Sealing of high pressure water fissures in South African Mines

By L.G. van Schalkwyk [1] and field research by: R.E.S. Bellamy[2]

[1] Rodio/Rosond (South Africa) Geotechnical and Mining Contractors
[2] Sci Nat Senior Geologist Oryx Mine South Africa.

ABSTRACT

This paper deals with cementation and grouting techniques for sealing underground water fissures in mines operating in depths between 500 and 3000 metres below surface. Precementation of deep mining tunnels at depths averaging 2400 metres requires considerable skills and know-how in the drilling field and cement grouting technology. Very high sealing pressures are applied and the transport of all grouting material is affected through high-pressure lines and nominal size holes drilled into the rock to intersect the water bearing fissures and fault planes. The main purpose of cementation is to seal large water and gas-bearing fissures before exposing such by blasting of tunnels and other excavations. Unusual ground conditions require unusual grouting methods which in turn necessitate stringent safety precautions.

All mines which have to combat water must answer the question:
Draining of the water and pumping it out, or sealing off potential water ingress?
Sealing may be expensive but it is a once and forever operation.

INTRODUCTION

A mine is quite naturally an extensive drainage system in itself but there are other reasons which make grouting necessary, such as thickness and nature of overburden and of overlaying rock-strata, nature and situation of the natural ground water table, or fossil water trapped under high pressure at greater depth, but also the need to combat : extensive moisture in refrigerated areas, humidification of ambient air temperatures, heat transfer from hot fissure water into the enviroment, or sealing off of methane gas yielding fissures.

Draining and pumping is an ongoing activity, the cost of which depends mainly on:
- Life span of mine;
- Economic viability of mine;
- Market fluctuations;
- Capital and maintenance cost of pumps and pipelines;
- Cost of electricity; and
- Inflow of water being constant or erratic.

The initial drilling and sealing of fissures in the pre-exposed excavations prior to continued mining operations has the following advantages:

1. It increases the safety of the mining operation;
2. It minimises water and gas inflow during developing and stoping;
3. It minimises the time lost due to additional grouting operations once exposed by blasting and hence costly standing time of mining equipment;
4. It provides detailed information of the geology of the proposed tunnel. Information on anomalies, dykes, faults as well as reef intersections can be obtained from the evaluation of the cores of the precementation boreholes.

PHYSICAL BACKGROUND

A philosophy of underground fissure water management must be defined. Fissure water is a problem that must be solved to the point of no further trouble from the aspects of safety and production hazards. It is a known fact that high yield, water-bearing fissures, and in the case of the Mine in discussion, Oryx, under very high pressure, occur in the Witwatersrand sediments throughout the Free State Goldfields. The majority of the water-bearing fissures occur as steep inter-connected joints, fault planes or contact zones of intrusive dykes, that also vary in direction and strike. For this reason all development in virgin ground must be cover-drilled to prevent catastrophic inrushes of fissure water; bearing in mind that the flooding disaster in the early 1960 years on the Merriespruit Mine occurred almost on the doorstep of this new Mine. Water intersections vary from negligible amounts to as much as 226 000 litres per hour.

Strata seldom undergo displacement without suffering fracture to a greater or lesser extent at the same time. In our case the fractures vary over a wide spectrum, from micoscopic to "wide" (plus 2 - 3 mm in size) , the latter becoming ideal water carriers or aquifers that yield sufficient water to constitute enormous reservoirs. These fissures also became infilled by mineral material-deposits from different solutions, which will be addressed in this paper.

Dewatering History

The Beisa shaft had to be dewatered prior to the commencing of operations on Oryx Mine. The Rest Water Level (RWL) in the Beisa shaft was at -935,85 metre below Datum (m.bD) . The datum line at Oryx Mine is 1 828,797 m above Mean Sea Level. Dewatering was done from Oct. 1987 to Apr. 1988 and a total of 4 097 megalitres (Ml) of water was raised to surface. Since the above dates, normal pumping operations including water from the Oryx sub-shaft resumed and until June 1992 a total of 20 720,066 Ml of water was raised to surface (fissure and service water). Refer to Table 1 for the volume of water raised monthly since 1992.

The RWL's were measured in three surface boreholes and the latest results indicated that the RWL was descending at between 5,1 m and 8,9 m per month. This proved that water was drawn into the workings.Temperatures of water were also measured. Refer Table 2 .

The underground water on Oryx Mine is contained in compartments defined by andesitic dykes. There is a slight difference in the volume of water intersected on either side of these dykes, especially in the old Beisa development areas. In the development done in the Beisa area (- 1 400 m .bD) , as well as on the lower levels (- 2 500 m . bD) , the water is generally more associated with the harder quartzite (MF4 of the St. Helena formation and the LF1-6 of the Virginia formation). Where brittle , deformation created more and more permeable fissures. In the softer quartzite (MF3) the existing fissures appear to be more impermeable and were probably closed due to the more ductile reaction of the rockmass during deformation.

Table 1 :

MONTH	TOTAL WATER RAISED (Ml/month)	CASCADE WATER DOWN (Ml/month)	CALCULATED FISSURE WATER (Ml/month)
Jul . 1992	302,467	74,290	228,177
Aug . 1992	335,365	77,323	258,042
Sept . 1992	315,044	67,172	247,872
Oct . 1992	306,113	88,953	217,160
Nov . 1992	304,104	85,908	218,196
Dec. 1992	326,282	36,574	289,708
Jan. 1993	298,673	32,731	265,942
Feb. 1993	346,582	56,366	290,216
Mar. 1993	327,601	58,225	269,376
Apr. 1993	378,575	71,327	307,248
May . 1993	459,294	118,814	340,480
June 1993	486,192	83,709	402,483
July 1993	411,010	49,490	361,520
Aug. 1993	438,678	15,184	423,494
Sept. 1993	486,961	8,043	478,918
Oct. 1993	580,929	8,106	572,823
Nov. 1993	575,145	10,738	564,407
Dec. 1993	549,243	9,488	539,755

LEVEL	DEPTH (m. bD)	TEMP (°C)
5	- 1 460	34
17	- 2 335	44
18	- 2 385	45
19	- 2 435	46
20	- 2 486	47
21	- 2 535	48
22	- 2 585	48
23	- 2 635	49
24	- 2 685	50

Table 2 :

At the lower levels, the temperature gradient is 1,7 degrees C / 100 m.

Water analysis

Ten underground water samples were analysed and the average of the results were as follows:

Cl^-	(ppm) -	1 866
F^-	(ppm) -	5
NO_3^-	(ppm) -	6
SO_4^{-2}	(ppm) -	22
Na^+	(ppm) -	1 220
K^+	(ppm) -	22
Ca^{+2}	(ppm) -	72
Mg^{+2}	(ppm) -	2
Total Dissolved Solids	(ppm) -	3 245
Conductivity	(mS/cm) -	6
pH	-	7.8
Total alkalinity as $CaCO_3$	(ppm) -	23

Project description and environment

The purpose of the mining was to develop nine levels of highspeed (treble shift) haulages and cross cuts to the reef horizon, to verify gold values as detected by the surface boreholes, in order to justify the major change of scope i.e. previously mined uranium, then changed to gold mining. Unfortunately the encountering and intersection of major water-bearing fissures, in excess of what was anticipated, slowed down the entire operation with subsequent loss in time and mine management was forced to review sealing and coverdrilling procedures. As sealing and drilling were mainly done by outside Contractors they had to be part of the problem solving task force. Pumping of produced water to surface has pretty much reached maximum capacity and any further influx of water had to be prevented.

Experimental Procedures and Considerations

High pressure grouting invariably results in dilation of the fissures to be grouted as well as in opening of weak joints and possibly in propagating of fissures, but not necessarily in hydrofracturing of the rock formation. High pressure fissure grouting often requires the location and identification of characteristics of a single fissure in order to adapt the grouting process to in situ conditions. The method of ground water sealing was based on this grouting technique incorporating cementicious (cement + pulverised fly-ash slagment) and bentonite grouts. This method proved mixed results ; from moderate seals to completely ineffective seals. Tunnels effectively sealed during coverdrilling and grout injection subsequently intersected water in development pilot holes and the frequency of these intersections were increasing . Even during ringcover operations, after proper grout sealing, water was sometimes still present in the check-holes. This was intolerable and it became obvious that something was radically wrong.

On recommendation from the Contractors a devoted hydro-geologist was appointed to investigate the fiasco. The research and findings are reflected in this paper. The water fissure zones were related to the lithologies represented in the mine's stratigraphy. The more competent and therefore less plastic lithologies have fractured more readily during the deformation of the Oryx area rocks.
Possible reasons why coverholes were not intersecting all the water fissures were:

- percussion drilled holes deviated excessively from their projected lines,
- fissures were not open and therefore not receiving or taking grout,
- work done by Contractors became under suspicion.

To minimize the deviation, experiments were conducted with shorter coverholes. Standard practice was to drill 60 metre coverholes ; these were shortened to 15 metre, 25 m , 30 m , 35 m, 40 m and 45 m. However, this experiment had a drastic effect on production, i.e. ends available for blasting became erratic and too frequently tied up in drilling of coverholes, especially when drilling ring-covers of 8 or 9 holes per end. Finally a dual action plan was adopted for coverdrilling : start with 30 metre percussion drilling ring-cover in the advancing development end, then blasting for 25 m, cover for 30 m, blast 25 m etc. , whilst from a cubby on the side of the advancing end a cover cum prospect diamond drilling hole of 200 metre was being drilled concurrently with all other activities. The 30 m ring-cover addressed the concern of percussion holes deflecting far off line. In a 60 m cover holes deflected as much as 8 - 10 m off line where as with a 30 m cover the deflection came to only 2-3 m , which was acceptable. Further the number of holes per ring-cover were either 3 , 4 , 5 , 6 , 8 or 9 depending on the fissure- water characteristics (yield , pressure) and the size of the advancing end.

In addressing the closed fissures, also known as hairline fissures, hydro-fracturing by high pressure packers were evaluated, but the dangers evolving around the opening up of unknown water reservoirs discarded this idea almost immediately. For the major fissures (+ 2 mm width) the installation of a batch grout plant underground is being planned, and it is envisaged to start this project in the very near future.

Regarding the concern of drilling and grouting Contractors being suspected of not executing work to required standards, the following steps were taken:

- crew effeciencies were observed and monitored by "watch dog" patrols, including time studies;
- equipment for grouting was evaluated;
- grout materials were laboratory tested;
- mixing of grout was examined ;
- grout was dyed with red oxide in order to , where fissures became exposed by blasting, evaluate the filling of fissures and the stability thereof;
- samples of the final grout was removed from the fissures and analysed;
- exposed fault and fissure planes were scraped for mineral or chemical traces to determine "hold" and interaction characteristics of the rock face towards the grout injected;
- underground visits by senior mining officials accompanied by senior contracting officials, at irregular intervals and odd shifts, to observe both the mining and contractors' activities;
- consulting with grout specialists and suppliers of cementitious as well as chemical grouts, and;
- the implementation of a dedicated maintenance and backup system for all equipment to eliminate breakdowns and unnecessary replacement of equipment.

Analysis And Corrective Action Taken :

Observing the grouting operations revealed that at the end of each shift, mixers , pumps and ranges were flushed with clean water. On arrival of the next shift the grout line is "re-opened" by flushing again clean water through the system. This practice although customary raised the question whether the injection of water does not disturb the setting process of the grout. The change-over system was changed to a take-over in the workplace, i.e. never stopping the grout process whilst in progress. This resulted in major sucesses and after just a short time it became obvious that the overall "sealing time" per grout operation improved by almost 40 percent. Further, because the equipment was in continuous use , breakdowns and sabotage almost disappeared. Mixing equipment is currently being modified with dual mixing blades to improve turbulance and colloidal effects of mixing.

Grout tests and laboratory results:

1) Basic cementitious grouts were found to be still the most reliable, and could easily be applied with minor modifications according to local needs. The frequency of large yields and fissures encountered (observed after exposure) made it possible to start thickening up mixtures of grout from the second shift pumping, to a 1 : 1 mixture, and continued until sealing pressure was obtained. Caution had however, to be exercised, to prevent sealing pressures being exceeded to prevent hydro-fracturing.

2) On determining and identifying the location and size of fissures it was decided that where water was to be drained, that the operation would be confined to boreholes intersecting the gold reef horizon, in order not to fracture the reef plane any further, nor to contaminate it with grout.

3) Analysis of grout penetration into the exposed fissures revealed that cement had only entered the wider fissures ($\geq$ 1-2 mm). The finer fissures only contained pulverised fly-ash (PFA) which is finer than cement and has little, to none, cohesive properties. At some instances it was washed out by trickles of water present in the fine fissures.

4) In fissures where a yellowish chemical deposition was encountered on the fissure plane, the cement did not bond at all, and could easily be removed. It was determined that the cement grout in pyrophyllite rich bedding planes did not bond with the rock.

5) In the larger fissures traces of leather , sawdust and nutshell were observed, and it seemed that these materials were most successful as bulk filler and fibre-net, to trap the cementitious grout.

6) Hardened grout in cover-holes was seen to be laminated and showed strong evidence of differential settling of the particles based on density and grain size. The coarser and more dense cement settled out first, and the finer less dense PFA settled on top. Preliminary lab. studies revealed several features. The differential settling of the slurry particles based on size and density is not just confined to practical mining conditions. The PFA on the top of the set medium is very soft and is not suitable for conducting uniaxial compressive strength (UCS) studies. Although not cured to underground rock and water temperatures, there were strong indications that after eight hours the grout medium has set enough for controlling the mixture, i.e. to start thickening or adding chemical retardents, plasticisers or hardeners, etc. The worst characteristic discovered, was that only after 48 hours did the grout start to develop strength. (Refer Table 3)

7) Although the cementitious grout used in the sealing of fissures was mixed to the ratio 70 percent OPC to 30 percent PFA, it apperared as if only 50 percent of the set grout medium had the characteristics of cement.

8) The yellow coating previously referred to on the plane surfaces of some fissures, contained significant amounts of sulphates; mostly ferrous sulphate, which is known to be detrimental to the full development of the setting and strength potential of the grout medium.

9) It was also confirmed that the high sodium chloride (NaCl) of the fissure water had a retardant effect on the settling time of cement, and it was also suspected of significantly effecting the strength development of the grout.

10) The high temperature (+ 50° C) of the fissure water, on the contrary, had an accelerative effect on the setting time of the cement.

Table 3

UCS Test Results

Cement / water ratio 20 kg/100 litre = 1 : 5

Environment	: Underground water from controlled drain hole on 21 level
	: Temperature 50 ° C
	: Atmospheric pressure
8 Hours	< 4 MPa (estimated)
16 Hours	< 4 MPa (estimated)
24 Hours	~ 4 MPa (estimated)
48 Hours	- 7,7 MPa
96 Hours	- 23,5 MPa

The interaction of these chemical ingredients in the fisuure water and those on the fissure surfaces, with the temperatures that prevail will have to be further investigated to detemine the effects (positive or negative) this has on the strength and competence of the set grout, bearing in mind that the behaviour of cement and cementitious grouts are known to be "site specific".

The underground visits by senior officials resulted in a weekly "summit", whereby both Mine and Contractor officials were given the opportunity to air grievances, discuss sub-standard performances, non-compliance to procedures, or outstanding achievements. The facts were then evaluated and action plans formulated. Once such plans were instituted, weekly progress had to be reported on. In retrospect one can, without hesitance, state that these meetings made the breakthrough and for the first time, water control was properly managed. Cover-drilling and grouting operations were now carried out with expert precision, and delays in blasting, i.e. ends stopped due to grouting operations, decreased immensely. It was clear that both Mine and Contractor were now more concerned regarding continuous production.

Geological studies of the fissure characteristics revealed that it was definately high yield water-bearing, under very high pressure. The majority were observed as steep inter-connected joints from vertical to obliquely angled, and formed a distinctive network of water arteries. It was also discovered that some of the same fissures varied in width from very narrow to wide, i.e. from 0 ,2 mm to 2 mm. Some even narrowed down to 0,1 mm in width. This explained the phemonenon why grout injection sealing failed; the common coarse cement grains could not penetrate the hairline cracks, and thereby not sealing fissures off completely. This problem led to a major change of strategy in coverdrilling and the implementation of multi-hole cover, concentrating on covering the sprectrum and not so much the end only, especially in water prone areas. In reducing the hazard factor during the intersection of very high pressure water, the safety equipment attached to the drill hole was upgraded and customised.

Research And Theories Applied In Practice

In essence a Mine can be regarded as a complicated drainage system, therefore it is important to determine by measurement and analysis the most important parameters:

a) Establishing a regional water regime:
b) Defining and determining the sub-regional water compartments which have an effect on the inflow of water into the Mine:
c) Determining the characteristics of the barriers of these compartments, such as, leakage, the water head, during flow through these barriers and any changes that may occur.

A new prototype Ground Penetrating Radar (GPR) system, developed in collaboration with Geophysical Survey Systems in the USA, is operating very successfully. A recent application being the delineation and mapping of dykes that may be associated with water bearing fissures. This system provides high resolution maps of geological features over distances of up to 50 m ahead of the mining face. The system is designed to interface with a conventional personal computer and is supplied with software for data processing. Applied as a profiling technique, or as a transmission technique in boreholes, the system provides the required maps by providing advance knowledge of hazardous features such as faults and dykes, water fissures and rock fracturing, as well as general stratigraphy, ores and ore morphologies.

The effectiveness of past and current grouting and drainage depended on the following factors:

a) the size, frequency, direction and extent of each fissure system,
b) the back pressures , the sealing pressures and hydro-static head of fissure water which had to be recorded and plotted properly in order to determine the hydrology of the mine,
c) the direction of the boreholes for drainage and grouting in relation to the fissure configuration .

In principle, for effective results, a borehole should "cross" as many fissures as possible and preferably perpendicularly, if possible.

Grout Material Properties

The properties of the grout material is characterised mainly by cohesion (Bingham Yield Stress), viscosity and the sedimentation behaviour, and in particular sedimentation velocity. In general terms the cohesion determines the maximum distance the grout slurry travels at a certain pressure, and the viscosity determines the time the grout requires to reach that distance. In fine fissure grouting (< 0,2 mm width) the effectiveness of grouting is also determined by the grain size of the cement.

1) Particle size:

Cement grout is a particulate suspension which in essence means that small particles by virtue of their shape, fineness, relative density, etc. , are held in suspension for a certain period of time. The particle size of OPC ranges from 0,005 mm to 0,1 mm. Therefore, OPC does not fall into colloidal sizes. Cement particle size is critical in the determination of the groutability, particularily in fine fissure grouting. High pressures are required to inject fine fissures with cement grout. It has been found that for cohesionless materials "arching" of small particles occurs during the flow of these materials through orifaces (fissures) approximately 3 to 5 times the grain diameter. Thus based on this information, bridging of grains may occur at an equivalent width of fissures 3 to 5 times the mean grain size. Therefore assuming a mean grain size of 0,030 mm, fissures up to 0,150 mm will not be groutable with cement at low pressures. Invariably water will pass through these fissures, thus high pressure grouting or chemical grouting may be the only satisfactory methods. However chemical grouting is very expensive and one is forced to examine ultra fine cement mixtures and / or silica fumes. As the hydration process commences as soon as the cement particles are wetted, the importance of the use of dispersants or defloculents, for fine fissure grouting to avoid aggregation of particles or "flocs" is apparent.

2) Hydration:

Defined in simple terms hydration is the chemical reaction between cement and water to form new components with improved strength characteristics. Hydration is an exo-thermal process. Cement technology is well researched and details are readily available. In this paper we endeavour to discuss hydration and cement properties, as they may be of interest for grouting purposes only. To facilitate hydration, the wetting of each particle, however small, is very important. It is this duty that high speed shear mixers perform very well. The cement grain has a RD of 3,14 ; in the fully hydrated phase the volume is approx. doubled, hence the RD of a hydrated grain is approx. 1,6. Therefore, rapid hydration of the particles delays the sedimentation process. Efficient wetting will, therefore, accelerate the hydration process and prevent early bleeding of the grout. Small grains hydrate faster, therefore, grain size is critical to the hydration process. Under high pressure, the water is force-bled resulting in incomplete hydration. This phenomenon may result in drill rods getting stuck when cement is re-drilled. Where the grout is circulated for long periods of time or where heat development (prolonged mixing, environmental conditions, deep mining conditions, etc.) influences the hydration process hydration may be more rapid.

3) Flow Properties:

Water is the medium of transportation of cement particles and will determine the flow properties of the cement grout. Water in excess of the quantity required for hydration is undesirable in a grouted formation. In high pressure grouting application where thin mixes are used, the grout viscosity is low and pressure losses are small. A grout at a high water / cement ratio has a plastic viscosity, i.e. viscosity will be higher at high injection velocities. As grouts are thickened to densities above 1,5 g / m^3 (water / cement = 1 : 1) flow properties become more critical even for high pressure grouting. Flow properties of grouts are also dependent on the size and shape of the cement particles; small spherical particles (e.g. fly-ash) will reduce internal friction and thereby the viscosity of the grout, hence also the improved fluidity by adding small quantities of bentonite to cement grouts.

4) Bleeding / Sedimentation:

Bleeding is the autogenous flow of mixed water within the grout caused by the settlement of the solid materials within the mass. The cement particles of the suspension settle under gravity thereby expelling the unbound water. The higher the water / cement ratio, the larger the percentage of bleeding water or water gain. Grouts with high bleeding percentages are defined as unstable; grouts with little or no bleeding are called stable. A small percentage of bentonite will reduce the bleeding considerably. High pressure grouting of fissures results in force bleeding or forced sedimentation; this process is also sometimes referred to as filtration. Large cement particles settle out first, followed by fine cement particles and ultimately bentonite and water will flow at the outer boundary of the injected material. Therefore, high pressure grouting can be done successfully with relatively unstable grouts, hence the success of paddle mixers in underground mining applications.

5) Durability:

Cement grouts are durable under normal conditions. Where high pressures are used , the cement grout is cured under pressure usually with a lower water content than at the initial water / cement ratio. Thus, the required durability and strength are normally achieved . Environmental reactions as a result of pollution or the salty water environment may be detrimental to cement grout, in particular sulphates may reduce the long term quality of the cement grout.

In order to manage the grouting and sealing of fissures effectively an understanding of some general properties of grout slurries is important. Some are listed below:

a) Cement quality is variable and grout slurries are more sensitive to these variations than concrete.
b) Finer cement such as rapid hardening cement has a higher cohesion and a lower sedimentation velocity than OPC.
c) Higher temperatures do have a significant effect on hydration and hence the flowability and penatrability of cement slurries. Little data is currently available, nevertheless we know from grouting at Oryx Mine that cement grouting for cover is not as effective, in the longer boreholes. One of the effects may be the higher rock / fissure water temperature, as an increase in temperature, may result in an almost exponential increase in cohesion. (Taken from Krizek, October 1993). However, do not attach too much importance to the absolute values , but the tendency is important.
d) The addition of fly-ash (PFA) in significant quantities to cement slurries retards the setting of cement.
e) Ordinary Portland Cement (OPC) can be used to grout fissures of approx. 3 to 5 times the median grain size, therefore the grouting of fissures with OPC which are finer than 0,2 mm, at reasonable pressures, is difficult, if not impossible. Nevertheless, such fissures may produce large quantities of water.
f) The addition of bentonite to cement slurry will increase the cohesion and will decrease significantly the sedimentation velocity, but will not lubricate the fissures.
g) Fine fissures (less than 0,2 mm width) will require a different approach to grouting than wide fissures (+ 2 mm)

Practical Applications

Once the characteristics are understood the certain measures and tests should be introduced for determining the required properties; such as:

1) The Marsh Cone for simple testing of the viscosity of the material, particularly when changing to other or better materials.
2) A sedimentation cylinder to test the bleed and sedimentation velocity.
3) The Kasumeter, a simple sedimentation cylinder to determine the cohesion of materials.

These measuring devices are simple and needed only to be used, when the mix was changed, and a few other times for the control of quality and consistency.

Pressure Applied

Pressure to be applied is dependent on the size of the fissures, the viscosity and cohesion of the material and the existing water head.

1) The existing water head is low at approx. 10 to 15 bar.
2) The fissures varied over the full spectrum from fine (< 0,2 mm) to wide (2 to 3 mm) i.e. it becomes absolutely necessary to equip all injection pumps with pressure gauges in order to apply the correct pressure during pumping as well as to monitor the back pressures and sealing pressures. The norm adopted for sealing, was 1,5 to 2 times the water head. This also became a good standard for the 80 - 20 principle;i.e. 80 percent of all fissures grouted were now being sealed in 20 percent of the time. In the past there was a tendency to seal all fissures at +20 MPa, but after the field tests, it was clear that valuable time was wasted and the standard was changed to the present one of sealing at maximum 2 times the water head. This principle also led to a great saving in time, and thus better blasting advances in each development end.
3) The average equivalent pressures at Oryx Mine are 10 MPa water head with a relevant 15 MPa sealing pressure.

Technique for Cover Drilling and Grouting

1) Drilling of Boreholes

The grouting process is closely linked to the physical characteristics of the formation . As variations can be substantial in ground characteristics such as width and extension of fissures, fissure frequency, strength of formation, etc., the grouting method which includes the drilling pattern must be correspondingly flexible. In tunnelling it is common practice to specify initially a systematic drilling pattern based on the initial geotechnical investigation. Nevertheless, the most important aspect of a carefully executed grouting project is the flexibility on site to continually review the additional information acquired and to react accordingly. Generally, percussion drilling is more economical than diamond core drilling. However, the latter provides better information of the formation, therefore a compromise must be reached and in practice this results in a combination of the two drilling methods. As soon as water loss is experienced during drilling, cuttings will enter the formation. Where high pressure grouting is applied, the fissures to be grouted will be flushed and / or dilated during grouting. The design of the grouting should specify the following parameters:

a) Location of boreholes is determined by a systematic pattern based on the initial geotechnical investigation modified according to actual conditions encountered in the formation.
b) Grout hole size is usually "A" size and the "in-filling" grout holes in "A" or "B" size by percussion drilling as required.
c) Spacing of boreholes again depends on the formation encountered. Usually the initial systematic pattern (splitting pattern) will have a spacing of 1m or 2m between primary holes. Subsequent "in-filling" holes will be located on the centre line or staggered at the mid-points between these holes. The nominal number of holes for maximal cover is nine boreholes,in the wider ends and five in the standard size ends. Close spacing may sometimes result in inter-connection between grout holes which may be desirable in certain cases.

d) Depth of grout holes is very much a function of the geological formation, thus large water-bearing fissures underground are treated when they are intersected. The length of cover-holes became critical. Very short holes (10-15 m) and very long holes (60 m and more) were cumbersome and not optimal for various reasons. The most convenient length was found to be between 25m and 35 m depending on the type of end being advanced. (On reef 25 m and off reef 30 to 32 m).

e) Inclination of grout holes should be as such as to maximise the chance of intersecting potential water-bearing fissures or weak joints perpendicularly.

f) Type of drilling depends on the information required and the economics of the effectiveness of the various methods. Down-the-hole hammer percussion drilling is usually not economical except where deep holes are required.

2) Procedure for Drilling

The basic procedures followed in cover drilling are:

a) Drill first borehole, say 30 m. When water is intersected, stop and inject grout. At this point we shoud mention that intersections of 500 (and less) liter / hour is not grouted initially, and drilling is first completed before grouting commences.

b) Drill second borehole, diametrically opposite the first. Constantly endeavour to correlate water intersections. Continuously measure water inflow to determine reduction (or even increase) of inflow for each additional hole drilled to detect any possible link-ups.

c) Drill third and fourth boreholes, diametrically opposite. In each case measure flow if water is encountered.

d) Drill fifth borehole in centre if the water in all four boreholes have reduced to a certain inflow, and within a certain time. If however these standard guide parameters have not been acheived, then continue with additional holes to reduce any risk of intersecting undetected fissures during subsequent blasting operations.

e) Each hole must show some reduction in inflow as a general rule. The criteria for testing the efficiency and effectiveness of the method applied should be:

(i) the absolute reduction,

(ii) the "speed" of reduction per borehole and per time.

f) The direction of holes to be drilled (laid out) in such a way, to "cross" as many fissures as possible, as this will ensure better coverage, especially in cases of vertical fissures. The latter were quite prominent in Oryx's case, and explained why previous cover holes failed to intersect the water bearing fissures, when single or even four coverholes were drilled per end.

g) The historical custom of drilling either cover or pilot holes, at the normal symmetrical pattern with holes inclined outwards between 5 and 10 degrees, soon became evident that it was unlikely to be the optimal pattern for Oryx's problems. Mainly, because of the complicated network of vertical and obliquely angled fissures where in the same fissures, width varied (from less than 0,2 mm to 1,5 mm) and further , criss crossed the rock strata. Therefore it is of utmost importance to endeavour at all times to establish the predominent flow, or placement-direction of cement grout,in order,to be able to change accordingly, the direction of the holes.

3) Grout Mix Design

The most common designation for grout mixes is the water / cement ratio which basically indicates the amount of water required per unit volume or unit mass of cement. The classical South African approach, particularly in underground mines has been to commence grouting by pumping thin mixes e.g. water / cement ratios of 8 : 1 , 6 : 1 , etc. The mix is then thickened as required after a certain predetermined period of time or if pressure fails to increase. Experience has shown that thin mixes will dilate the fissures and allow the grout to travel over relatively large distances, thus depositing the cement at substantial distances from the borehole by pressure-bleeding (forced sedimentation). If the procedure is commenced with thick grout , the fissures will be blocked within a few metres of the borehole and the cover e.g. for a tunnel or shaft will be inadequate. Thin grouts have been rejected outright in Australia (Houlsby 1982) and generally in the U.S.A., mainly because of the bleeding process, although recently even in the U.S.A. (Albritton 1982) there is some change of opinion as the following quote by Albritton shows: "Recent experience and case histories have shown that thin grouts are more effective than they were previously thought to be".

4) Grouting Pressure

The grouting pressure is the most significant single parameter of the grouting process. The terms high and low pressure are relative with respect to the strength of the rock formation. Factors affecting the allowable grouting pressure include rock strength, geology, hydrologic conditions, orientation of rock discontinuities or fissures, and consistency of grout. The " Anglo Saxon" rule of thumb for determining the maximum allowable pressure i.e. 1 lb per sq. inch per ft. of overburden is equivalent to the overburden weight of a material with a density of 2.3 g / cm^3. The European rule of thumb for determining the allowable pressure i.e. 1 kg / cm^2 (1 bar) per metre of overburden is approximately four times the pressure resulting from the overburden. The wide range of allowable grouting pressures indicates again the need for flexibility on site and as grouting pressure is such an important parameter and its proper determination is vital for the execution of successful grouting, rules of thumb should be developed and proven at each site. The "Anglo Saxon" rule of thumb may be regarded as a lower limit, and the upper limit should not exceed the pressure at which general hydro-fracturing occurs. Localised limited fracturing and opening of weak joints would probably occur within these pressures. In general, high pressures are also desirable for economic reasons to minimize the time of injection.

5) Grout Mixing Equipment

There are basically two types of mixers, i.e. high speed shear mixers (often incorrectly referred to as colloidal mixers) and low speed paddle mixers, sometimes referred to as agitators or storage tanks. Various designs of high speed mixers have been described in available literature (eg. Houlsby 1982) and are considered essential by the proponents of the low pressure grouting methods for effective cement grouting in rock. High speed mixers are very effective in wetting and separating cement particles to improve the hydration process and hence the stability of the suspension. 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 underground high pressure grouting in the 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.

6) Grout Pumping Equipment

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

a) Where high pressures of up to 40 MPa are required,piston pumps are the only solution.
b) Pulsating flow as produced by the reciprocating 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.
c) Piston wear has been reduced to acceptable limits and does not present any difficulties.
d) With the correct design, cleaning of valves and clearing blockages in the pump can be done in seconds.
e) Reciprocating pumps are rugged and have proven themselves in underground mines as well as in civil engineering applications.
f) In general, these pumps are mechanically simple and are manufactured locally (also by Rodio / Rosond).
g) Where pulsating flow is unacceptable, simple air cylinders attached to the grout line will dampen the peak considerably.
h) Significant volumes can be achieved i.e. 3-12 cubic metres per hour or more.

Reciprocating pumps are standard equipment in underground grouting projects. Many tons of cement/sand grouts at densities up to 1,9 g/cm are being pumped daily over long distances (+ 2000 metres). For improved control of pressure and volumes, hydraulically driven pumps are being used in civil engineering applications where relatively low pressures (up to 6MPa) and low volumes, are adequate. Finally, 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 minig applications.

7) Quality Control

The control of the grouting process entails the following steps:

a) Control of cement and grout properties.
b) Control of grouting process(injection rate, pressures, mixing process).
c) Control of formation behaviour (leaks, deformation, etc.).
d) Control of final desired result (Lugeon test, strength test).

The quality of the grout ingredients i.e. cement and water may be important as ordinary portland cement may differ in quality and grain size distribution according to variations in the raw materials. Water should be potable water; tests for hardness, calcium, sulphates and sulphides may be required. The fluidity of the grout on site is measured by the Marsh funnel which is a useful instrument for quality control of field mixes. From approximately 30 - 50 seconds, the Marsh funnel results exhibit an almost linear relation with plastic viscosity. The pressure and flow of grout should be measured continuously. Continuous measuring devices have been used on various sites in the Republic such as the Drakensberg Pumped Storage Scheme and the Palmiet Pumped Storage Scheme.

In shallow formations the control of surface grouting by monitoring visually leaks of the grout, and by surface deformations, can be very effective. For measuring deformations in rock masses, the sliding micrometer has become a valuable tool, as it measures the actual deformation in a borehole to one-thousandth of a mm per meter length. In this manner the opening and closing of fissures can be detected and the grouting programme structured accordingly. The Lugeon test is a crude but very effective means to determine the permeabilities before and after the grouting process. However, it must be realised that the Lugeon test originated in Europe where high pressure grouting techniques have been applied. The extrapolation of results of the Lugeon test done at lower pressures to a 10 bar standard pressure should be done with caution as test results at low pressures and laminar flow are not comparable to high pressure results at turbulent flow.

8) Guidelines For Cementation Procedures

a) Only double drum mixers are to be used for mixing grout. (Double drum paddle mixers are adequate, although high speed, high shear mixers produce a better product)
b) A suitable pressure gauge is to be installed at the pump to monitor the system pressure for each hole that is grouted.
c) Before grouting starts the pressure of the water head and flow rate is to be measured.(Vital)
d) The grout pump is to be connected to the casing manifold and water is to be pumped at 40 strokes and 80 strokes per minute for 15 minute durations each. The pressure is to be noted at both these rates and given to the Geologist. The initial grout concentration is to be decided by the Geologist / Hydrologist.
e) Pumping rates are to remain constant when testing for pressure variances.
f) Standard measures are to be used for adding cement to the mixing drum.
g) Grout concentration are to follow this pattern unless otherwise instructed:
    (i) 50 kg of cement 2 : 1
    (ii) 100 kg of cement 1 : 1
   Note pressure after pumping 2 barrels, continue with another 5 barrels and note pressureconstantly. If the pressure rises by 1 bar within this period then stay on that mixture until sealing pressure is reached. If no pressure increase is recorded then continue to the next thicker mixture. Do not pump a thicker mix than 1 : 1.

CONCLUSIONS AND RECOMMENDATIONS

In an effort to penetrate the very fine fissures the PFA component in the cement mixture, should be either substituted by, or at least be supplemented with micro fine cement or silica fumes. The cost factor is accepted as critical (expensive) in this regard, but so is the time lost due to excessive time consumed in lengthy grouting operations, and then still risking an inferior grout seal. Continue the use of red oxide ubiquitously to enhance and aid fissure character examination and investigation. Measures to "anti - sulphate" fissure planes are to be pursued and further investigated.

In this paper the author has described various aspects of high pressure grouting and highlighted certain mechanics of operation which are the bases for the success of this type of grouting technique. The ultimate test of a grouting technique has always been the successful application in practice. High pressure grouting has been applied successfully in Europe and in the

Republic of South Africa. The choice of the method depends on the characteristics of the formation encountered; it may require high or low pressure, thick or thin grout mixes, etc. it has been maintained that 70 % of all accidents in geotechnical engineering are related in some way or other to water. Therefore, the application of correct grouting techniques is the most effective way to cope with these water problems.

It is in the interest of the client, indeed it is his duty, to choose a geotechnical contractor that is capable of offering the entire spectrum of grouting processes required to tailor-make and find solutions to specific problems. Furthermore, as has been emphasized before, due to the nature of rock formations i.e. the large variation in rock characteristics, the grouting process must be reviewed and adapted on site continually and decisions must be taken immediately to ensure a satisfactory and safe result. This may entail changing a parameter of the method or changing to a different method altogether.

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The views expressed in this paper are those of the author and not necessarily those of any of the Mine's personnel, and in no way is any of the information intended to implicate either the Contractor or the Mine and is solely intended for use by readers, who may have experienced the same type of problems.

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APPENDIX A

Modifications of Rheological Parameters

Bingham Fluids

Bingham fluids are described by two parameters: plastic viscosity and yield point.

1) Plastic Viscosity

Definition (ASTM): "the property of resistance to flow exhibited within the body of a material".

This parameter is a function of:

a) The concentration of solids.
b)The size and shape of the solid particles.
c)The viscosity of the liquid phase.

Plastic viscosity increases with increasing solid content or, for constant solid content, with increasing number of fine particles that is, with increasing specific particle surface. Conversely, it decreases with decreasing solid content or, for a given solid content, with increasing number of coarser particles, i.e. with decreasing specific surface (flocculation).

2) Yield Point (Stress)

Definition (ASTM) "the shear stress required to initiate flow"

The yield point results from cohesive forces between the particles, due to the electric charges on their surfaces. The magnitude of these forces will depend on:

a) The type of solid and their surface changes.
b)The amount of the solids present.
c) The ion concentration in the liquid phase.

High yield points may be due to:

a) High specific surface area.
b) Increase in solid content, with consequent decrease in inter-particle distance.
c) Contamination by salt, gypsum, etc. which favours flocculation of the particles.
d) Insufficient concentration of the thinning agent, the function of which is to neutralize the attractive forces.
e) High bentonite content.

Thus plastic viscosity may be reduced (or its increase retarded) by de-sanding, de-silting, centrifuging, treatment in sophisticated vibrators or by dilution. The yield point will be reduced by the additions of substances neutralizing the electric charges, such as thinning agents, superplastercizers, etc.

As a general rule, it would seem that plastic viscosity can be lowered by reducing the solid content, while the yield point is more readily affected by chemical treatments.

APPENDIX B

Water Cement Ratio	Mixing Water Temperature (° C)	Yield Stress (mPa)	Plastic Viscosity (mPa / s)	Apparent Viscosity (mPa / s)
	35	1100	72	105
1 : 1	20	310	72	35
	5	210	72	31
	35	50	72	2.2
3 : 1	20	25	81	2.2
	5	10	70	2.5

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Mixing Water Temperature:

As shown in the above table, increasing the temperature of the mixing water from 5° to 35° C increased the yield stress five-fold, with the majority of the change occuring between 20° and 35° C. The plastic viscosity was relatively insensitive to temperature changes, as was the apparent viscosity for the 3 : 1 mix; however, the apparent viscosity of the 1 : 1 mix increased three-fold as the temperature of the mixing water increased from 5° to 35° C, with more than 90 % of the increase occuring between 20° and 35° C.