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Mining Grouting in South African Deep Mines

Historical Overview and State-of-the-Art

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ABSTRACT:

The South African Mining Industry has been declining drastically.

The most important reasons are:

a) Some large gold fields and mines have come to the end of their economic life.
b) South African mines are deep and hence mining is costly, therefore, competitiveness on a worldwide basis is decreasing.
c) Productivity is low.
d) The gold price is low.

With the limited life and limited number of deep gold mines, the water control and grouting techniques utilized under these conditions may also phase into oblivion.

Therefore, in this paper the author gives a historical overview of the cement grouting methods developed in the deep mines in South Africa to control water. At the same time, the author presents a State-of-the-Art summary of the South African Mining cement grouting techniques, which have been and are being utilized successfully in the deep mines.

Some material has been presented at earlier IMWA congresses and other conferences but for the benefit of South African mining engineers and to celebrate the first IMWA congress being held in South Africa, it seems appropriate to present Mining Grouting in South African Deep Mines at this congress.

INTRODUCTION:

The South African Mining Industry is the largest producer of gold in the world. However, during the past few years' production has been declining drastically from a peak production in 1970 of 1000 tons to approximately 490 tons in 1997; production in 1998 is set to decrease again by approximately 5 to 7%. During the peak production, South Africa produced at 1000 tons, approximately 80% of the world's total production whereas the present 489.2 tons make up approximately 20% of the present world production.

The gold mining industry has always been a major foreign exchange earner for South Africa and its most important employer; from over 500 thousand employees the industry has now reduced to less than 200 thousand. The large mining houses have rationalized their production and closed many shafts in the process. At present (1998) new strategies in this industry seem to be tending towards developing shallow, open cast mines outside South Africa and to concentrate on very few, very deep mines with high gold grades.

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HISTORY OF MINING GROUTING

Gold was found in the Witwatersrand area in 1885. Soon it became apparent that water could become a problem for some of the deeper mines. In general, South African mines are not "watery" mines when compared to some of the copper mines in Zambia. Nevertheless, in some parts of the gold fields, mine workings are overlain by water bearing formations such as dolomites with almost unlimited water storing capacity and very high transmissivity. Several shafts and some mine sections, have been lost due to flooding. Most have been recovered though, at great cost. In some mines, such as Oryx, excessive water is still an important cost factor as well as a hazard.

Soon after gold production started mines encountered water problems, which ultimately lead to the development of a grouting process characterized by high pressure grouting and specifically designed thin slurries. In South Africa, the introduction of cement grouting into the mining industry must be attributed to Monsieur Albert Francois, a Belgian mining engineer and entrepreneur. After developing the cement grouting process in Belgium and Yorkshire, by using pumps successfully, he came to South Africa in 1917. (Parry-Davies, 1995). Francois applied his patented cementation process for the first time at ERPM. Initially, he established the Francois Cementation Syndicate under the auspices of Rand Mines Ltd. In 1919 the Francois Cementation Co. Ltd. was incorporated first in England, with Albert Francois as the first managing director and then the Francois Cementation Company (Africa) was established, to facilitate operations in Southern Africa. The Francois Cementation Company was instrumental in the development of cement grouting during those years.

At the same time as Francois Cementation Co. (Africa) was developing mining grouting techniques in South Africa, RODIO, which was founded in 1922 developed grouting methods for dams and other foundations during the great dam building era in Switzerland, France and Spain.

A new impetus to cement grouting resulted from the extension of the original Witwatersrand Goldfields around Johannesburg to the Far West Rand Goldfields. Several shafts had to be abandoned at great cost in that area; as early as 1912 a shaft had to be abandoned at Venterspost. The main problems were the water carrying dolomites, which were overlying the gold bearing rock in these areas.

A further tremendous impetus to the mining industry resulted from the Orange Free State Gold Field around Welkom, which started developing rapidly during the fifties.

MINING GROUTING IN SOUTH AFRICAN DEEP MINES

The unique environment in South Africa created specific methods and technologies, which have been developed over many years in the deep mines in South Africa. In essence most methods relate to or are a result of the very high water pressures encountered at large depth. In this paper, the author endeavours to present a summary of these methods, which have been developed for deep mining specifically with respect to water control and grouting.

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The most significant differences between South African Deep Mine Grouting and other types of grouting, are the extremely high pressures used for grouting and the relatively thin (unstable) cement mixes used.

In 1956, RODIO entered the South African mining industry and introduced several new techniques which were based on European developments in grouting engineering:

1. With RODIO's European background and origin, it advocated the use of even higher pressures up to 30MPa or higher and soon made its mark on the industry (Du Bois, 1963).
   Rodio had the equipment and gained an excellent reputation for underground cementation. RODIO commenced work at Stilfontein, James Shaft under extremely difficult conditions. Stilfontein Gold Mine operated under dolomite and was considered a wet mine.

2. By empirical means, RODIO found that high speed mixing produced the highest quality cement slurry least susceptible to sedimentation. Therefore, from its commencement of work in South Africa RODIO used colloidal high shear mixing methods. The word colloidal had not been applied in this context at that time. As RODIO used relay stations underground the cement slurries were batched on surface by high shear colloidal mixers and transported underground to be reconditioned and distributed by relay stations.

3. RODIO, as a specialist geotechnical contractor with its origin in the civil engineering industry, also advocated the use of packers in the boreholes used for grouting.

4. RODIO generally used relatively "thick" slurries, although still thin and unstable by normal civil engineering standards.

The grouting techniques used in the deep South African mines have been successful although by some standards (Houlsby, 1982) these methods are not acceptable. In general, the South African mining grouting is akin to the European classical method, which uses much higher pressures (within limits) ie. 1 kg/m^2 (1 bar) per metre of depth as compared to the Australian/American practice of using 1lb/sq.inch per foot of depth. The latter rule is lower by a factor of 4 and is equivalent to 0.23 kg/cm^2 per metre of depth.

The European grouting technique, developed in the twenties and thirties by among others RODIO, can be characterized by the use of relatively high pressures and by grouting mixes of W:C ratios that would be flexible and changeable as the fissure treated required, implying a relatively thin (unstable) mix to start, thickening gradually to avoid choking.

Although slurries as thin as W:C:8:1 were rarely used, W:C ratios of 6:1 and 4:1 to commence were quite common. Of course, pressures of 1 bar/metre depth were quite common e.g. at Alcantara (Spain) completed in 1969 the following max. pressures were used: Stages 20 - 30m, 25kg/cm^2 and deeper than 30m, 35 kg/cm^2. Similarly at Almandra

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Dam (Spain) completed during 1970 (height 197m) grouting pressures for the 40 - 60m stages were 40kg/cm² and deeper than 60m; 60kg/cm².

In South African Deep Mines water pressures at a depth of approximately 2000m normally reach 70 - 80% of the theoretical hydrostatic water at that depth. Therefore, if the water table is close to surface, a water pressure of approximately 14 to 16 MPa can be expected. In order to grout effectively at this depth a grouting, sealing pressure of 50% higher is required, resulting in 21 MPa to 24 MPa.

What is generally little understood, is the fact that at these pressures, no particulate suspension is stable and forced sedimentation (pressure filtration) is ever present. The normal criteria of limiting bleed to 3 to 5 % in a decantation cylinder is meaningless in this context.

It is important to realise that "stable" grouts are really grouts stable under gravitational forces only. Therefore, stable means that either sedimentation is so slow that it is negligible or thixotropic action, hydration or other reactions and possible forces prevent sedimentation.

In order to reconcile the mining grouting technique and civil engineering grouting methods, which are diametrically opposite in philosophy and application, it is important indeed necessary to differentiate between STATIC PHASE and DYNAMIC PHASE grouting (Heinz, 1995).

The ideal STATIC PHASE is shown by cement slurry settling in a measuring cylinder where sedimentation is predominantly influenced by:

> **particle interference, gravity, very low particle velocity, almost stationary continuous phase, laminar flow.**

A classical, practical example of static phase grouting is the COLCRETE or ROCRETE methods where voids of a coarse gravel are filled at low pressure by cement grout. Hence low pressure, low velocity grouting (permeation grouting) is so similar to the "ideal" static phase that it can be categorised as static phase grouting; in fact, plug flow or low velocity laminar flow would fall into this category.

In contrast, in the DYNAMIC PHASE of cement grouting the sedimentation process is predominantly regulated by:

> **High velocity resulting from high pressures, forces which change the resultant force on the particles in contrast to gravity only, different velocities for the suspended particles and suspending phase, selective and forced sedimentation sometimes also referred to as pressure filtration, turbulent and laminar flow, ratio of particle velocity to suspending fluid velocity.**

Typical examples are high pressure grouting e.g. cover grouting in South African deep mines.

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Both phases require control and manipulation. It is incorrect to assume as is often done that if the static phase is "stable" the dynamic phase is also "stable". Stable in the dynamic phase requires the properties of the grout to remain essentially **similar before and after moving through the rock mass**. It must be assumed that even in static phase grouting some forced sedimentation does occur though it may be negligible as is evidenced by the filter cake formation during diaphragm wall construction.

Differentiating between static and dynamic phase grouting enables one to determine practical and scientifically based parameters relating to the various phases; boundary limits of application in analogy to the differentiation between laminar and turbulent flow by the Reynolds number can be established. These parameters will have to be developed but will have to include possibly the sedimentation velocity in relation to the velocity of the slurry in the fissure, the reaction of the rock structure and pressures (in situ static water pressures, grouting pressure etc.)

Specific techniques which have been utilized successfully in the South African deep mining context include the following: (Heinz, W.F. 1991)

1. **Dewatering of Regional 'Compartments'**
   Compartments are areas of several square kilometers enclosed by near impervious dykes, faults etc which are dewatered to enable mining activities to proceed under these 'compartments'
2. **Precementation of Deep Shafts**.
   Precementation has been applied successfully to overcome difficult hydrological conditions during shaft sinking and the initial development of the mines.
3. **Cover Grouting and Drilling under High Water Pressures.**
   Special drilling and grouting techniques have been developed to allow safe and efficient advance during shaft sinking and development of mines.
4. **Conveyance of Cement and other Slurries for Cement Injection and Support Systems**
   Underground relay stations facilitate cement injection at practically any distance from the shaft (up to 6km) and at any depth (up to 4000m).
5. **Development of Robust High-Pressure Plunger Pumps.**
   Electro-hydraulic and air-driven plunger pumps capable of achieving pressures up to 50MPa have been developed over the years and are universally used.

1. Dewatering of Regional Compartments

Water control in deep mines is naturally more hazardous mainly for two reasons being the high pressures at which water may occur and the high temperatures. Associated with these problems is the high cost of pumping water to surface. (For historical data see Table 1, Kleywegt, 1982).

Therefore, dewatering of entire regional compartments is an interesting option as has been successful particularly in the Far West Rand, which covers an area of approximately 1500

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square kilometers to the south west of Johannesburg. Igneous intrusions in the form of dykes subdivide the areas into reasonably watertight compartments. (Heinz, 1991)

In order to facilitate the dewatering of compartments and find equitable solutions for all parties concerned and to solve problems related to dewatering, legislation was introduced in 1956. The Act of 1956 introduced the basic principle that the mine, which caused the sinkholes by dewatering, is to compensate the damaged parties.

During the past three decades, enormous strides towards the understanding of the effects of dewatering in dolomite have been made:

a) Over 4000 boreholes have been drilled to considerable depths in the area;
b) Intensive gravity surveys have been made;
c) Data from shaft sinking operations and other mining activity have been collated and evaluated.

Recently risk assessment in these dolomites before dewatering have been made based on aerial surveys, geophysical data, borehole data and water table monitoring.

Preventive measures are now introduced where dewatering is to commence.

Research has indicated that the following factors affect subsurface stability:

- The position of the original water table.
- The presence of weak manganiferous residuum (Wad).
- The character of any overlying material.
- Steeply sloping bedrock contours.
- Bedrock pinnacles.
- Susceptibility to erosion of the ground profile.
- The ponding of surface water.

The most recent permission to dewater was granted in 1986 to dewater the Gemsbokfontein compartment.

For the first time in South Africa, significant preventive measures were taken before dewatering commenced. Indeed, the permission for dewatering was granted on the basis that the high-risk areas be treated by grouting prior to commencement of dewatering.

The Gemsbokfontein compartment is not densely populated, however, an important traffic route crosses the compartment. In order to protect this highway against possible sinkhole development a grouting technique was developed to stabilize the areas classified as high risk.

An extensive grouting programme was executed, where 44,000 m^3 of grout was placed over 2.7 km of highway. Grout holes up to 30m were drilled. Since the start of dewatering no major subsidences or sinkholes have developed in the high risk areas which have been grouted. The grouting can be regarded as successful. (Gregory, 1988).

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TABLE 1: HYDROLOGICAL DATA OF SOUTH AFRICAN MINES

By volume:

MEGALITRES PER DAY	MINES PUMPING OUT WATER		MINES SENDING WATER U/G		MINES 'MAKING' WATER	
	NO. OF MINES	TOTAL QUANTITY	NO. OF MINES	TOTAL QUANTITY	NO. OF MINES	TOTAL QUANTITY
0,01 - 2	4	5.35	13	8.28	9	5.87
2,01 - 4	4	11.70	6	18.73	6	2.23
4,01 - 6	7	33.68	5	25.07	5	23.80
6,01 - 8	2	15.20	5	35.87	1	7.51
8,01 - 10	3	27.00	1	8.46	3	24.46
10,01 - 12	3	34.22	2	23.51	1	10.79
12,01 - 14	5	65.32	0	0.00	4	52.20
14,01 - 45	9	254.82	3	58.08	7	201.86
Over 45	4	360.70	0	0.00	3	301.26
TOTALS	41	807.99	35	178.00	39	629.98

By area:

AREA	NO. OF MINES PUMPING WATER	TOTAL QUANTITY PUMPED (Mℓ/DAY)	NO. OF MINES SENDING WATER DOWN	TOTAL QUANTITY SENT DOWN (Mℓ/DAY)	NO. OF MINES MAKING WATER	TOTAL QUANTITY MADE (Mℓ/DAY)	AVERAGE QUANTITY MADE PER MINE (Mℓ/DAY)
FAR EAST RAND	5	35.56	5	8.87	5	26.69	5.34
EAST RAND	3	22.19	0	0.00	3	22.19	7.40
CENTRAL RAND	2	60.98	2	13.48	2	47.50	23.75
WEST RAND	2	78.24	2	8.72	2	69.52	34.76
FAR WEST RAND	11	392.12	9	43.15	9	348.96	38.77
KLERKSDORP AREA	7	114.88	6	37.58	7	77.29	11.04
ORANGE FREE STATE	11	104.03	11	66.20	11	37.83	3.44
TOTAL & AVERAGES	41	808.00	35	178.00	39	629.98	16.15

2. Precementation of Deep Shafts.

During the late forties and early fifties when the development of the OFS gold fields gained momentum and many shafts were sunk, the delays experienced during sinking of shafts as a result of water bearing strata were significant. During 1959/1960, 37 shafts were in various phases of development on the South African gold fields.

For example during sinking of Harmony Gold Mine, Shafts No.3 and the ventilation shafts, 100 days were lost per shaft due to cover grouting and drilling to a depth of only 579m (1900

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ft). These costly delays led to the development of precementation or pregrouting of deep shafts in South Africa.

The most obvious solution was to extend the high pressure grouting methods developed by Francois during the twenties to the pregrouting of deep shafts. One of the first shafts to be pregrouted was Harmony GM No.2 shaft. The pregrouting of this shaft was a great success when compared to other shafts sunk in the area, (Newman, 1956) as the following table shows:

Harmony Shafts:	**Shaft No. 3**	**Ventilation Shaft**	**Shaft No. 2**
Depth (m)	600 (1970 ft)	579 (1900 ft)	610 (2000 ft)
Cement injected:			
a) During pregrouting (t)	-	-	733t
b) During sinking (t)	995t	1036t	60t
Cover grouting & drilling delays	100 days	100 days	9 days

Some interesting aspects of the precementation of No. 2 shaft were:

1. Grouting pressures applied were 1lb/sq. inch per foot depth at collar (within limits).
2. Length of grouted stages: 30 to 37 m (100-120 ft).
3. Grouting was also done through hole deflections to improve results.
4. Retarder was used to reduce time spent on redrilling.
5. In addition to the normal stages, grouting was done on water loss in the hole and above known contacts.
6. Three holes were drilled to pregrout Shaft No. 2.

After this initial success, precementation of deep shafts gained rapid momentum.

Many shafts were pregrouted during the past 40 years on the gold fields in South Africa. Most pregrouting exercises were successful, however, there were some notable failures of shafts that had been pregrouted and were flooded during sinking. Best known to date are Western Deep Levels No. 1 Shaft (Solms, 1984) and Westonaria South Deep Shaft. Shaft No. 1 of Western Deep Levels was pregrouted with 3 boreholes, whereas South Deep was pregrouted with one borehole only.

Some interesting conclusions based on experience over many years are as follows:

1. Precementation of deep shafts is technically feasible and can be economical.
2. Precementation increases the safety of the shaft sinking operation.
3. Precementation minimizes the water and gas inflow during shaft sinking.
4. Precementation reduces the time lost due to grouting during sinking operations. Costly delays and standing time of the sinking crew and equipment is significantly reduced.
5. Precementation improves rock strength for excavations (stations, etc) in the immediate vicinity of the shaft areas.

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6. Precementation provides advance detailed geological information that may be important for the mine as well as the contractor.
7. Precementation minimizes interruption during sinking, allowing the sinking crew to establish the preplanned rhythm of sinking operations.
8. Initially, pressures according to the rule 1lb/sq. inch per foot depth up to 2000ft was used, however, this was found too low so that the rule of grouting to 2.5 times the hydrostatic water pressure was introduced and seemed to work satisfactorily within limits.

Several additional observations based on precementation in general may be of interest:

1. The behaviour of grout including the distance of travel, penetration, etc., the actual grouting procedure, optimal grouting pressures still require research and more experience.
2. Equipment such as pumps and drill rods, has a shorter life due to the high abrasion characteristic of cement.
3. The presence of wedges remains a hazardous factor, nevertheless good results have been obtained. Where grouting is required at larger depths only, deflections facilitate a more economical solution by using one master-hole in the upper, tight zone and by grouting from deflections further down. Deflections can also improve the angle at which fissures are crossed once the fissure direction is known.
4. A meticulous and comprehensive site investigation is a prerequisite for the success of a precementation operation. In particular the determination of the natural drift of boreholes in the area may reduce the number of wedges required and hence reduce the overall risk of the drilling operation.
5. Piloting by large diameter percussion drilling is not recommended due to the greater deflection of holes, spiraling of boreholes, etc., with this drilling technique.
6. One borehole per shaft may be adequate under certain circumstances as additional deflections can be achieved by guiding the borehole around the shaft by the installation of wedges.
7. Although cement is normally redrilled with non-coring bits, in certain cases the prints obtained from fissures in cement cores provide interesting information on the way the grout entered the fissures and on the deformation of the fissure under pressure during the grouting procedure.

3. Cover Grouting and Drilling Under High Water Pressures

The first approach to base cover grouting and drilling on a more scientific basis was attempted at Western Areas Gold Mine in 1976. During this period, development at this mine was severely delayed due to intersection of water and time consuming injections of cement. The BRGM (Bureau de Recherches Géologique et Minières) was consulted as it is renowned for its expertise in hydrogeological work. The BRGM's recommendations related on three aspects (Coetsee, 1978):

a) Structure of rock mass
b) Permeability of rock mass
c) Grouting technique

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This project was successful and emphasized that a systematic, scientific approach was necessary; conclusions were as follows:

1. A structural and permeability analysis is essential for any attempted development in dolomite. The analysis provided data regarding the direction and attitude the haulage should take during development.
2. Careful monitoring of the grouting technique prevents unnecessary wastage of labour, material and time.
3. An attempt should be made to inter-connect the grout during injections between the various boreholes as this controls the flow of grout within a sphere of predetermined influence for the haulage.
4. An increase in the number of boreholes in a ring cover is preferable to an excessive injection of large quantities of grout. The control of boreholes is superior to the control of cement grouting, particularly with respect to quantity (time).
5. Due to the capability of small fissures to emit large volumes of water, it is imperative that the grouting is effective and efficient. Blasting can easily open inadequately sealed fissures, with catastrophic results.
6. The grouting of each water intersection of a borehole is a unique exercise. Treatment varies according to the inter-connection between the water intersections of the boreholes and the width of the fissures.
7. Drainage and support of major unstable fissures are essential once development has penetrated through them, to prevent any sudden inrush of water.

In an extension of this method and prompted recently by similarly difficult water problems, it was necessary to further develop this rational approach to cover grouting and drilling. This new rational approach to cover grouting evolved during the past decade and was presented in detail at the 6th IMWA symposium in Bled (Heinz, 1997). The method is summarized subsequently:

The objective of cover grouting is related to safety; nevertheless, disruption to routine mining operations should be minimal. In order to maximise the advance, it is essential that the cover grouting procedures and the materials used, be tailor-made to the specific conditions existing on the mine. Cover drilling and grouting in the context of shaft sinking are essentially the same as required for normal routine mining operations.

In essence, cover drilling and grouting procedures depend on:

1. The type of rock formation (strength, fissure characteristics, drillability, groutability etc.)
2. The existing water regime (water table, pressure, direction and volume of flow).
3. The fissure and water regime dynamics (the fissure behaviour as a function of time as induced by the mining operation).
4. The specific mining method.
5. The cover grouting technique:
   a) The type of drilling (percussion and/or diamond drilling)
   b) The grouting technique (equipment, grouting pattern, pressure)
   c) The grouting material used.

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In general, in previous years, cover grouting techniques have been reasonably successful, although cement slurries were injected rather indiscriminately. The basic grouting techniques originated from earlier periods of mining where grades were higher, labour costs lower and material costs, such as cement, also lower.

As cover grouting is always an additional cost to mining, it is imperative that these costs are minimised without sacrificing safety, yet allowing maximum speed of advance. Even under conditions where cover grouting activities are not on the critical path of the main stream mining activity, cover grouting activities are probably on a sub-critical path in most mines. Where cover grouting is executed simultaneously with development, it may disrupt the mining activities.

A prerequisite to control water and operate underground in safety is a comprehensive analysis of the existing water regime, the creation of a hydrogeological model, its key parameters such as water table, direction and volume of flow and its key dynamics such as changes as a result of mining action.

The following Steps I - VII indicate a systematic and rational approach to designing and implementing a tailor-made grout cover technique which, if properly executed, should result in an optimal, economical result and most importantly an increased speed of advance at acceptable safety standards and acceptable water inflows.

STEP I - ***Drilling Productivity Curve***

Based on these curves, Fig. 1a) and 1b), (for core and percussion drilling) an optimal drilling cover pattern can be designed. In general, percussion drilling is faster and hence less expensive and typically deflects more than diamond core drilling; diamond core drilling is safer and preferable for high water pressures but slower and hence more expensive. It is important to remember that typically the control of boreholes is superior to the control of grouting techniques.

STEP II - ***Determine Water Intersection Pattern***

Determine and analyse the characteristics of the water intersections. Volume of flow and pressure at water intersections should be measured routinely.

A frequency histogram showing water intersections should be compiled as shown in Fig. 2.

Pressure and volume must be monitored at each water intersection. This will furnish the mine specific type of intersection pattern. It may vary for different areas of the mine.

STEP III- ***Grouting Effectiveness Curve***

The total time taken to achieve the required sealing is vital to the effectiveness of the grouting exercise.

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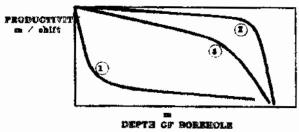

FIGURE – 1(a) : Productivity of drilling equipment.

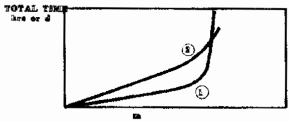

FIGURE – 1(b) : Total meterage of grout cover (per cover).

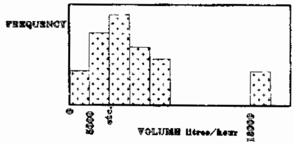

FIGURE – 2 : Frequency histogram of typical water intersections.

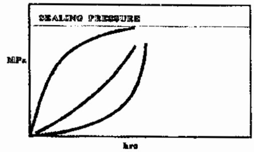

FIGURE –3(a) : Time taken per intersection to reach sealing pressure.

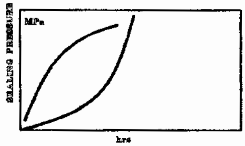

FIGURE –3(b) : Time for all fissures per borehole.

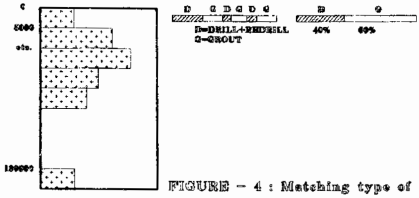

FIGURE – 4 : Matching type of intersection with time taken to drill and grout.

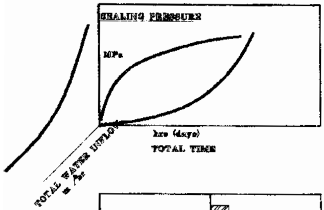

FIGURE – 5 : Total water inflow into mine as a function of sealing pressure typically used on mine.

FIGURE – 6 ; Possible fissure sizes and frequencies for typical cover grouting and drilling.

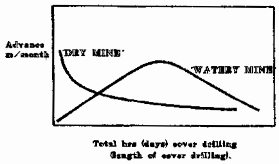

FIGURE – 7 : Mining advance against time spent on cover drilling and grouting.

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The grouting effectiveness curve envelope is shown in Figure 3(a). The total time required for each borehole cover must also be shown as a function of the sealing pressure. The underlying assumption here is that higher sealing pressures will result in a longer grouting time required to achieve this pressure. Fig. 3(b).

STEP IV - ***Matching Water Intersection with Grouting Procedures***

Matching of the type of water intersection with the time required for drilling and grouting is an important consideration. If maximum benefit is to be achieved it is vital that the grouting procedures are adapted to in situ conditions. If the choice of grouting material, pressure, typical procedure, etc., is well adapted to the characteristics found at the mine an optimal result must evolve.
Figure 4 indicates how this could be done.

STEP V - ***Water Inflow Related to Sealing Pressure***

Match sealing pressure specified and sensitivity to change of sealing pressure with inflow of water (volume).
The underlying assumption here is that higher final sealing pressures may reduce the water inflow into the mine. Therefore, it is very important to monitor water inflow at several critically important positions within the area underground to obtain factual results and to indicate changes when procedures are improved. Figure 5 indicates a possible presentation of these results.

STEP VI – ***Fissure Characteristics***

Cover grouting time must be reduced to a minimum in order to achieve minimum interference with mining operations and maximum speed of advance.

Fig. 6 aims at showing the fissure characteristics typically found on the mine:

STEP VII - ***Speed of Advance as a Function of Cover Time***

Ultimately the most important curve giving grout cover time against advance in metres per month must be determined and should be the result of the systematic rational approach to cover drilling and grouting as described above. (Figure 7).

The author believes that even relatively "raw" and inaccurate data should give reasonable indications of certain trends when following a rational approach in cover grouting and drilling.

4. Conveyance of Cement and other Slurries for Cement Injection and Support Systems

The size of the South African Deep Mines has necessitated the development of special methods to transport cement slurries over long distances. These techniques evolved during

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the fifties (Du Bois, 1963) when RODIO developed automatic batching plants on surface and relay stations underground to facilitate efficient reticulation.

The RODIO system had several advantages over other comparable distribution systems:

1. Automatic batching as developed for civil engineering dam projects, produced better quality grouts with greater consistency.
2. High speed, high shear mixing as applied in the surface batching plants produces a more stable grout, vital for the prevention of sedimentation when conveying slurries over long distances.
3. The inclusion of relay stations facilitates the reconditioning of the cement slurries, which improves long distance stability and grouting characteristics.
4. With relay stations, reticulation is closer to the mining action, hence control is better and wastage is minimized.
5. With the inclusion of underground relay stations, slurries can be conveyed over practically any distance.
6. RODIO's distribution system using underground relay stations avoids high pressure grout ranges in the shaft which is desirable and safer.
7. Back pressure in vertical ranges has been found to prevent excessive wear as free fall is prevented.

5. Development of Robust High Pressure Plunger Pumps

The most common pump for grouting used in South Africa is the plunger pump. For high pressure grouting, plunger pumps present the only possible choice with the following advantages:

1. Where high pressures of up to 50MPa are required, plunger pumps are the only solution.
2. Pulsating flow as produced by the reciprocating plunger pumps will delay settling of cement particles in unstable grouts due to turbulence and high velocities in the fissures. Pulsating flow will also limit the bridging effect, as the compression wave, which is propagated along the fissure, will tend to break the arches formed by small grains. More solid particles (higher solid content) can be transported by pulsating flow than by uniform flow under comparable conditions.
3. Plunger wear has been reduced to acceptable limits and does not present any difficulties.
4. With the correct design, cleaning of valves and clearing blockages in the pump can be done in seconds.
5. Reciprocating pumps are rugged and have proven themselves in underground mines as well as in civil engineering applications.
6. In general, these pumps are mechanically simple and are manufactured locally.
7. Where pulsating flow in unacceptable, simple air cylinders attached to the grout line will dampen the peak considerably.
8. Significant volumes can be achieved i.e. 3-12 cubic metres per hour or more at pressures of 50 to 15 MPa respectively.

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Reciprocating pumps are standard equipment in underground grouting projects. Many tons of cement/sand grouts at densities up to 1,9g/cm³ are being pumped daily over long distances (over 2000 metres). For improved control of pressures and volumes, hydraulically driven pumps are being used in the more modern, automated surface batching plants and underground really stations.

It may be interesting to point out that the most efficient pump which is required to keep particulate suspensions flowing is the human heart, a pulsating pump; it is also interesting to note that under normal conditions the human heart operates at similar pulse frequencies as reciprocating pumps in underground mining applications.

There are basically two types of mixers used underground and on surface for mining applications i.e. high speed shear mixers and low speed paddle mixers, sometimes referred to as agitators or storage tanks. Various designs of high speed mixers have been described in the literature (Houlsby, 1982) and are considered essential by the proponents of the low pressure grouting methods for effective cement grouting in rock. Indeed, high speed mixers are required in low pressure pore grouting as velocities of the grout are low and sedimentation rate is relatively high. Also, return circulation lines require stable grout and are essential in low pressure pore grouting. High speed mixers are very effective in wetting and separating cement particles to improve the hydration process and hence the stability of the suspension. Nevertheless, there are indications that pumping over a prolonged period of time, using return lines, may increase the particle size and possibly prevent effective penetration of the grout mix in cases where fine fissures are grouted at low pressures.

The success of high pressure grouting and the usage of thin mixes is less dependent on the stability of the grout and hence paddle mixers can be used and indeed are being used successfully in South African mines. Furthermore, the usage of high pressure plunger pumps produces pulsating turbulent flow into fissures which has an additional mixing effect and the thin grouts which are relatively unstable will adequately fill the fissure with cement at a significant distance from the grout hole.

THE STATE-OF-THE ART OF MINING GROUTING IN SOUTH AFRICA

A summary of the State-of-the-Art of grouting in general has been presented by Heinz in "Cover grouting - *a rational approach*" at the 6th IMWA (Heinz, 1997). For the purpose of this publication, we concentrate on mining grouting with emphasis on the South African mining industry.

The single most important parameter in grouting is pressure.
Pressure applied during grouting should be related to:

a) In situ rock mass strength and allowable deformation.
b) In situ hydrostatic water pressure.

In general terms, the hydrostatic water pressure has to be 'equalized' before the grouting process can contribute to the actual grouting of fissures. At the same time, deformation

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limits have to be determined to avoid excessive 'damage' to the in situ formation. Answers to the following questions need to be found:

1. Should hydrofracturing be allowed?
2. Can deformation of the in situ rock mass be allowed, if yes, to what extent?

During the development of precementation of shafts in the fifties, pressures of 1lb/sq. inch per foot depth to a certain upper limit was applied. It was found that these pressures were too low, as subsequent cover grouting during sinking still required too much effort relating to grouting. The State-of-the-Art at present requires grouting at 2,5 times the static head of the existing water table. This has been operating reasonably well and was applied at Joel Shaft no. 1, 2, 3 and 4.

The flaw in this pressure application is that no cognizance is given to the rock strength and deformation limits. The determination of rock strength parameters such as hydrofracturing, in situ stresses and their direction should be added to this grouting process. These methods are available (Rummel, 1985) but have not been applied in this context.

Pressures for underground mining grouting have been applied at values approximately 50% above the in situ hydrostatic pressures and have been found to be successful. In this context rock strength criteria have not been established "scientifically" for grouting purposes.

As an empirical guideline, pressures applied should be 20 - 30% below hydrofracturing (Cornet, 1988) in order to prevent too much "damage" to the rock mass. Nevertheless, some European grouting experts are of the opinion that it is better to hydrofracture and force some cement into the formation than do nothing at all. If the failure caused by hydrofracturing resulted in the opening of one or two large fissures, the latter statement may be true, however, if the hydrofracturing is causing many fine fissures to open as well, it would do more damage than good and should definitely be avoided as most of these fine fissures will not be filled with standard cement grout. Unfortunately, present hydrofracturing tests are not able to distinguish between failure resulting in the opening of a few large fissures and/or many fine fissures.

The other most important parameter that distinguishes mining grouting from any other grouting techniques, is the application of "thin", unstable grouts. The use of these slurries has caused and is still causing much controversy in literature and elsewhere. It is interesting to peruse some of the facts and arguments, i.e. the pros and cons of "thin", unstable particulate grouts.

Facts:
1. All particulate grout suspensions are unstable at high pressures.
2. "Thin, unstable" grouts have been successful in mining grouting in South Africa.

Some of the advantages of the application of "thin, unstable" grouts are important and are summarized below:

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The technique is applied successfully in Europe but in its extreme form possibly only in the mines at large depths in South Africa.

1. Thick grouts choke boreholes, therefore when the next round is blasted a few metres into rock, water can rush in again. Therefore, the water has to be "flushed back" considerable distances. Only thin grout can do that effectively. (W:C, 8:1, 6:1, 4:1). Sometimes these grouting techniques are even referred to as "Water Grouting".
2. Deformation of the rock i.e. opening of the fissures is desirable, indeed necessary, in order to obtain a larger distance and a more comprehensive grouting of the fissure network. This requires high pressures and thin grouts.
3. High velocities do not normally damage sound but fissured rock. If some clay is washed out it can only be beneficial.
4. High pressures and velocities are required to obtain long distances.
5. High velocities will prevent the settling of relatively 'thin, unstable under gravity" grouts as the applied forces are higher than the gravitational forces.
6. It has been established in slurry transportation (coal slurries, etc.) that pulsating flow is more efficient in transporting particulate slurries than any other way i.e. the percentage of material that can be transported in suspension is highest for pulsating flow. Hence, the human heart uses pulsating flow for very efficient flow into "fine fissures' with a frequency of between 60 to 80 pulses per minute, similar to the normal plunger pump frequencies as used in the mining industry.
7. With pulsating flow, high shear mixing is desirable but not as critical as for low pressure grouting, as the water is used primarily for transporting the cement to where it is deposited; the finer particles of cement move further, the finest cement particles are pushed even further until finally only water and bentonite remains. Therefore, most water does not remain where the cement is deposited. The author has termed this segregation, SELECTIVE SEDIMENTATION or FORCED SEDIMENTATION. Forced sedimentation occurs at very low pressures already, as is shown by the filter cake development in piling and diaphragm wall construction and during drilling with bentonite muds.
8. The back pressure of the formation once the grouting has been completed, presses (squeezes) the water out and compresses the cement grain structure so that the cement in the fissure not only gains strength from hydration but also from compaction of the grout.

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The following Table 2 attempts to summarize the most salient differences between mining grouting and in South African deep mines and civil engineering grouts.

Table 2: Civil Engineering and Mining Grouting Differences

	Low Pressure Civil Engineering Grouting	High Pressure Mining Grouting
Soil/ Rock type	Weak, porous, fissured	Strong, fissures
Pressure (arbitrary)	Low, 50 bar ≤	High, > 50 bar
Deformation	Not allowed	Allowed, necessary
W:C ratio	W:C ≤ 1:1	W:C ≤ 8:1
Slurry	Stable, "thick"	Stable and unstable, "thick" and "thin"
Flow scheme	Plug, laminar	Laminar, turbulent
Slurry velocity	Slow	Slow and high
Hydrofracturing	Not allowed	Localized failure allowed
Viscosity	High/low	Low
Shear stress	High/low	Low
Low speed paddle mixers	Not allowed	Allowed
High pressure plunger pumps	Not allowed	Necessary
Mono pumps	Allowed	Not recommended
High shear mixers	Necessary	Recommended

CONCLUSION

The South African mining industry presents unique problems with respect to the control of water. Grouting is an integral part of water control in this context.

From the early days of the development of the mining industry in South Africa, special grouting techniques were developed by mining engineers such as A. Francois in the twenties and thirties. There are indications that South African grouting experience contributed more in these early days to grouting engineering worldwide than has generally been recognized. The development continued during the fifties when experience from dam grouting was integrated into mining grouting technology.

Some methods used in South African mining grouting are not accepted elsewhere but as these methods have been successful, an explanation is required. This refers particularly to the application of thin, unstable grouts.

The author hopes that this paper goes some way in explaining some of the special grouting techniques, which have contributed significantly to the success of mining in South Africa.

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