Recommendations for site investigation, design, construction, testing, monitoring and maintenance of permanent intruded concrete plugs

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Synopsis

Following study of historical South African practice and a review of recent experience gained during the design, construction and testing of the high pressure plugs at the South Deep Water Barrier Project, this paper makes recommendations to improve practice. Initially, site investigation requirements are described with reference to geological, hydrogeological and seismic considerations, including site preparation and pre-grouting of the surrounding rock mass, if permeable. Structural and hydraulic aspects of plug design address topics such as residual permeability, aggressive mine water, plug materials, mortar strength and bleed. *In situ* thermocouples and piezometers are recommended to optimize the timing of plug tightening and monitor plug performance during service. Plug construction covers aggregate preparation, mortar quality control, plug tightening grouts, injection pressures, records and the overriding need for a method statement specification to control all aspects of plug construction. On completion of the plug, tests to establish surrounding rock stress regime, plug strength, and residual permeability are described to enable a comparison with original design assumptions. Monitoring and maintenance procedures are proposed to ensure satisfactory long-term performance of the plugs.

Introduction

Based on experience gained at the South Deep Water Barrier Project, this paper seeks to make recommendations for consideration in future practice, particularly where permanent plugs are required to retain water under high pressure and the consequences of failure cannot be tolerated. The recommendations that augment current guidelines should be read in conjunction with the 'Code of Practice for the Construction of Underground Plugs and Bulkhead Doors using Grout Intrusion Concrete' published by the Chamber of Mines of South Africa in 1983.

Site investigation

Geological assessment

The 1983 code states 'The site of the work should be situated in an area of sound homogeneous rock. This infers that the ground for a distance of three plug lengths is free of structural weaknesses such as faults, fissures, shales, schists, friable or soft material or other excavations.'

This is an ideal requirement that is not always practicable. Consequently, a 3-dimensional structural geological investigation, including discontinuity classification, should be carried out via face mapping and cored holes to confirm that there is an acceptable uniformity and mechanical competence, i.e. an absence of detrimental structural geological discontinuities or lithologies that could impact on the stability of the plug and surrounding rock mass forming the water barrier.

A numerical analysis of the stress environment at the plug site is also recommended, since it is important to assess if flooding will create tensile stresses capable of opening discontinuities within the rock barrier. Where doubt exists over the magnitude of minor principal stresses (σ_3) in the rock mass, these should be measured *in situ* at the plug site using techniques such as hydrofracturing.

To facilitate structural design and any associated mathematical modelling of the plug under service conditions, the compressive strength, stiffness, Poisson's ratio and shear strength of the surrounding rock mass should be obtained.

During the geological study, the impact of ongoing mining in the vicinity of the proposed water barrier should be investigated. If close-proximity blasting is envisaged, a maximum allowable peak particle velocity should be established to ensure that periodic blasting will not open discontinuities within the barrier or damage the rock/plug contact zone.

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Hydrogeological assessment

A hydrogeological assessment of the rock mass forming the water barrier is required, in order to identify potential conduits as far as possible, predict the changes in the water regime when the plug is completed and subjected to the maximum hydrostatic pressure, and the probable resulting water seepage around and beyond the plug in service. It is also necessary to evaluate the quality of the water in haulages because of its potential impact on the durability of plug materials.

Where faults and joints are encountered, their persistence (continuity) should be assessed. If these features contain thick infill/gouge materials, the *in situ* fabric and mineral content of the materials, together with groundwater chemistry, should be studied to determine dissolution rates and risk of erosion for the known hydraulic gradient over the service life of the plug.

In order to establish the extent of rock mass grouting that may be necessary, borehole permeability tests should be carried out in order to provide a profile of watertightness above and below the plug location, and laterally beyond both walls.

The holes should be drilled beyond the mining induced fracture zone, e.g. at least 6 m into the surrounding rock mass, and deeper if permeable conditions are encountered. Multi-pressure Lugeon tests are recommended in accordance with the practice of Houlsby (1976) since the results permit assessment of the flow characteristics of the permeable discontinuities.

All exploratory holes should be backfilled with as thick a cement grout as possible, e.g. water/cement ratio = 0.4 by weight.

Consideration of seismicity

In order to investigate possible threats to the long-term effectiveness of the plugged water barrier posed by future seismic activity, a statistical analysis of return period significant events (e.g. Richter Magnitude > 3.0) over the past 100 years for a region 100 km radius should be attempted, together with examination of a range of possible modes of failure in the rock mass that could cause damage to the plugged water barrier.

Where the volume of water to be retained is extensive, e.g. in the event of flooding adjacent mines, the possibility of fluid-triggered seismicity should also be studied.

As an outcome, the overall likelihood of each possible mode of failure should be quantified so that the risks and consequences can be properly assessed at the design stage.

Preparation of site

Barring and scaling should be carried out to sound rock, but where stress-induced fracturing or friable rock is encoun tered, barring should continue for a depth of at least 0.5 m before approval of the surface is given.

In order to minimize the need for localized drilling and blasting that may induce stress relief and fracturing, it is suggested that only if naturally tapered sections are unfavourable, i.e. where the wedge or taper increases distally from the wet end of the plug, should an appropriate geometry be engineered in the surrounding rock.

After barring, scaling and cleaning, the plug dimensions should be surveyed at 1m intervals to:

- estimate the volume of the plug
- determine the final shape in plan, longitudinal section and cross-section
- ensure that the natural irregularities in the shape are adequate
- prepare as-built drawings.

Pre-grouting of surrounding rock mass

Where it is judged that permeable features are remote, e.g. greater than 2 m, measured normally from the face, stage grouting of these features in a primary-secondary sequence should be considered in advance of plug construction, as it may not be possible to carry out grouting cost-effectively via conventional inclined plug tightening holes.

Study of the range of fracture thicknesses determines the most appropriate grout mixes to be employed, e.g. ordinary or microfine cement. Choice of grout stage length within the range 0.5 m to 3 m is dictated by the spacing of the permeable discontinuities.

Pre-grouting should commence at a distance from the general rock face, e.g. 1 m, such that there is an overlap with the subsequent plug tightening phase after mortar intrusion.

On completion of pre-grouting, independent verification holes located between the grout holes should be subjected to water testing to determine the residual watertightness attained in the rock mass. Supplementary grouting can be directed, if necessary, until the specified residual watertightness is attained.

Plug design

Structural and hydraulic aspects

In parallel-sided plugs, a ‘rough’ rock/plug interface is essential in order to:

- provide frictional bond and mechanical interlock at the rock/plug interface, and thereby ensure that the rock/plug interface is not the weak link
- increase the seepage path and thereby reduce the hydraulic gradient along the interface of the plug.

To provide maximum mechanical interlock it is suggested that the undulations in cross-sectional dimensions of the excavation, prior to plug construction, should be of the same order or greater than the maximum size of the pre-placed coarse aggregate, e.g. 300 mm.

No guidance on hydraulic gradient limits for plugs is provided in the 1983 code. As a consequence, high pressure grouting to seal the rock/concrete plug interface and the surrounding rock mass is employed routinely to address the potential problem of leakage *in situ*. No residual permeability is recommended in the code but where it is important to limit seepage, a watertightness ≤ 1 Lugeon should be obtained after grouting.

Aggressive mine water

Where the plug must resist highly acidic mine water and the anticipated design life is long, e.g. ≥ 100 years, consideration should be given to the dissolution of the concrete at the wet face. If dissolution is deemed a potential problem, the application of a layer of low permeability inert material such as a bentonite geotextile will be prudent, since this will inhibit dissolution of the intruded concrete.

In such circumstances, the dissolution of cement-filled fractures in the surrounding rock mass should also be assessed, where parameters to be considered by a cement chemist include source, type and rate of acid production after plug closure, neutrality of groundwater in surrounding rock, availability of free oxygen, permeability of cement grout, hydraulic gradient at plug, permeability of grouted rock mass, and cement content in the annulus of grouted rock around the plug.

Materials for intruded concrete

For ease of handling and packing by hand, bulky angular coarse aggregate should range in size from 300 mm down to 75 mm. In areas of congested pipework, the smaller aggregate size should be used to minimize voidage. The type and source of coarse aggregate supplied to site should be recorded.

Relatively uniform sands graded 2 mm down with not more than 4% passing a 75 micron screen should be permitted, as experience confirms that the resulting finer-grained mortars have high fluidity, low bleed and an absence of segregation without compromising setting or strength. The 1983 code applies the 4% limit to the 150 micron screen. The type, source and particle size distribution of all deliveries of sand should be recorded.

To facilitate any back-analysis of results and for record purposes, a cement certificate, including typically specific surface area, main chemical compounds and setting times for cement paste, should be provided by the cement manufacturer for every delivery supplied to site.

Mortar mix design

To improve concrete durability and produce a shear strength that is compatible with the safe design shear for Witwatersrand quartzite of 0.83 MPa in the 1983 code, the mortar mix should be designed for a minimum 28-day unconfined compressive strength of 25 MPa. The minimum 28-day UCS quoted in the code is 17 MPa.

To ensure efficient void filling of the pre-placed coarse aggregate and minimize residual bleed lenses, only stable mortars should be permitted, i.e. with a bleed capacity not exceeding 5%. This maximum bleed is generated normally within 2 hours in high strength sand/cement mortars.

Instrumentation

Thermocouples

Where there is no precedent experience for the size of plug or the mortar mix design, including constituent materials, two thermocouples should be placed within the plug in order to monitor temperature rise followed by temperature dissipation with time after mortar intrusion. The results determine the optimal time for the start of plug tightening. To minimize any heat sink effect, the thermocouples should be located centrally and preferably not less than 1.5 m from the rock/plug interface or plug face.

The operation of the thermocouples should be checked:

- daily during plum placement for accidental damage
- immediately prior to mortar intrusion to record the ambient temperature
- on completion of intrusion, as a start point for regular temperature monitoring.

Thereafter, readings should be taken every four hours until the peak temperature is reached, after which temperatures can be monitored daily.

Piezometers

These instruments permit the pore pressure distribution (gradient) to be measured and thereby provide invaluable information on the performance of the plug concrete during service. Where a plug is constructed in segments, a piezometer should be located at each cold construction joint.

Plug construction

Method statement specification

A construction method statement specification, including site preparation, construction procedures, plant and equipment, materials and mix designs, instrumentation, testing, records and design performance requirements, should be prepared by the contractor and approved by the supervising engineer in advance of construction.

The method statement acts as a reference document and provides for all parties:

- an engineering framework for the creation of an intruded concrete plug
- detailed systematic procedures for the controlled construction of the plug
- documentary evidence that will confirm the adequacy of the plug.

Intruded concrete and grouting are specialist processes that are particularly sensitive to quality of workmanship. As a consequence, only personnel with the necessary expertise and experience should be employed. All key phases of the construction works should be supervised, approved, and subsequently signed off by the supervising engineer and a representative of the contractor.

Shutter construction

Where a temporary timber shutter is held in position by restraining rods, these rods should be offset laterally by at least 200 mm during the construction of any follow-on segments of the plug. This staggered format avoids a preferential seepage path through the plug.

Preparation of aggregates

Since the strength of intruded concrete is sensitive to the quality of bond between pre-placed coarse aggregate (plums) and intruded mortar, it is recommended that all coarse aggregate should be double washed, e.g. high-pressure water jet spraying at the stockpile, followed by hand washing and brushing prior to final placement in the plug.

Prior to delivery, the sand should also be double washed to remove fines (silt and clay-sized material) and impurities, as far as practicable.

Batching and mixing of mortar

In order to produce high quality mortar consistently, batches of the constituent materials should be measured by weight. The moisture content of the sand should be taken hourly during mortar intrusion, so that appropriate adjustments can be made to the amount of mixing water in the batch. To ensure a well-hydrated and homogeneous mortar, high speed, high shear mixing is recommended with a minimum mixing time of 2 minutes after all the constituents have been added.

Mortar quality control

For high-quality mortar intrusion, a trained quality controller with knowledge of test procedures should be dedicated full time at the batching/mixing plant during intrusion to oversee the testing, maintain records and ensure that the specified design requirements are met.

Since 28-day cube strengths are retrospective in nature, earlier test results, such as density for control of mix proportions, flow time to ensure adequate pumpability and bleed at 2 hours to check stability, should be obtained hourly during mortar intrusion. Bleed should be measured in a graduated cylinder at least 50 mm in diameter, as smaller diameters can give falsely low results.

The proposed mortar mix, including standard properties (e.g. density, fluidity, bleed, and strength development) should be provided in advance of construction by the contractor. Before mortar intrusion of the plug is permitted, the mortar should be prepared and pumped to the plug site using production plant and checked for absence of segregation. This field trial also permits useful acceptance criteria for density and flow cone readings to be established in advance of intrusion.

Placement of mortar

To limit the amount of residual bleed generated within the intruded mortar at the top of the plug, the pumping rate should be reduced to 2 m^3 per hour, or less, during the latter stages of intrusion. In this way, the residual bleed should not exceed 5% of 4 m^3, i.e. 0.2 m^3.

High-point injections

High point injections can commence as soon as bleeding of the mortar ceases, e.g. after not less than 2 hours. Neat cement grouts with a water/cement ratio of 0.4 by weight (or as thick as possible) should be injected at pressures up to at least 1.5 times the maximum hydrostatic pressure anticipated during service via pipes previously located at the surveyed local high points.

Plug tightening of the rock/plug interface and surrounding rock mass

The number and locations of tightening pipes should be determined on the basis of the surveyed surface area of the plug, in conjunction with the 1983 code limits on area per pipe.

Depending on the thickness of the interface or permeable fractures to be sealed, a neat cement grout with a water/cement ratio of 2.0 by weight, combined with a thickening sequence down to a water/cement ratio of 0.4, should be planned and stage closure criteria agreed. Injection should proceed in a primary-secondary sequence in stages of 0.5 m to 1 m over a distance of 2 m (measured normal to the plug interface) with a maximum injection pressure not less than 1.5 times the maximum hydrostatic pressure anticipated during service.

Verification of the effectiveness of the plug tightening and compliance with the specified residual watertightness, e.g. 1 Lugeon, should be checked by water testing via independent holes at intermediate locations between the grout tightening holes.

On completion of grouting, all holes and pipes should be filled with as thick a grout as possible, e.g. water/cement ratio = 0.4 by weight.

Scabbling of dry face of plug

For a plug built in segments, the full dry face area should be scabbled by chiselling or grit blasting, in order to expose the aggregate and create a rough surface overall (including the mortar) onto which the new mortar from the next segment can bond. The rough interface ensures that there is no preferential leakage path across the cold construction joint.

Scabbling should take place after completion of plug tightening as the shutter protects the concrete face from being contaminated with oil from drilling machine exhaust. Generally, the depth of scabbling should be 10 mm to 20 mm. Small patches (5 cm^2 to 20 cm^2) of the original face can be left in place provided the smooth areas are not interconnected.

The scabbled face permits close visual inspection of:

- the structure and integrity of the intruded concrete
- bond between mortar and coarse aggregate
- bond between concrete and the surrounding rock.

In single segment plugs, selected areas of the dry face of the completed plug should be scabbled to provide the same information.

Records

For mortar intrusion, high-point injection and plug tightening, records should be prepared covering all quantities, mixes, injection pressures and quality-control test results to confirm compliance with the specified requirements. The volume of mortar intruded should also be determined and compared with the surveyed volume of the plug after barring, in order to calculate the percentage porosity filled.

On completion of the plug, an as-built construction report should be submitted to the supervising engineer by the contractor within 30 days of completion of plug tightening. This report should contain as-built drawings, supplier certificates for all materials and components, photographs of key construction stages, a summary of all aspects of plug construction and testing, and an analysis of the results, including notification of any non-compliance and its significance. Once the report has been approved by the supervising engineer, it should be signed off by representatives of the client, supervising engineer and contractor.

Special tests

Cores of the intruded concrete, rock/plug interface and surrounding ‘grout tightened’ rock should be taken for examination of the structure of the *in situ* materials and for compressive strength, stiffness and shear strength (c and ∅) testing.

The cored holes should be subjected to water/pressure testing to establish the watertightness of the intruded concrete, rock/plug interface and the 'grout tightened' surrounding rock. Thereafter, hydrofracture tests in the same holes are recommended to establish the normal stress (σ_n) at the rock/plug interface.

The normal contact stress (σ_n) can be combined with the shear strength parameter (∅) at the interface to determine the *in situ* shear strength for comparison with the design assumption. No reliance should be placed on cohesion as a resistance parameter, as it reduces to zero after a small shearing displacement.

Monitoring

Overall water seepage

The overall water seepage at all levels associated with the water barrier should be recorded via electronic monitoring of flow over weirs constructed across haulages. During flooding, if significant increases in the seepage rate are encountered, the flood water level should be recorded and the potential source investigated.

Access

Safe permanent access to the dry side of the plugs should be maintained to facilitate monitoring and maintenance of the plugs, including the measurement of any localized seepage downstream of the plugs during service.

Plug site inspection

The plug site should be inspected on a regular basis. Abnormalities, if any (e.g. sudden change in piezometer readings, water seepage, fractures in the plug or rock), should be recorded in terms of magnitude and location, and reported immediately to a designated responsible mine official.

Drain holes (typically 3 m long and fitted with short standpipes at entry) should be considered through the rock faces immediately downstream of the plug, e.g. 1 m from dry end. Where appropriate, the holes should be drilled to intersect known discontinuities. The monitoring of these holes should include water seepage rate, water sampling and water quality assessment.

If the water seepage contains solids, the total suspension of solid particles and dissolved chemical components should be measured. Such sample analyses and whether the seepage rate is increasing or not, can help determine the cause and likely source.

Seismicity

Where seismicity is a potential concern, a geophone should be located within the water barrier so that mining-induced or natural seismic events can be monitored routinely. After any significant seismic event, seepage and pressure readings, together with a plug inspection, should be carried out.

Records

For ease of assessment, the results should be tabulated or plotted against time so that trends and changes can be easily recognized.

Maintenance

Watertightness checks

For a plug critical to the safety and operation of the mine, selective watertightness checks of the rock/concrete interface and the rock immediately surrounding the plug should be carried out annually via a single ring of existing tightening holes in the plug. In the following years, the procedure should be repeated using alternative rings of tightening holes until all accessible holes are checked over a period of time, before restarting the sequence.

Supplementary grouting

Where a rock/concrete interface or stage watertightness greater than originally specified is measured, the hole should be grouted, in accordance with standard plug tightening procedures.

After supplementary grouting of the interface or stage within a tightening hole, the watertightness should be re-measured, and if necessary the stage regrouted (and re-tested) until the specified residual value, e.g. 1 Lugeon or less, is confirmed.

Remedial grouting

If during service, water seepage is observed at the rock/plug interface or through fractures in the rock mass immediately surrounding the plug, then all accessible tightening holes should be redrilled, water-pressure tested (Lugeon method) and grouted.

In these circumstances, the purpose of grouting all tightening holes is to provide an engineered thickness of grout treatment over both the rock/grout interface and the surrounding rock mass adjacent to the plug.

In the event that the observed water seepage is more remote from the plug, then depending on its magnitude and location, fissure grouting should be considered to form a grout curtain and thereby reduce the permeability of the grouted rock mass.

Conclusions

The recommendations in this paper are based on observations and lessons learned during the planning and execution of the Water Barrier Project at the South Deep gold mine. Since the recommendations augment current guidelines in the 1983 Code of Practice, it is hoped that consideration will be given to a review of the current code in order to update and advance plug technology for the benefit of the mining industry, both at home and abroad.

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Johnson Mattey releases ‘Platinum 2006’ review*

Platinum market in deficit for 7th year

World demand for platinum reached 6.7 million oz in 2005, an annual rise of 160000 oz, according to Johnson Matthey in ‘PLATINUM 2006’, released today. Purchases by the autocatalyst sector again grew strongly. Supplies of platinum grew by 140000 oz to 6.63 million oz, with greater output from South Africa and Russia. Accordingly, the platinum market was undersupplied by 70000 oz, the seventh successive year of deficit.

Diesels drive surge in autocat demand

Autocatalyst demand for platinum surged by 330000 oz to a new high of 3.82 million oz. Most of the growth occurred in Europe and stemmed mainly from tighter emissions rules and the increased use of catalyzed soot filters on light duty diesel vehicles. Purchases of platinum for jewellery manufacture fell by 200000 oz to 1.96 million oz. The high price of platinum prompted a reduction in stocks across the trade and an increase in recycling of old jewellery.

Positive outlook for 2006

Platinum autocatalyst demand will strengthen in 2006, with further growth from the European diesel sector taking total purchases past the 4 million oz mark. Demand for platinum jewellery from affluent consumers in all major regions remains relatively robust, but further appreciation of the platinum price may bring about more liquidation of trade stocks. If supplies from South Africa increase as planned, Johnson Matthey expects the platinum market to remain in moderate deficit in 2006.

Funds could push platinum price to $1250

The price of platinum traded between $860 and $880 for much of the first half of 2005. The second half was marked by increased volatility and a strong rally, as a substantial influx of fund money propelled the price to $1012 in December. With no end in sight to the current commodities bull market, the price has potential to reach $1250 during the next six months, with good end user demand likely to limit the downside to $1025.

Palladium

Palladium demand recovery continues

Palladium demand grew by 480000 oz in 2005 to a five-year high of 7.04 million oz, primarily due to increased purchases by Chinese jewellery manufacturers. As in 2004, mine production was supplemented by substantial year-end sales of Russian metal from stocks and, at 8.39 million oz, total mine supplies of palladium exceeded demand by 1.35 million oz.

Jewellery manufacturing up sharply

Demand for palladium from the Chinese jewellery trade jumped by 71 per cent in 2005 to 1.2 million oz. The low cost of financing palladium, and the higher profit margins available compared with platinum, enabled manufacturers and retailers to establish and maintain large inventories of palladium jewellery. In contrast, purchases of palladium for autocatalysts increased by less than 1 per cent to 3.8 million oz in 2005, as average catalyst loadings continued to decline.

Mixed prospects for demand this year

After rising strongly for the last three years, demand for palladium could flatten out in 2006. Autocatalyst demand prospects are positive, as OEMs in the USA and Asia are increasingly replacing platinum with palladium in autocatalysts for gasoline engines. The outlook for jewellery demand is less certain. Although retail sales in China may well strengthen, the large inventories of palladium jewellery built up in 2005 could stifle any growth in purchases of metal by manufacturers. With South African mine output expanding, and Russia continuing to sell state stocks, another surplus in supply in 2006 is likely.

Palladium price could pass $400 but downside risk remains

The liquidity in the palladium market capped the price at or just above $200 for the first nine months of 2005, before fund buying in the fourth quarter pushed the price to $297. If speculative buying continues, Johnson Matthey forecasts that palladium could trade as high as $420 over the next six months, but that in the event of a major fund sell-off the price could drop to as low as $260. ◆

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