-cement mixtures at varying solids contents and under varying curing conditions (averages of three tests)

### Curing Conditions

As part of the trials on mixing time, the influence of curing conditions was examined. Two lots of samples from series D and F were cured under different conditions: one lot from each was cured under water at 22 to 25°C, and the second lot was cured at 90 per cent relative humidity at 22 to 25°C. Fig. 6 summarizes the results of these tests. Several important conclusions can be drawn from these results. It can be seen that, for a given curing condition, the solids content is more important than the RPT:cement ratio. It is also apparent that, for a given RPT:cement ratio and solids content, a reduction in the available water during curing significantly increases the strength of the material.

Consider lines A and B. These indicate that an increase in the solids content from 70 to 80 per cent results in the same strength with half the amount of cement, even though the relative humidity during curing increases from 90 to 100 per cent. The financial, operational, and logistical implications of this are considerable for a large, deep-level mine with widely scattered working places. Lines C and D present the possibility of greatly improving the properties of a cemented fill material simply by careful control of the water content. Control of the water content and solids size distribution are far more important than the absolute cement content.

### Ratio of Width to Height

The importance of lateral confinement on the strength and behaviour of most materials dealt with in mining and rock mechanics is now widely recognized. It was initially planned therefore to investigate a range of likely fill materials under triaxial loading conditions. The very low permeabilities obtained when allied to the solids contents required for workable mixes cast a considerable doubt over the validity of triaxial testing even under drained conditions. Thus, it was decided to conduct a series of compression tests on slabs of varying width-to-height ratios. This did not eliminate the possibility that porewater pressures would develop, but it was felt that the results would probably be more directly useful in the underground layout stage of the project.

The slabs were prepared in the same manner and with the same material as those used in series B. Width-to-height ratios of 2, 4, 6, and 8 to 1 were evaluated at RPT:cement ratios of 5, 10, 20, and 30 to 1. Figs. 7 to 9 are stress-strain curves for curing periods of 1, 3, and 28 days respectively. The values for width-to-height ratios of 1 and 2 and RPT:cement ratios of 10:1 and 20:1 have been omitted from the diagrams for clarity, but they fall in the expected positions.

In Fig. 7 it can be seen that there is little significant difference in the deformation patterns. Strains of about 40 to 60 per cent occur for stresses in the region of 1 to 5 MPa. Once the material reaches these strain values, it rapidly accepts load and the strain is unlikely to exceed 70 per cent. At lower width-to-height ratios, the influence of that ratio is apparent and slightly more predominant than is the RPT:cement ratio.

Emerging from the 3-day strengths shown in Fig. 8 are more distinctive patterns with respect to both width-to-height ratio and cement content. For both illustrated cement contents, the slabs with a width-to-height ratio of 4 show considerably more strain at equivalent stresses than those with width-to-height ratios of 6 and 8. With regard to cement content, the 5:1 slabs at large width-to-height ratios perform fairly well, yielding strains of about 30 per cent at stresses of 20 MPa. The 30:1 slabs initially strain to a greater extent but latterly seem to climb more steeply than do the 5:1 slabs. The slabs with a width-to-height ratio of 4 exhibit approximately parallel deformation curves, with the 30:1 slabs giving a fairly regular 10 per cent greater amount of strain than do the 5:1 slabs.

The results of the 28-day tests are shown in Fig. 9. There is now a marked difference in behaviour due to both cement content and width-to-height ratio. The slabs with a 5:1 ratio of RPT to cement all exhibit considerable strength (about 4 MPa) before straining excessively. At a 30:1 ratio of RPT to cement, the slabs with a width-to-height ratio of 8 and 6 strain to about 20 per cent at low stresses, but then strain much more slowly to carry 20 MPa at about 35 per cent strain. At 30:1, the slab with a width-to-height ratio of 4 exhibits considerable strain (in excess of 50 per cent) at 20 MPa.

With these results it should be possible to optimize on the performance and cost of a fill material. For example, based on 28-day behaviour patterns, the use of 30:1 material in pillars with a width-to-height ratio of 8, in place of 5:1 material in pillars with a width-to-height ratio of 4, would reduce the consumption of cement by at least one-third without affecting performance. This would also improve early behaviour since, as Figs. 7 and 8 show, the slab with a larger width-to-height ratio has a better early performance curve than has the slab of smaller ratio.

### Elastic Modulus

In the series of slab tests, the deformation measurements were used in calculating the elastic moduli of the various materials. Attempts at the measurement of lateral deformation were unsuccessful. The elastic modulus was found to be a function of time, stress, strain, and cement content, and it was not possible to

evaluate this relationship in quantitative form. Fig. 10 indicates the band in which the values occurred. The width-to-height ratio and time seem much more significant in this context than does the cement content. Hence, it seems likely that detailed theoretical studies based only on elastic theory would not be of much significance except in a very general way. A detailed analysis could possibly yield adequate properties for a non-elastic theoretical approach but, given the great number of variables involved, the task is a formidable one and has not been attempted.

Other Binding Agents

A series of tests were conducted on the influence of

additives, for example lime, and the effect of non-cement binding agents. The materials investigated included, among others, fly- and clinker-ashes, milled granulated blastfurnace slag, Slagment, silica gels, and reactive shales. In general, these proved ineffective except for certain ashes and slags, but even these tended to be required in comparatively large quantities and consequently present potential logistical and operational problems. Work on a limited scale is continuing with these materials, but at this time the results do not appear to be very promising.

Design Parameters for Fill Support Systems

Filling has been carried out in South African gold

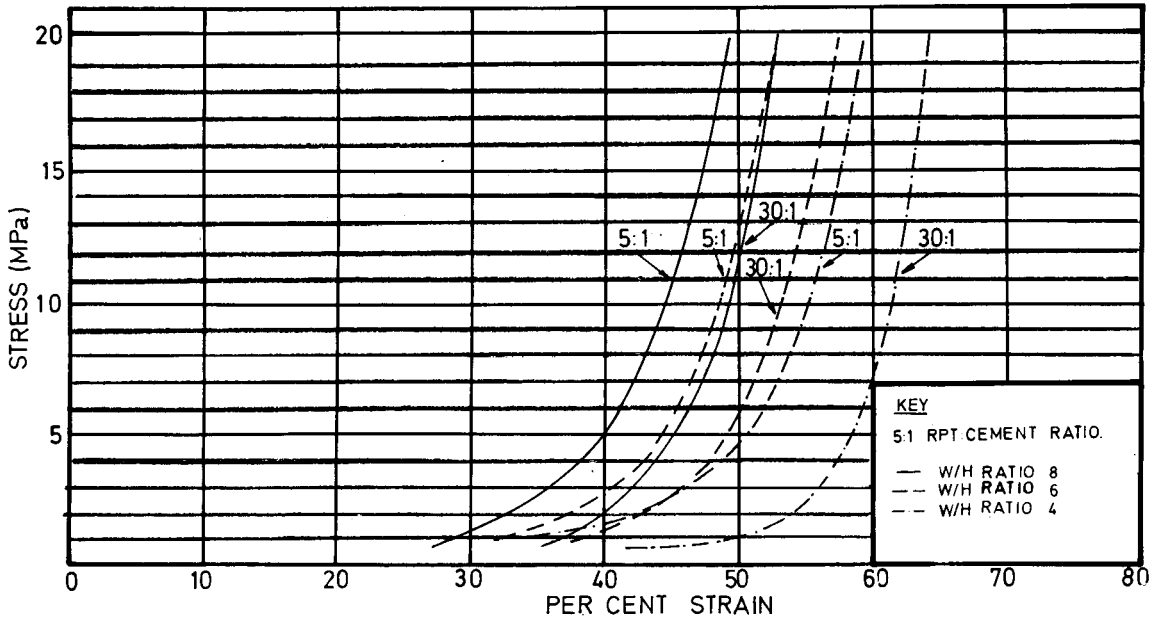


Fig. 7—Stress-strain curves for 1-day old slabs of RPT-cement mixtures

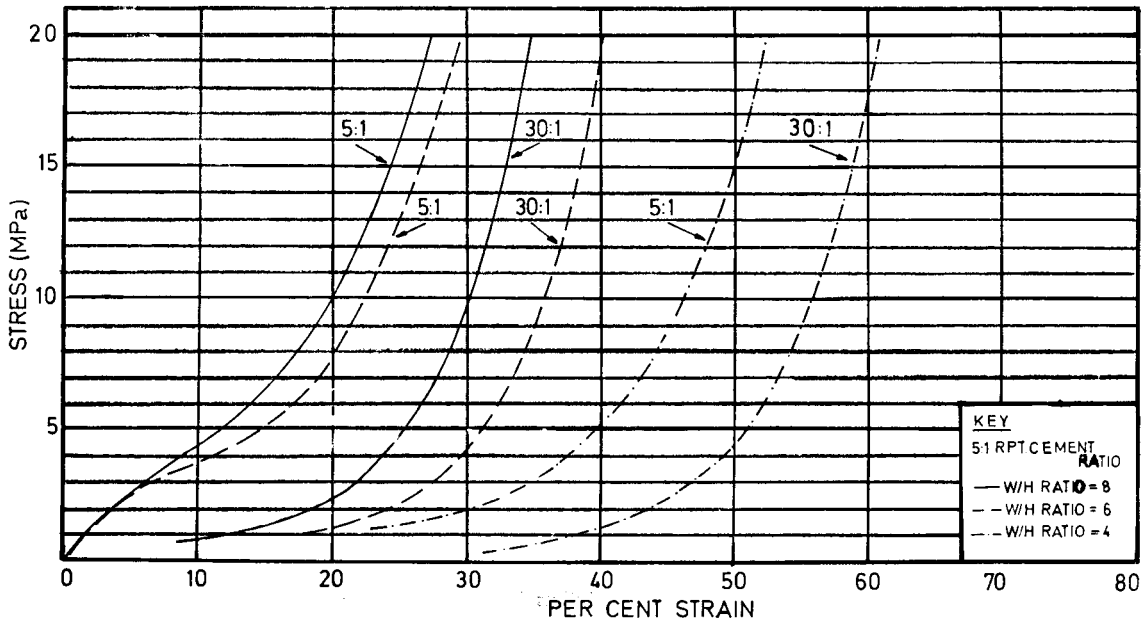


Fig. 8—Stress-strain curves for 3-day old slabs of RPT-cement mixtures

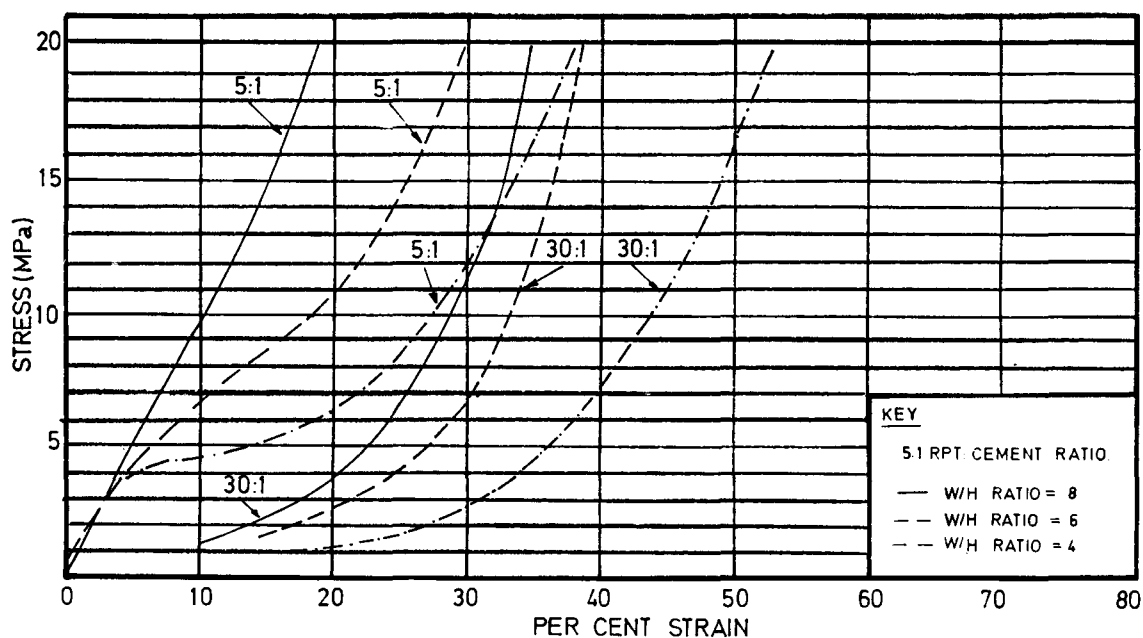


Fig. 9—Stress-strain curves for 28-day old slabs of RPT-cement mixtures

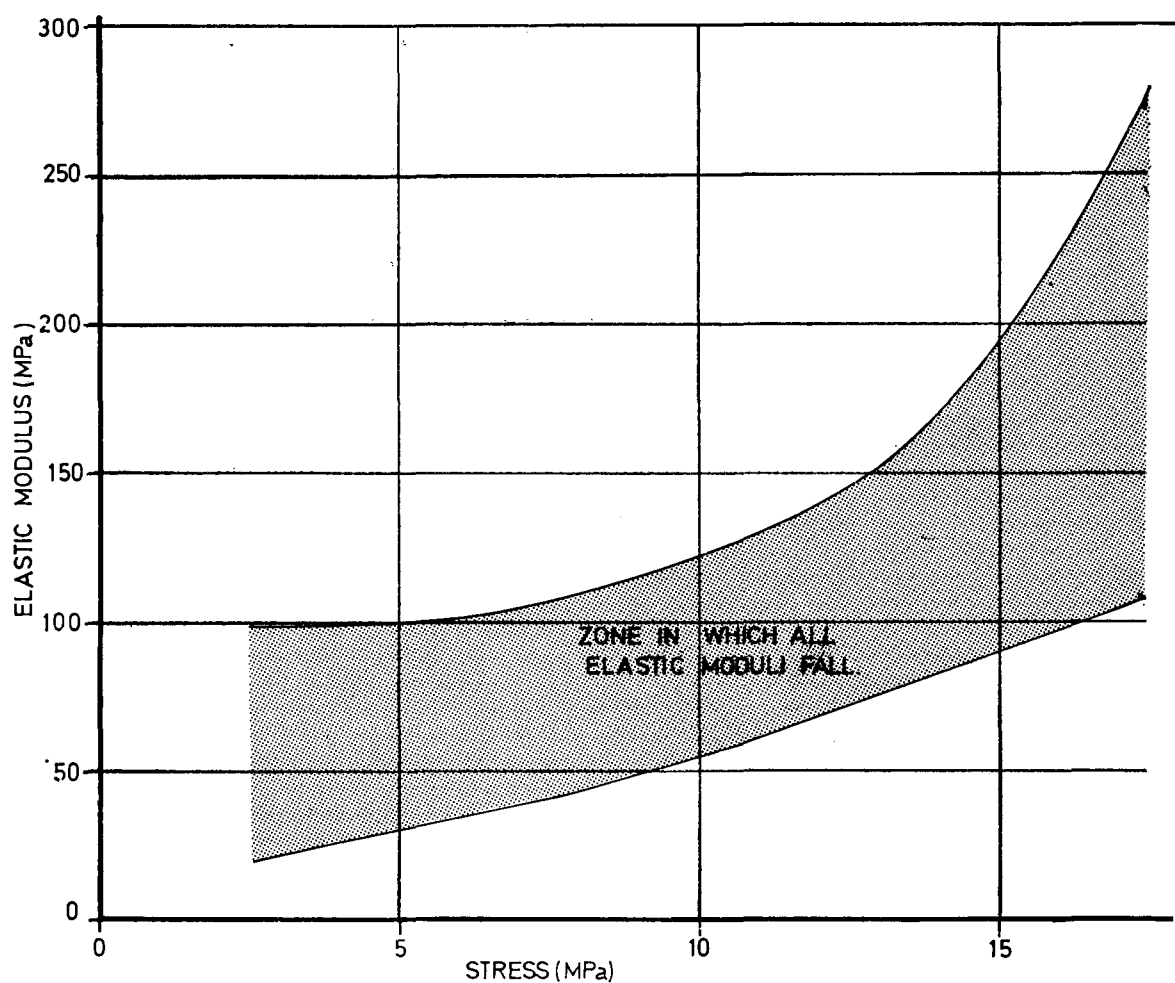


Fig. 10—Band of elastic moduli as determined from slab tests

mines in two forms: sand filling and waste stowing. Sand filling is no longer practised because of the change to all-slimes milling, and waste stowing has had only a limited use in applications where, theoretically at least, it reduces convergence and hence energy release. This section examines in general terms the design requirements and practical difficulties likely to be encountered if a fill support system is used in South African gold mines. The term *fill* as used here means material placed in a stoped area that has a definite and significant support function. It should not be confused with *waste disposal*, which is the placement of rock in old workings for convenience and economy rather than to provide support.

### Properties and Behaviour of Materials

RPT are the most commonly used fill material<sup>5</sup>. In most base-metal operations, the tailings are relatively coarse with an appreciable quantity greater than 74  $\mu\text{m}$ . Typically, the material smaller than 74  $\mu\text{m}$  is removed, and the remaining material is transported and placed hydraulically. The removal of the minus 74  $\mu\text{m}$  material usually results in an acceptable percolation rate, and the transport water is collected and recycled. The percolation rate must not be too high (which causes piping and cement loss) or too low (which yields an unsatisfactory, unstable material and slow re-entry times).

Two major problems arise when RPT are used in this conventional manner. The first is the fineness of this material (approximately 25 per cent minus 10  $\mu\text{m}$ ). As indicated, the material has an extremely low permeability and relatively poor performance at low solids contents, thus making hydraulic placement unacceptable. The second is that the relatively flat, thin tabular nature of the reefs makes it difficult to conceive a fill support layout that is capable of replacing conventional support while allowing rapid face advance. Of these two disadvantages, the first is formidable. The only apparent way to remove the water at an acceptable rate is to perform a physical dewatering operation on the RPT slurry. The equipment at present available is either of unsuitable mechanical complexity and size or is relatively untried. The solution of this first problem will essentially resolve the second since the constraints associated with hydraulic placement no longer apply.

On the assumption that the dewatering problem can be solved, the transport and placement systems must be considered. If the dewatering operation can be performed in the near vicinity of the stope, hydraulic transport can be used to distribute the material to the required stoping areas. A serious disadvantage is the need to install a new, and extensive, network of pumps and pipelines underground. The pipe diameters needed are not large, but the system is essentially mine-wide. The advantages of a separate network are that it can be largely automated and, once installed, it will probably require little maintenance. A hydraulic supply system also has the advantage of flexibility, and interference with other transport operations would be eliminated. Hydraulic transport presents a disadvantage in that all the water used to transport the material into the mine must be removed from the mine. It may be possible to

minimize this problem by separate surface and underground circuits as discussed later, but it is unlikely that it can be entirely eliminated.

Local tests confirm the general principle that, the higher the density of the fill material, the better the fill properties. To achieve this high density, the final water content must be as low as possible and this must be achieved relatively quickly. Where cement is used, the build-up of strength tends to follow a typical concrete curve, about 50 per cent of the 28-day strength being achieved in 3 days and about 75 per cent after 14 days. These factors have been determined in laboratory tests, and care must be taken in the design of a fill support system to ensure that the best possible conditions for achieving them underground are obtained. It is apparent that high early-strength mixes are not feasible, and the fill cannot be relied upon for immediate localized support. Based on these factors, it is possible to establish further system requirements. Any fill support system must place the material in such a fashion that the highest possible initial *in situ* density is obtained, and must place the material as quickly as possible after extraction of the ore so that the strength starts building up at the earliest possible time and at the maximum possible stoping width.

The reduction in convergence, and hence energy release, is related to the stope width at the moment of placement, and not to the mined stope width. Bearing in mind the total gold-mining environment, pneumatic placement seems the most satisfactory since it can fulfil transport, placement, and densification functions.

Further aspects that are fundamental in the design of fill support systems are the absolute particle sizes involved and the particle-size gradation. A good gradation of particle sizes is more important than the absolute sizes of the particles. The importance of particle size lies in its effect on the size of the pumps and lines required to handle the material. As the particle sizes increase, pipe sizes necessarily increase, leading to more expensive systems and greater difficulty in physical handling, installation, and maintenance. Since relatively small quantities of material are required at a great number of sites, it may be difficult to fully and efficiently utilize the available capacity of large-diameter systems.

### Design of Fill Support Systems

In the proposed system, the fill material will initially take the form of rib (or strike) pillars. Other layouts are practicable, but it seems reasonable to assume that such changes can be considered only once the actual *in situ* behaviour of the fill material is known. The design of rib pillars can therefore proceed, and this is an area in which considerable theoretical and practical experience is available. Two factors predominate virtually to the exclusion of all others:

- (1) the behaviour of the fill material under a triaxial state of stress, and
- (2) the time-dependent development of strength in cement mixtures.

#### *Dimensions of Rib Pillars*

The first factor above can be expressed in terms of the



width-to-height ratio of the strike rib. The general principle is that an increase in the width of a pillar for a given height gradually increases the failure strength of the pillar. The process is not linear, and the greatest benefits are achieved with the early addition of a slight confining stress. Hence, there is a minimum size of pillar at which this effect starts, and a size at which the increase in strength due to this effect becomes negligible.

A large number of *in situ* and laboratory experiments indicate that a pillar must have a width-to-height ratio of at least 4 if a strength greater than the uniaxial compressive strength is required. Likewise, little benefit is gained by an increase in the width-to-height ratio much beyond a value of 10. This has been confirmed in the laboratory for RPT-cement mixtures, and there is little reason to doubt the validity of these figures for the application under consideration. It is reasonable to assume, until evidence is available to indicate otherwise, that any rib pillar that is part of a systematic fill support system must have an effective width-to-height ratio of at least 8.

### *Spacing of Rib Pillars*

The load that a rib pillar must carry is extremely difficult to determine, and theoretical models tend to be of little value since they do not allow for the fractured nature of the ground surrounding a stope. As a first approximation, the fill ratio can be used. Two considerations follow from this. The first is the relationship of the span between ribs to the fill ratio, and the second is the non-linear relation of the rib-pillar stress to the fill ratio.

It is obvious that, the higher the fill ratio, the less the span between adjacent ribs. Since it is necessary to maintain a minimum width-to-height ratio for the pillar, this span will be a function of both the fill ratio and the pillar height. Thus, at a fill ratio of 50 per cent and a width-to-height ratio of 10, the span will be 10 m for a stoping width of 1 m and 20 m for a stoping width of 2 m.

The importance of this span dimension is difficult to assess. If all the operations can be absolutely maintained on the face, it can probably be varied over wide limits that involve only the sidewall stability of the rib pillar. However, if safe access between rib pillars must be maintained, it will have to be held to a relatively small dimension. This therefore implies an increase in the fill ratio (i.e., pillar width) above the minimum necessary simply to ensure pillar stability.

It is impossible to determine a unique failure strength for a rib pillar but, if the previous recommendation with regard to ratio of width-to-height is observed, practical failure is quite unlikely. At low fill ratios, the rib-pillar stresses can be expected to be extremely high. However, once the fill ratio exceeds about 50 to 60 per cent, the rate of decrease in theoretical rib-pillar stresses is low and there seems little necessity to fill beyond this range. It may be necessary to increase beyond this point for other reasons, such as were noted earlier with regard to span.

Since it is hoped that the rib pillars will become highly loaded, they must be kept a reasonable distance from

gullies if failure of the gully sidewalls is to be avoided. In view of the likely sloughing of the rib-pillar sides, the planned distance from the rib-pillar side to the gully side should be not less than 3 m for a gully of conventional depth. Should the gully depth be increased, the distance to the rib-pillar side should be increased by an equivalent amount. For similar reasons, care must be taken to ensure that off-reef excavations are not damaged by stresses transmitted by the rib pillars.

In cases where these proportions and dimensions cannot be conveniently worked into conventional layouts, special consideration will have to be given to possible alterations in the total stope layout in order to meet the various requirements as effectively as possible.

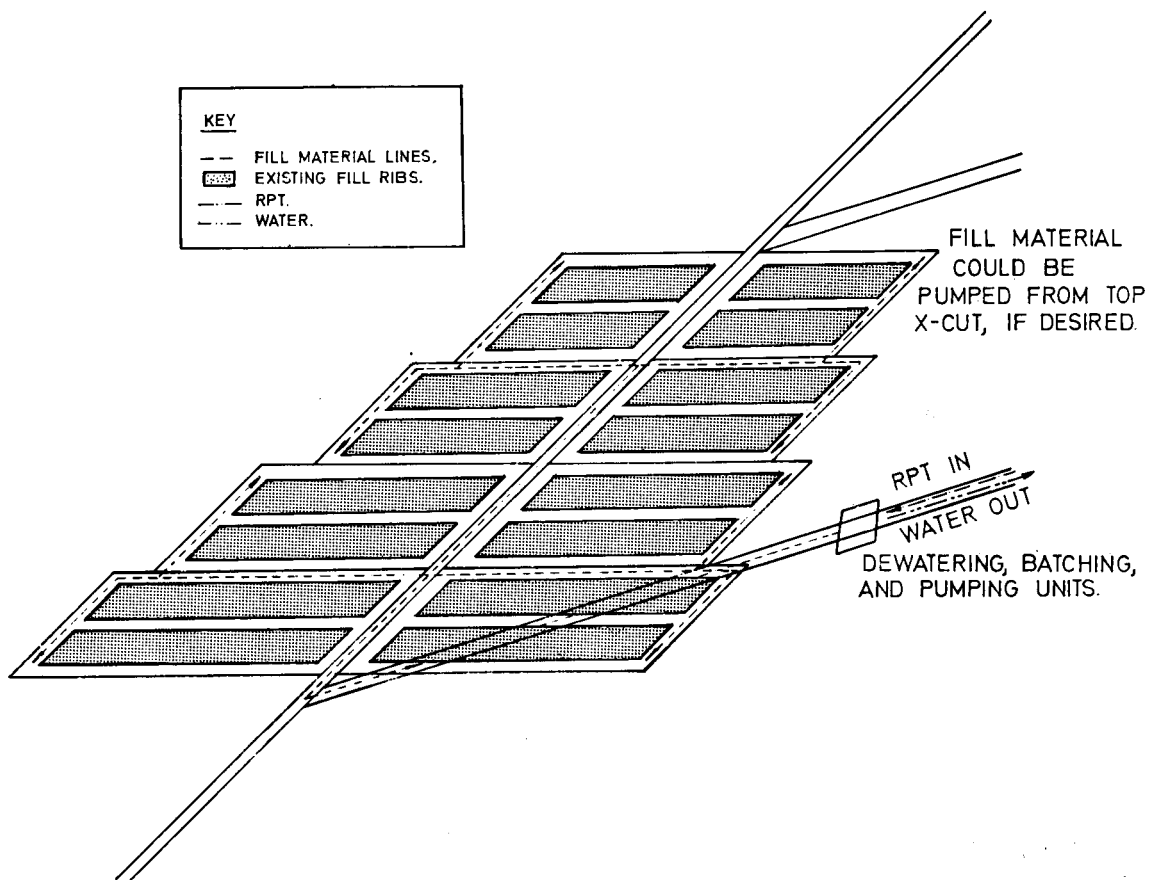
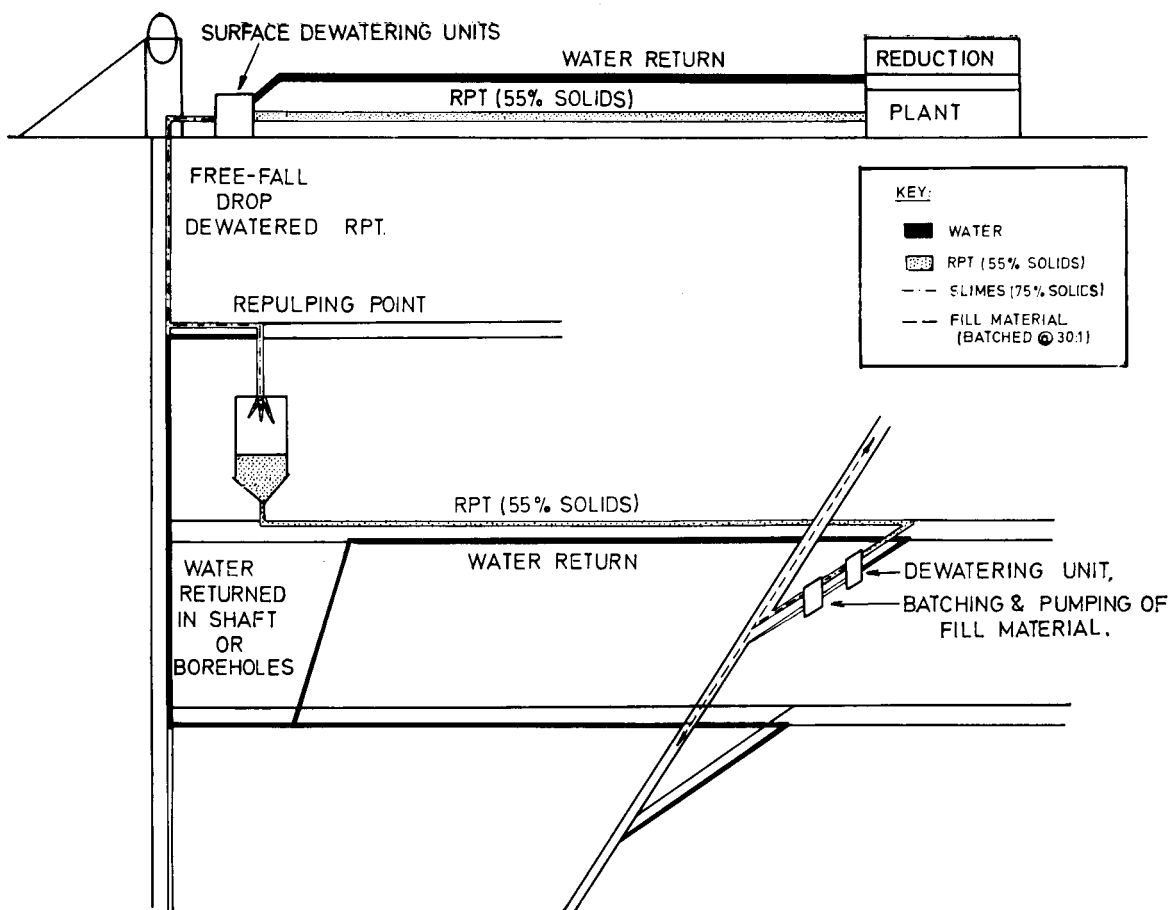
### **Immediate Face Support**

Two factors govern the build-up of strength in a rib pillar. The first is the compaction generated by stope closure, and the second is the cohesion developed by the bonding agent. In both cases, the development is time-dependent and it is necessary to consider face support as separate from rib-pillar support.

Since it is impossible to develop a practical fill material that achieves a rapid and acceptable early strength, rib pillars cannot be expected to provide adequate support for face operations, and immediate face support systems are therefore required. Ideally, the face support and fill support systems should be compatible, and should not have redundant or duplicate functional members. If hydraulic props and pneumatic placement are used on a per-blast basis, packs and sticks on the face can be eliminated. Experience with the hydraulic props at present available indicates that, even under adverse geological and stress conditions, faces can be kept open and stoping maintained at the desired width and on the desired horizon. Experience also indicates that, given adequate motivation and supervision, all operations including sweeping can be maintained within the prop-supported area for stoping widths of up to 2 m. No experience is available for stoping widths greater than this. If it can be accepted that access behind the last row of props is not required and will not be allowed, then the rib pillars can be maintained right up to this point and maximum benefits will be gained. A viable fill support system requires that three (or four) rows of hydraulic props should be used for immediate face support, that all stoping operations should be absolutely confined to the prop-supported area, and that fill should be placed as a part of the stoping cycle on the basis of advance per blast.

### **Ancillary Features**

Other considerations must be taken into account in the design of fill support systems. They are not directly related to material properties and placement operations, but, if they are neglected or ignored, they cause the system to be less efficient than possible and could even cause it to be rejected as unacceptable in the practical operating environment. Communications are particularly important among these in view of the confined conditions at the point of placement and scattered working places. Other factors include dust suppression,



start-up and shut-down procedures, safety, and protective clothing.

### Proposed Fill System

A proposed fill system is shown schematically in Figs. 11 and 12, and consists of surface and underground reticulation systems (Fig. 11) and a stope preparation and placement system (Fig. 12).

The RPT are pumped from the reduction plant to the shaft bank. At the shaft bank, they are dewatered and dropped down the shaft in a suitable column, the water being returned to the reduction plant for re-use. Dewatering the RPT before they are dropped into the mine eliminates the need to pump large quantities of water back out of the mine.

At a suitable level underground, the RPT sludge is diverted and repulped to a suitable water content. It is then pumped as a slurry to the various working places throughout the mine. At a point near the stoping — probably in an adjacent cross-cut — the material is dewatered again, the water being returned to the shaft bottom to repulp more incoming sludge. The dewatered RPT are collected, batched with the appropriate amount of cement, and pumped into the stope. The material is then blown by pneumatic nozzles onto the ends of the strike ribs.

So that the practicability of such a system could be evaluated, a pilot scheme was run on surface. This was in no way intended to represent the actual system proposed or the equipment likely to be used, but was simply meant to test the concepts involved. RPT slurry was obtained from the Western Holdings tailings line at about 50 per cent solids and was dewatered in a 46 cm by 71 cm centrifuge. This was a small research unit capable of supplying about 1 ton of dewatered RPT per hour. The dewatered material was then placed on a wet-mix Shotcrete machine that had both mixing and placing capabilities. Cement in low proportions was added and mixed in, and the resulting fill material was then blown into place in a mock stope. See Figs. 13 and 14. The mock stope included sticks on 1 m centres to represent hydraulic props and had moveable shutters to represent the hangingwall and face. The footwall consisted of a 2-inch layer of Shotcrete. These trials proved to be completely successful, bearing in mind the original objectives. Completely untrained Africans quickly learnt to operate all the equipment and became very adept at placing the material effectively. Some 30 m<sup>3</sup> were placed in this manner, and specific gravities from 1.7 to 1.9 were achieved.

On the basis of these trials and the results achieved, it was concluded that the general concepts involved were reasonable and provided an adequate foundation upon which a complete fill support system could be developed. Given this general concept, detailed consideration could be given to optimization of the various operations involved and their inter-relationships.

### Pumping Requirements

The pumping of relatively dilute (40 to 60 per cent solids by mass) RPT slurries is not considered to be a problem<sup>9</sup>. The necessary technology exists, and con-

siderable experience with long-distance pipelines conveying this type of material is available. There is no need to flush lines prior to the cessation of pumping; restarting is a routine operation in the pumping of slimes provided adequate attention is paid to the layout and gradients of the pipeline. There is no settling or dropping out of particles during pumping if an adequate velocity is maintained. Finally, wear in the pipelines is usually negligible, and the proper selection of pumps yields acceptable wear and costs on these items.

It may well be possible to design a system using a gravity pressure head only. While initially attractive, this system is unlikely to be as versatile or as simple as a pump system, and it would probably be more difficult to co-ordinate and control.

### Dewatering

Of all the operations involved, dewatering is of crucial importance and is the most difficult to do. The main problem is the extremely fine nature of the RPT. The techniques that are generally available at present are based on filters or centrifuges, and for a variety of reasons these are not suitable for use in the underground mining environment.

Detailed consideration was given to two potential systems. The first consisted of two cyclone stages feeding a vibrating dewatering screen, and the second a proprietary device still in the development stage. The decision was made to concentrate on the latter, and the results to date are sufficient to indicate that underground dewatering units for use on gold RPT are practical.

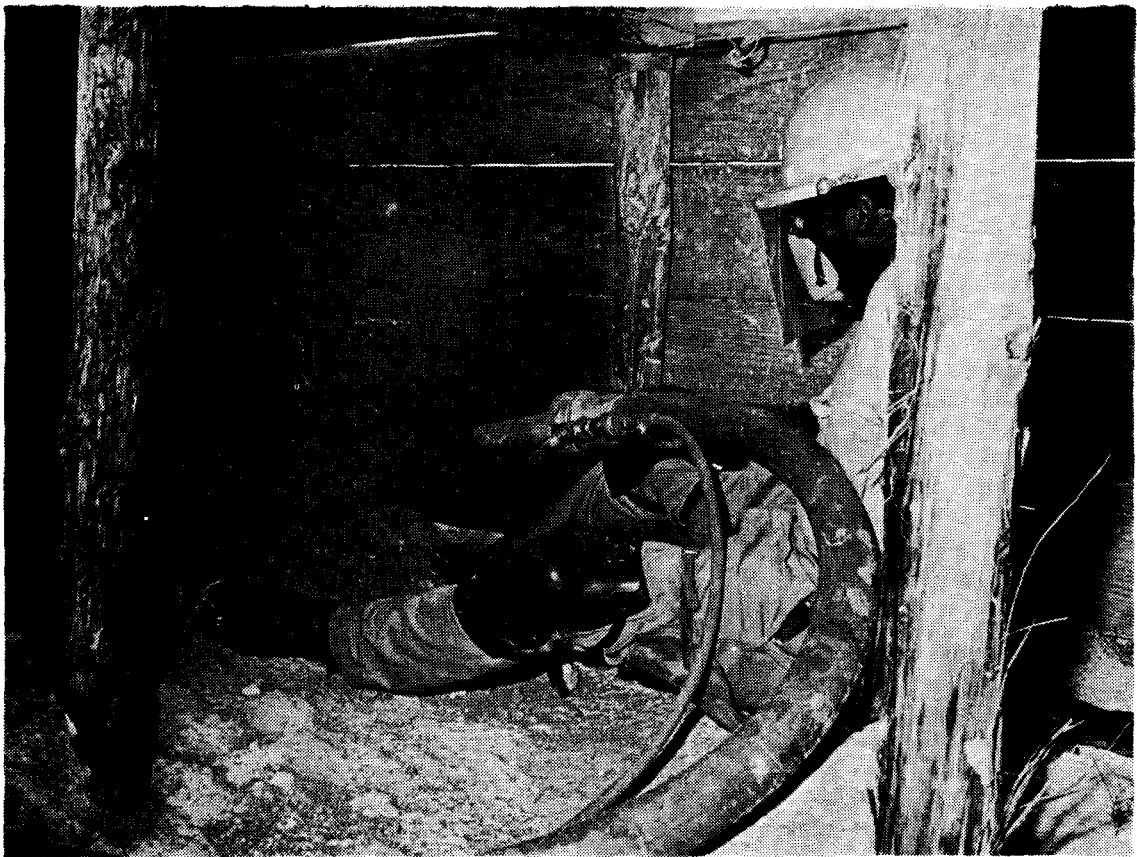
### Batching

The testwork (both in the laboratory and the field) has established that dry cement powder can be adequately mixed into damp RPT at the mixing times used for conventional concrete. It is preferable to use a continuous mixing system rather than a batch process. Several concepts, such as vane mixers in the outlet line of the fill pump and ribbon-type open-scroll screw conveyors, are under consideration.

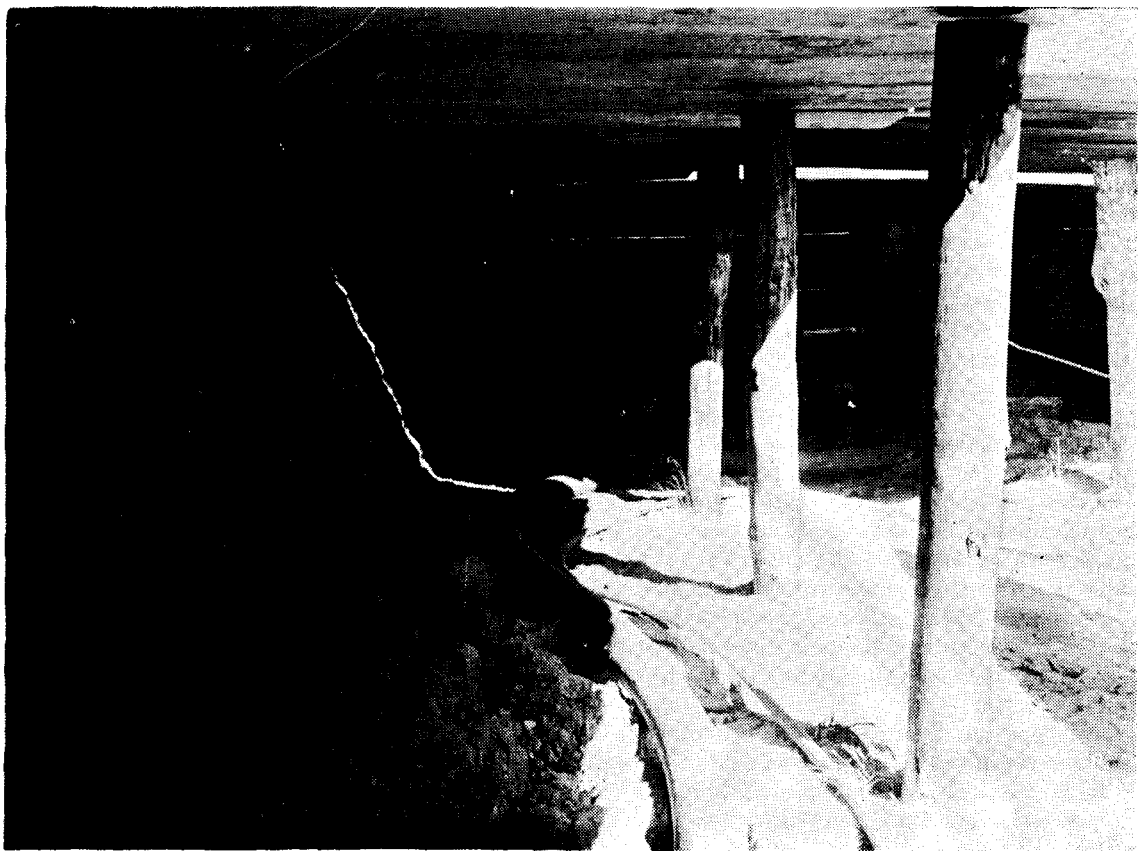
Pneumatic transport is the most convenient and economical method of conveying large quantities of cement underground, but this is impractical for the horizontal distances involved. This latter movement can best be performed by large-capacity, dry-cement tank cars. These can serve as both transport and storage units, thus eliminating cement storage problems in the immediate stoping area. Since these cars need not be handled full in the shafts, capacities of up to 12 t per car are feasible and practical.

### Transport and Placement of Fill Material

At the moisture contents envisaged, the RPT fill material behaves like a stiff cement mortar. Very extensive enquiries, involving over thirty manufacturers, were made into a wide range of equipment used in the handling and placing of Shotcrete, concrete, cement, and plaster. These enquiries established that suitable pumps for the handling of up to 100 m<sup>3</sup> per hour are readily available. Aids to the handling of fill material, such as plasticizers and fluidizers, are also being investigated.



**Fig. 13—Fill material being blown into place in a mock stope**



**Fig. 14—Another view of the mock stope**

In view of the very fine nature of the fill material, abrasion is not likely to be a serious problem and the reticulation system for the fill material can consist of either conventional mild steel or plastic pipe. All bends and curves will be made of armoured rubber hose rather than of conventional pipework.

Pumping does not supply an adequate velocity to place the material on the end of the strike rib, and hence a pneumatic nozzle such as is used with wet-mix Shotcrete is necessary. This is an important aspect of the operation since the high velocity of impact ensures a dense fill that is completely tight against the hanging and footwalls. It may also eliminate some free water and allows good control over quality. Placement rates of up to 10 m<sup>3</sup>/h can be achieved manually in Shotcrete applications. This rate is higher than required, and, since a lower quality of work is acceptable in filling, manually held nozzles can be used. In the congested environment on the face, this is advantageous since it eliminates another mechanical system in the area.

### Labour

Careful consideration was given in the design and evaluation of all equipment to minimize labour requirements in both operation and repair and maintenance. It may also be necessary to reconsider working procedures in the stoping operations themselves.

### Transportability

All units are being designed to fit into standard mine cages and to be suitable for transport either on ordinary mine cars or as rail-mounted systems. A modular system of standard-capacity units is being used. These units are assembled on the multiple-unit principle to achieve any desired overall capacity. This increases utilization, simplifies repairs and maintenance, and reduces spares stocks.

### Economic Evaluation

It is difficult and time-consuming to evaluate in detail the economic implications of fill support systems. This is particularly the case with potential gold-mining systems since many of the techniques have yet to be proved and mine-wide layouts are available only in conceptual form. The breakeven point for a fill support system used in routine stoping is when the placed cost of the fill equals the installed costs of the support replaced. It is very difficult to evaluate other less tangible factors. The main savings will be in materials, primarily timber (which is offset somewhat by the cost of cement) and total labour, both of which are rapidly increasing in cost and decreasing in availability. The main limitation at many shafts is not rock-handling capacity but men and materials handling. Since rock- and materials-handling facilities are not usually interchangeable, a saving in the latter may be much more valuable and useful than an increase in the former.

Thus far it has not proved possible to establish a unique value or set of values for the cost of conventional support. It is relatively easy to establish the direct costs of the materials but much more difficult to establish the final installed costs. Nevertheless, preliminary economic analyses indicate that fill support is eco-

nomically competitive with conventional support on a direct replacement basis, and that it offers considerable potential savings under difficult or awkward stoping conditions. It was found that cost per cubic metre filled is a much more useful criterion than cost per centare filled. Use of this factor allows the extrapolation of costs to varying stoping widths since the operating costs involved are relatively independent of scale.

Many other advantages can be claimed for the fill system envisaged, but their monetary value is either difficult to assess or varies considerably. Hence, their final values in a particular situation are essentially those placed on them by management in a judgemental fashion. The value of these is also dependent upon the proportion of filling used relative to total stoping activity. Those potential benefits include the following:

1. improved regional support and reduced face stresses,
2. improved ventilation control and effectiveness,
3. reduced fire hazard,
4. relative insensitivity to increased costs,
5. potential for concentrated stoping,
6. ability to work high stoping widths at high rates of face advance,
7. ability to work at greater depths,
8. better control of support costs,
9. elimination of tramming and storage congestion underground,
10. reduction in hoisting of support materials,
11. application to geologically difficult or unusual ore-bodies, and
12. water savings on surface tailings dams.

### Conclusions

It has been concluded that a fill support system based on the materials and concepts discussed is viable both practically and economically. Certain development work remains to be done primarily in the dewatering areas. Intensive work is in progress on dewatering investigations, and a detailed study of the pumping of high-density materials has started using a 250 m test loop. A complete system is now being assembled for extensive surface trials prior to testing underground. The results of this work will be published in due course.

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