Grouting of Permanent Intruded Concrete Tunnel Plugs at South Deep Gold Mine, South Africa

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ABSTRACT: The potential closure and subsequent flooding of a neighbouring mine necessitated the construction of a rough parallel intruded concrete plug within each of the tunnels connecting the two mines through a 40m thick boundary rock wall. The paper describes the design and construction of three 30m long tunnel plugs formed in Witwatersrand quartzite to withstand safely highly acidic groundwater at a maximum hydrostatic head of 1500m for 100 years and two 25m long plugs in Ventersdorp lava where the groundwater was neutral at a head of 1250m. For the known rock mass properties, design considerations include grout design for the rock/plug interface and rock mass, mortar design for injection of the preplaced aggregate and associated strength and stiffness properties. For plug construction, each critical element is described, i.e. rock preparation, pre-grouting of rock mass, placement of coarse aggregate, grouting plant, injection procedures and the associated quality controls.

DESIGN OF PLUGS

Strength and shear resistance of rock and mortar intruded concrete

Of the five plugs to be designed for a service life of 100 years, three were founded in Witwatersrand quartzite to be subject to a head of 1500m and two were founded in Ventersdorp lava for a predicted head of 1250m. Table 1 indicates the typical engineering properties of these lithologies.

Table 1. Typical engineering properties of Witwatersrand quartzite and Ventersdorp lava

Property	Witwatersrand quartzite	Ventersdorp lava
UCS (MPa)	175	295
Elastic modulus (GPa)	70	87
Angle of internal friction ($ø^0$)	53	59
Cohesion (MPa)	32	31
Rock Mass Rating	75	82

Bearing in mind the very high Unconfined Compressive Strength (UCS) of these rocks, the weakest structural element was the intruded concrete and by reference to ACI 322-72 for a 28-day UCS of 25MPa, the safe shear was calculated as 0.83MPa. The typical sectional dimensions of the parallel sided tunnels were 4m x 4.4m and for a uniform design safe shear of 0.83MPa and a maximum hydrostatic pressure of

15MPa, the structural length required was 18.9m. Barring and scaling to sound rock and an amplitude of surface roughness of at least 1-2mm was required to ensure an infinitely rough interface and thereby develop the shear strength within the mortar, as opposed to bond at the rock/plug surface.

Groundwater flow and hydraulic gradient

At South Deep, it was considered essential to reduce groundwater flow past the plug as far as practicable by (i) improving water tightness of the rock/plug interface and surrounding rock, and (ii) reducing the hydraulic gradient. Grouting was employed to improve the former while extending the plug length reduced the hydraulic gradient. The surrounding rock comprised very strong material with a low permeability ($k_w < 1 \times 10^{-10}$ m/s) but within the rock mass, permeable fractures existed of apertures from 0.01mm up to 10mm. Where the fractures were mining induced, i.e. within 1-2m of the tunnel perimeter, the fracture spacing was approximately 0.5m. For more remote geological fractures, the typical spacing increased to 5-10m. A residual water tightness ≤ 1 Lugeon (mass permeability ≤ 1×10^{-7} m/s) was specified for the rock/plug interface and rock mass, although beyond 5m the specified residual permeability was relaxed to 3 Lugeons. Based on precedent practice, a hydraulic gradient of 50 was specified leading to a plug length of 30m in the Witwatersrand quartzite and 25m in the Ventersdorp lava.

Aggressiveness of mine water

Given the 100-year design life, a further consideration was the aggressiveness of the mine water and its effect on the longevity of the intruded concrete. As the groundwater was highly acidic (pH = 1.8 to 2.8) at the Witwatersrand quartzite level, a low permeability inert bentonite impregnated geotextile sandwich (minimum thickness = 20mm) was specified for the front face of the plug. The bentonite expands on contact with water and the permeability of the seal is very low, i.e. 1×10^{-11} m/s. In addition, 1000kg of lime [composition 60% $Ca(OH)_2$ and 40% Na_2CO_3] was required to be deposited on the tunnel floor in front of the plug in order to neutralise the acidic water in the immediate vicinity of the wet face of the plug.

Constituent materials of intruded concrete

For the intruded concrete, the preplaced coarse aggregate comprised bulky angular quartzite in the range 300mm to 75mm. The minimum size of 75mm ensured efficient subsequent permeation of the sand/cement mortar through the voids in the coarse aggregate. The fine aggregate for the mortar was 1.18mm down river sand with no more than 4% passing the 75 micron sieve. The cement was ordinary Portland cement in accordance with SABS EN197 and the water was potable Rand water (pH = 7.9-8.3). The mortar design was based on a 1:1 sand/cement ratio, a water/cement ratio ≤ 0.64 by weight for a minimum UCS of 25MPa at 28 days, and a maximum bleed of 5%. Given this bleed that is developed over two hours, final "high point" grouting of each intruded plug was required using a neat cement grout (water/cement ≤ 0.5 by weight).

Instrumentation

For the mortar mix, a temperature rise of 12^0C per 100kg of cement per m^3 of intruded concrete was anticipated and for a field tested voidage of 53% and a cement content of $398kg/m^3$, a maximum temperature rise of 48^0C was predicted. As a consequence, given an ambient mine temperature of 35^0C, two thermocouples were specified for each segment of plug to monitor temperature rise and dissipation. In addition, in order to monitor pore water pressures within the plug during service, stainless steel pipes were specified to be installed extending from the dry face to each cold joint (construction joint between concrete segments).

CONSTRUCTION OF PLUGS

General

Intruded concrete construction and grouting are specialist processes that are particularly sensitive to the quality of the workmanship. As a consequence, all construction operations were supervised by a competent and experienced engineer. Specialist supervisory staff and key personnel were employed full time on the project and could not be withdrawn from the site without the prior knowledge and consent in writing of the supervising engineer.

The long plug lengths coupled with the small tunnel cross sections led to restrictions in placing the inclined grout tightening pipes. As a consequence, each plug was constructed in four segments (7.5m long in the Witwatersrand quartzite and 6.25m long in the Ventersdorp lava).

Rock preparation

At all plug locations, barring was carried out to gain sound rock and a clean infinitely rough surface was provided. After barring, segment dimensions were surveyed at 1m intervals to (i) estimate the volume of the plug segment, (ii) determine the final shape in plan, longitudinal section and cross section, and (iii) prepare as-built drawings.

Pre-grouting of rock mass

Where appropriate, pre-grouting up to 9m from the perimeter of the tunnel was implemented in 3m stages via a ring of 12 holes using a neat cement grout mix with an initial water/cement ratio of 1.0 gradually reducing to 0.4 by weight.

Back retaining wall and bentonite geotextile

A 500mm thick reinforced concrete back retaining wall was cast initially to act as a back shutter for the first intruded concrete segment. Thereafter, four 5mm thick layers of bentonite impregnated geotextile were pinned onto the dry side of the retaining wall over the full face area of the plug plus an overlap of 0.3m on the rock perimeter. Bentonite paste was employed to seal textile joints and the junction of the fabric with the rock.

Front face shutter

At the front dry face of the segment, a timber shutter was erected in stages as the coarse aggregate infill was placed in layers. This shutter was secured in position with the aid of horizontal 16mm diameter stainless steel bars connected by a coupling to a bar fixed in the concrete of the back retaining wall or preceding plug segment, as appropriate. When additional segments were constructed, care was taken to offset these bars by at least 200mm from the locations of bars used on the preceding segment, in order to avoid the creation of a preferential seepage path. On completion of the shutter, the timber joints and grout pipe surrounds were hand plastered with cement paste to prevent mortar leakage during intrusion.

Preparation and placement of coarse aggregate

All coarse quartzite aggregate was high pressure water jetted prior to being sent underground. The aggregate was then double washed and scrubbed free of grit, dust and any adherent substances at the plug site, before being placed manually within the segment. Cleanliness of the coarse aggregate was important because the strength of intruded concrete is directly related to the bond between the mortar and the coarse aggregate. Coarse aggregate was packed tightly in maximum 1.5m layers using smaller sizes to fill the remaining voids.

Placement of mortar and grout pipes

25mm diameter seamless steel mortar intrusion pipes were placed at a spacing no greater than 2m horizontally and 1m vertically. Typically, 60 intrusion pipes were required for each segment. Grout tightening pipes were angled to intersect the perimeter of the segment and on average a pipe intersected the rock/plug interface every 3.5m^2. Up to 40 injection pipes were required for each segment. In addition, grout pipes were installed to intersect high points at the roof of the tunnel to permit final venting of bleed water and void filling.

Placement of thermocouples and piezometers

Two thermocouples were positioned within each segment. In all cases, the thermocouples were located at a distance not less than 1.5m from the rock perimeter and at horizontal distances of 2.5m and 4.5m from the dry face shutter. To monitor pore water pressures during service, three 50mm diameter stainless steel pipes were placed within the plug at cold joints.

Plant and equipment for mortar intrusion and grouting

Mixing was conducted in a high speed, high shear, colloidal mill mixer with a minimum mixing time of 2 minutes, in order to produce a well-hydrated homogeneous mix that was discharged at a rate of 4-6m^3/hour into a 200 litre agitation tank. Production pumping was via two electro-hydraulic 63.5mm diameter reciprocating ram grout pumps, each with an output of up to 3.1m^3 per hour and the discharge pressure was preset at 5MPa. Grout was mixed in a double drum, high shear mixer and pumped into place using a 50mm diameter reciprocating ram pump.

Mortar intrusion

The first batch of mortar (volume equivalent to 5 minutes of pumping time) was discarded due to its higher bleed capacity caused by the initial presence of water in the pipeline. Mortar was then injected into the voids of the preplaced aggregate via intrusion pipes. Intrusion started at the lowest level and nearest the wet side of the segment and then advanced towards the dry end. When mortar vented from the lowest and nearest pipe to the dry end, intrusion was moved to the second layer of pipes, the sequence being repeated at increasing elevations until a full return of mortar was observed to vent from the uppermost pipe, at which time intrusion was stopped. Mortar was pumped initially using two pumps, although during the final stages, intrusion was restricted to one pump. The reduced production rate limited the volume of residual bleed at the top of the segment. Generally, mortar intrusions were completed within 9-13 hours (7.5m segments) and 7-9 hours (6.25m segments). Ignoring occasional breakdowns, average mortar intrusion rates ranged from 5.9 to 6.9m^3/hour. All intrusion pipes were left filled with mortar before being abandoned.

High point injection

Not less than 2 hours and not more than 12 hours after completion of mortar intrusion, high point injection commenced using a neat cement grout (water/cement ≤ 0.5). Injection continued until the same quality of grout was observed to vent from the highest pipe. On completion of injection, the pipes were sealed by filling with stable neat cement grout before being abandoned.

Thermocouple readings

Thermocouple readings were taken daily during the placement of the coarse aggregate and immediately before the start of mortar intrusion, in order to establish ambient conditions. Thereafter, readings were taken hourly for the first 24 hours after which temperatures were monitored at least daily for a period of 28 days (Figure 1).

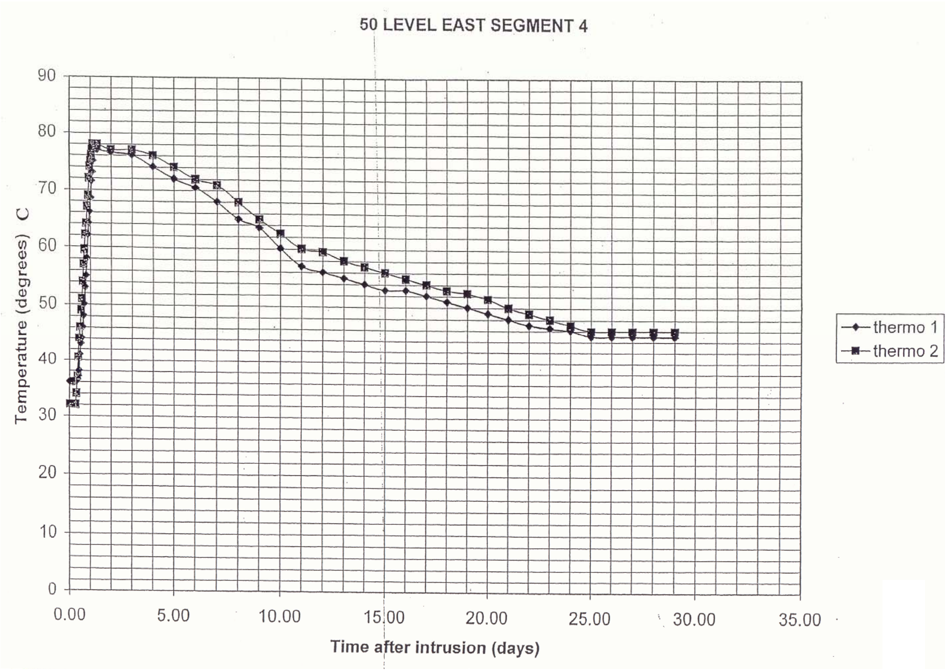

FIG. 1. Temperature after intrusion in one representative instrumented plug segment.

Scabbling of dry face of exposed concrete segment

The front timber shutter was removed generally 3 days after completion of the mortar intrusion. The full concrete face was then scabbled using air operated hammers, in order to expose the aggregate and create a rough surface onto which the new mortar of the next segment could bond. In addition, the rough face ensured that there was no preferential leakage path across a cold joint. Typically, the depth of scabbling was 10-20mm.

Grout tightening of rock/plug interface and rock mass adjacent to plug

Based on thermocouple results, grout tightening was not permitted to start until 28 days had elapsed after completion of mortar intrusion. Injection of the interface was carried out using neat cement grouts (water/cement ratio varying from 1.0 to 0.4). Injections were carried out advancing towards the dry side of the segment and grouting continued until the permeability was 1 Lugeon or less. If necessary, grouting of an individual hole was advanced in 0.5m stages into the rock mass. On completion of grout tightening and testing, all pipes were sealed by filling with a stable grout before being abandoned.

QA/QC AND CONSTRUCTION STATISTICS

Routine QA/QC for permanent plug construction

From the onset of the project, all parties were committed to consistently providing and assuring the highest practical standards of quality in every process of the underground works. In overview, the following quality initiatives were taken for some of the most critical processes described earlier.

- *Site selection and rock preparation* – Plug sites were carefully investigated, selected and mapped according to the quality of the rock mass and were prepared to provide boundary conditions of appropriate shape and cleanliness. The suitability of each site was then signed off jointly.
- *Pre-grouting of rock mass* – Upon completion of pre-grouting, where conducted, residual permeability was judged to be acceptable via post-grouting Lugeon testing.
- *Preparation and placement of coarse aggregate* – The close packing of the coarse aggregate and cleanliness of individual pieces were assessed approved and signed off jointly.
- *Mortar intrusion* – Records of mortar constituents, mortar intrusion volume, quality control test results, batch controller print-outs and temperatures during curing were forwarded by the contractor to the supervising engineer for assessment and approval.
- *Scabbling of dry face of concreted segment* – On completion of this work, the acceptability of the face conditions was inspected and approved by the supervising engineer.
- *High point injection and grout tightening* – Each hole was brought to refusal on the basis of attaining the specified maximum injection pressure. Contemporary construction records were maintained by the contractor and signed off retrospectively by the supervising engineer who also carried out random checks on the operations during the works.

On completion of each segment, an as-built construction report was required to be signed off by representatives of the client, supervising engineer, contractor and members of an International Review Panel.

QA/QC procedures during mortar intrusion

Bearing in mind that an acceptable grading curve envelope had been established for the river sand, random samples from discrete locations and deliveries were tested for compliance, together with moisture content checks on the sand, as stockpiled. Monthly cement certificates were obtained from the cement supplier.

At the batching plant, all materials were weight batched (1.5% accuracy) and Table 2 illustrates the routine tests carried out on the mortar produced at the batching plant.

Table 2. Routine QA/QC tests for mortar during intrusion

Property	Test method	Frequency
Fluidity	Marsh cone	Every hour
Density	Baroid mud balance/Salter scale	Every hour
Stability	Bleed cylinder	Every two hours
Strength development	100mm cubes	3 cubes every 2 hours

Mortar strength tests

The 100mm mortar cube strength development with time for all segments is summarised in Figure 2.

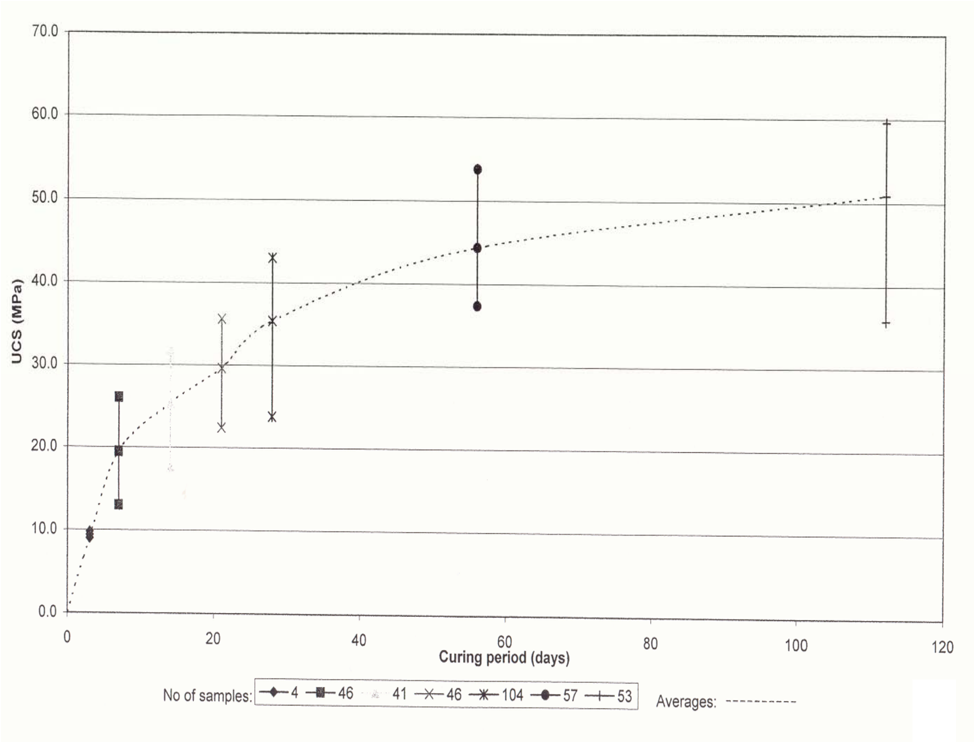

FIG. 2. Range and average of mortar cube strengths based on individual segment averages.

The key acceptance criterion (minimum of 25MPa at 28 days) was attained on average by every segment of every plug, the overall average being 35.6MPa.

High point injection

Each production segment was subjected to high point injection after the mortar had stopped bleeding. Volumes of 0.25 to 0.44m^3 were estimated to have been injected, equivalent to a bleed of 2-5% of the volume of grout placed in the final two hours that tied in with the batch bleed values.

SPECIAL TEST RESULTS

In situ structure, strength and stiffness of intruded concrete

Close examination of scabbled faces and cores from the intruded concrete indicated a homogeneous structure with excellent bonding of the mortar with the coarse aggregate and the surrounding rock. On a full plug face of $17m^2$, up to three minor lenses 2-3mm in aperture and 20-30mm long were observed located under the coarser aggregate due to entrapped water or air. These minor defects were not significant as they were not interconnected and the concrete was sensibly watertight, as verified by in-situ water pressure tests. There was no evidence of thermal cracking.

Concrete core samples (300mm diameter) were tested independently and one-year UCS values ranged from 36.3 to 42.8MPa with an elastic modulus of 10.7 to 21.0GPa. The density varied from 2.08 to 2.35 Mg/m^3.

Shear strength tests on 59-72mm diameter cores gave cohesions in the range 11.8 to 12.6MPa and highly variable angles of internal friction (ø) ranging from 29.2^0 to 53.1^0 due to the large size and distribution of the coarse aggregate.

Strength and stiffness of production mortar

While the unconfined compressive strength of the 100mm cubes of production mortar was confirmed at an average value of 34MPa at 28 days, this increased to 61MPa at 140 days. The elastic modulus ranged from 16.2 to 23.5GPa at 28 days and 14.7 to 21.2GPa at 140 days where the elastic modulus was calculated at 30%UCS.

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORKS

Once a tunnel plug has been completed, including grout tightening of the rock/plug interface and surrounding rock mass, it is recommended that high quality coring should be carried out randomly through the completed plug, in order to confirm the watertightness of the plug concrete, rock/plug interface and the surrounding rock. These boreholes must be independent of the grout tightening holes so that the tests can verify the residual watertightness attained in the adjacent rock. The cores of the intruded concrete, rock/plug interface and surrounding rock should also be tested to determine strength and stiffness properties. Piezometers should be incorporated at the construction joints of the plugs to measure internal pore water pressure gradients.

Wherever practicable, permanent boundary plugs should be commissioned, i.e. proof tested by controlled flooding, to provide field data on the watertightness of the water barriers incorporating the plugs. This approach would be similar to commissioning a dam by controlled reservoir impounding.

The successful construction of 20 production plug segments required a rigorous and unremitting attention to detail. They were constructed under the guidance of a very detailed method statement and under strict QA/QC conditions. The work was undertaken under arduous ambient conditions. The technical, logistical and environmental conditions of such mining projects demand transparent working relationships between the respective parties. For successful construction of plugs such as at South Deep, the commitments to quality, collaboration and implementation are absolutely essentially and totally intertwined.

ACKNOWLEDGEMENTS

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