INTRUDED CONCRETE PLUGS IN A DEEP GOLD MINE: AN EXERCISE IN QUALITY CONTROL, ASSURANCE, AND PERFORMANCE VERIFICATION

International Review Panel[1]

ABSTRACT

Five horizontal concrete plugs were designed and constructed in a deep gold mine near Randfontein, South Africa. Intended to resist water heads of up to 1500m, they were up to 30m long and measured 4 by 4.5m in cross-section. Each plug was constructed in four separate, contiguous segments using the mortar intruded preplaced aggregate ("colcrete") process. They have been designed conservatively to provide a service life of at least 100 years. This paper focuses on the construction aspects, and in particular the very intense levels of QA/QC and performance verification which were considered appropriate to the project, given the potentially horrific consequences of failure to the mine labor.

1. INTRODUCTION

In the event of flooding of Randfontein No. 4 Shaft of Harmony Mine, South Africa, five rough parallel-sided boundary plugs at the so called 58 and 50 mine levels of the adjacent South Deep Mine had to be designed to resist safely hydrostatic heads of 1500m (15MPa) and 1250m (12.5MPa), respectively. Given the unacceptable consequences of plug failure and the extremely high water pressure, all elements of the permanent plugs were designed conservatively for a service life of 100 years. To the authors' knowledge, there has never been a structural failure of a high pressure mortar intruded concrete plug, but water leakage that is obvious and extensive has been encountered in service. As a consequence, particular attention was paid to watertightness in the plug design at South Deep. A comprehensive account of the details of the design of the South Deep Plug was provided by Littlejohn and Swart (2004).

2. CONSTRUCTION OF THE PERMANENT PLUGS

2.1 General

Each segment of each plug involved a very well-defined construction sequence: preparation of the plug site construction of back retaining wall, fixing of bentonite

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geotextile, pre-grouting of rock mass, pre-placement of coarse aggregate, installation of intrusion and grout injection pipes, placement of thermocouples, mortar intrusion, highpoint grout injection, plug tightening, concrete scabbling, quality control tests and associated records. The specific requirements were included within the Method Statement. This document also included design performance requirements and was prepared in collaboration with the Client, Consultant, Contractor and the authors, in order to provide:

(i) the engineering framework for the creation of an intruded concrete plug,
(ii) detailed systematic procedures for the controlled construction of a plug, and
(iii) documentary evidence that would confirm the adequacy of each permanent plug, in terms of the design requirements.

All aspects of the plug design and construction either met or exceeded the recommendations of the 1983 Code of Practice and associated South African standards for materials and testing. All key phases of the works were supervised, approved and subsequently signed off by the Engineer of Record and a representative of the Contractor.

It must be appreciated that intruded concrete construction and grouting are specialist processes that are particularly sensitive to the quality of 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 roadway cross-sections, led to understandable restrictions in placing inclined grout tightening pipes. As a consequence, each plug was constructed in four contiguous segments, generally 7.5m long for the three plugs at 58 level and 6.25m long for the two plugs at 50 level. Permanent plug construction started in May 2001 and was completed in August 2003. The segments were approximately 4m by 4.5m in cross-section.

2.2 Rock preparation

At all plug locations, barring by hand was carried out to sound rock and a clean, infinitely rough surface was provided. Where friable rock was encountered, barring continued typically to a depth of at least 0.5m before approval of the surface of a segment was given. Occasionally, stress induced fracturing and minor strain bursting occurred in the sidewalks.

After barring and cleaning, segment dimensions were surveyed independently 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

2.3 Pre-grouting of rock mass

Pre-grouting up to 9m from the perimeter of the plug was carried out via a ring of 12 holes for the 2nd segment of 58 West 2 plug using a total of 155kg of cement. For the 3rd segment of the plug, two permeable faults and other permeable zones were pre-grouted via 35 holes (9m long) using 1721kg of cement.

Pre-grouting was carried out beyond the 3rd segment of 58 West 1 plug via 50 holes (9m long) using 1559kg of cement. Treatment beyond the 4th segment of 58 East plug was conducted to intersect and treat locally approximate east-west trending faults. 300kg of cement was injected via a ring of eight holes (9m long). All grouting and associated water testing was carried out systematically within the grout holes.

2.4 Minewater control at plug site

To prevent minewater flowing through the work site, one metre high concrete retaining walls were erected some 2-4m in front of and behind the proposed plug position. A flanged pipe was then assembled through the working area and connected to both retaining walls in order to divert the minewater. A 90° pipe elbow was fitted in the vertical position beyond the retaining wall on the wet side of the plug, so that the pipe could eventually be sealed efficiently by stable grout infilling.

2.5 Check point inspection of plug segment site and sign-off

As a check point before construction of any part of the permanent plug segment could proceed, the ground conditions and cleanliness of the site area were inspected, approved and signed off by representatives of both the supervising engineer and the Contractor.

2.6 Lime placement

1000kg of lime [composition = 60% $Ca(OH)_2$ and 40% Na_2CO_3] were deposited onto the floor of the roadway immediately in front of the wet face of the back retaining wall shutter.

2.7 Back retaining wall

A 500mm thick reinforced back retaining wall was cast as the wet boundary for the first segment of the plug.

2.8 Bentonite geotextile

Four 5mm thick layers of bentonite impregnated geotextile were placed and pinned onto the dry side of the back 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.

2.9 Front face shutter

At the front dry face of the segment, a timber shutter was erected in stages as coarse aggregate infilling 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 the 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 pipe surrounds were hand-plastered with cement paste to prevent mortar leakage during intrusion.

2.10 Preparation and placement of coarse aggregate

All coarse quartzite aggregates (plum sized 300mm down to 75mm) were high pressure water jet sprayed prior to being sent underground. The aggregates were then double-washed and scrubbed to be free of grit, dust and any adherent substances at the plug site, before being placed manually within the segment. During aggregate placement, all personnel had to wash their boots before entering the work area. The cleanliness of the coarse aggregate is important because the strength of intruded concrete is directly related to the bond between the mortar and the coarse aggregate. As a consequence, the cleanliness of the coarse aggregate as placed, and the maintenance of clean aggregate prior to mortar intrusion were subject to regular inspection. In the event of any contamination (e.g. dirty water flowing through the coarse aggregate at the floor of the plug site), the coarse aggregate was removed and replaced with clean aggregate. Coarse aggregates were packed tightly using smaller sizes to fill the remaining voids. Each segment was filled in horizontal layers up to within 1.5m approximately of the hanging wall. Thereafter, the final space was filled by packing from the wet side of the segment at 45° to the back and side walls as placement approached the access point at the top of the front shutter. In areas of congested pipework the smaller sized plums had to be used, in order to reduce the volume of voids.

2.11 Placement of mortar intrusion, grout tightening and high point injection pipes

Mortar intrusion and grout tightening pipes were placed at the locations illustrated in the design drawings, although on occasions the dry face locations were adjusted slightly to minimize congestion. Given that mortar intrusion is by gravity displacement, care was taken to place lower level intrusion pipes just above the floor of the segment. Grout tightening pipes were designed such that not more than 3.5m^2 of the rock/concrete interface were covered on average by each pipe. In accordance with the 1983 Code, on no occasion was less than one pipe provided for any 7m^2 of interface. High point injection pipes were installed at high points in the hanging wall.

2.12 Placement of thermocouples

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 for the 7.5m long segments (58 level) at horizontal distances of 2.5m and 4m from the dry face shutter. For the shorter 6.25m long 50 level segments, the horizontal distances were reduced to 1.75m and 3.5m.

2.13 Installation of piezometer pipes

Two stainless steel 50mm diameter pipes at a 1º inclination were initially planned at each cold joint. The 50mm diameter was chosen to permit subsequent re-drilling of any mortar infilling. In order to reduce pipe congestion, the number of piezometer pipes was reduced from six to three. Preferably, two piezometers were placed at the first cold joint from the wet end with a third piezometer placed at the second cold joint. Where only one piezometer had been placed at the first cold joint, a single piezometer was placed at each cold joint.

2.14 Supply checks on mortar constituents

For each delivery of cement to the site, a standard test certificate was requested from the cement supplier. Random samples of each batch of sand delivered to site were graded to ensure conformance with the specified requirements. The source of the sand was also provided.

2.15 Plant and equipment for mortar intrusion and grouting

For mortar intrusion, the materials storage, batching, mixing and pumping facility was located at SV1 on 50 level, from where the mortar was pumped via a 50mm steel pipeline to the plug sites.

Mixing was conducted in a high speed, high shear "colloidal" 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 per hour into a 1200 liter agitation tank. Production pumping was by two electro-hydraulic reciprocating ram (63.5mm diameter) grout pumps, each with a typical output of up to 3.1m^3 per hour at 60 strokes per minute. The maximum discharge pressure was pre-set at 5MPa. The level of stand-by key equipment and spares, capable of being brought into immediate use in the event of equipment failure was 100%. For grout injection of the rock/concrete plug interface and the surrounding rock mass, drilling of holes was by a hand held pneumatic rock drill with air leg. Grout was mixed in a double drum high speed high shear mixer and pumped into place using a reciprocating ram (50mm diameter) pump.

2.16 Mortar intrusion

The first batch of mortar (of volume equivalent to a minimum pumping time of 5 minutes) was discarded in each intrusion 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 pre-placed 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. This reduced production rate limited the volume of residual bleed at the top of the segment. Generally, mortar intrusions were completed within 7-9 hours for 6.25m segments and 9-13 hours for the longer 7.5m segments at 58 level. Ignoring the occasional breakdowns of plant items, average mortar intrusion rates ranged from about 5.9 m^3 to 6.9 m^3 per hour. All intrusion pipes were left filled with mortar before being abandoned.

2.17 High point injection

Not less than 2 hours and not more than 12 hours after completion of mortar intrusion, highpoint injection commenced using a neat cement grout (water/cement $\leq$ 0.5). Injection proceeded until the same quality of grout was observed to vent from the highest pipe.

On completion of the injection, the pipes were sealed by filling with stable neat cement grout (water/cement $\leq$ 0.5) before being abandoned.

2.18 Thermocouple readings

Thermocouple readings were taken daily during the placement of the coarse aggregate and immediately before the start of mortar intrusion. Thereafter, readings were taken hourly over the first 24 hours after which temperatures were monitored at least daily for a period of 28 days.

2.19 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 chipping 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.

2.20 Grout tightening of rock/concrete plug interface and surrounding rock mass

After water flushing the rock/concrete plug interface to remove any grit and water-pressure testing to check watertightness, injection of the interface was carried out using neat cement grouts within the specified range of water/cement ratios. Injections were carried out in a pre-determined sequence advancing towards the dry side of the segment, in accordance with the design drawing. The appropriate overall length of injection hole into the surrounding rock mass was determined from the results of water-pressure testing during the preliminary geological assessment of the plug sites. Rock exhibiting a watertightness value in excess of 3 Lugeons was grouted in order to reduce permeability down to 1 Lugeon or less.

Stage lengths of 0.5m were employed routinely, as each hole was advanced into the rock mass. This approach reflects a "descending stage" method of injection whereby previously grouted stages are subjected to additional treatment as the new stage is grouted. The short stages of 0.5m were particularly rigorous, bearing in mind that 1-2m stages are recommended in the 1983 Code. Post-grouting water-pressure tests were carried out to confirm that the specified watertightness had been attained. On completion of grout tightening and testing, all pipes were sealed by filling with a stable neat cement grout (water/cement $\leq$ 0.5 by weight) before being abandoned.

2.21 Records

Records covering surveyed dimensions of the segment, mortar constituents, mortar intrusion, quality control test results, batch controller print-outs, temperatures during curing, high point injection and plug tightening were forwarded by the Contactor to the supervising engineer for assessment and approval.

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 the International Review Panel.

2.22 Special features in plug construction

For the 58 East plug containing an existing water door, the exposed steel lining was grit blasted to remove scale and provide a sound "rough" surface. 50mm steel angle sections were welded vertically (i.e. located normal to the tunnel axis) onto the steel lining at 1m centers along the length of the door. The fourth segment was extended 4m beyond the end of the steel lining, as required by the design.

Two 150mm diameter stainless steel (S/S) pipes were installed in the 58 West 1 plug and eight 200mm diameter S/S pipes were incorporated in the 50 West plug. Within the concrete plug segments, Schedule 40 and 80 S/S pipes were connected by bolted flanges fitted with CGI gaskets comprising 316L stainless steel outer and inner rings and a central spiral wound graphite gasket insert. The final pipe sections that protrude through the dry face of each plug comprised Schedule 120 S/S pipe and the protruding ends were fitted with a Ring Type Joint (RTJ) flange connection. Depending on requirements during service, these flanges will be mated with RTJ machined blank flanges or ball valves.

For stainless steel piping in both plugs, satisfactory mill certificates were supplied covering steel composition and heat treatment, together with impact, flattening, ring tensile, metallurgical and non-destructive test results.

The installation of the pipes, including the fitting of wet end 90° elbows and standpipes, was carried out in accordance with the design drawings and approved by the supervising engineer. The installation of the dry end valve arrangements was carried out in accordance with a special method statement.

During the plug construction program, the high-pressure 150NB and 200NB Schedule 120 316L stainless steel pipe, 150NB high-pressure ball valves and 200NB blank flanges were pressure tested at the workshop of the Contractor.

For the maximum design working pressure of 15MPa, the 150NB piping and valves were tested up to 53MPa***** without any leaks, confirming a load safety factor of 3.53. The 200NB piping with 62mm thick flanges and separately a blank flange (68mm thick) were tested to 40MPa, when the CGI spiral wound gaskets in the pipe arrangements failed, thereby confirming a load safety factor of 2.67. These safety factors are considered to be acceptable.

3. QA/QC AND CONSTRUCTION STATISTICS.

3.1 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 accordance with the Method Statement. Specific site inspection duties were conducted by a third-party supervising engineer, hired by the Owner. Interim "sign off" at the "check points" was required prior to the Contractor being permitted to proceed to the next task, using an appropriate pro forma. Photographic records of each process were maintained. The Design Drawing for each segment was posted (properly protected) at each plug site during the construction as a general guide to all personnel involved.

The Contractor was responsible for Quality Control (via a dedicated QC engineer underground), and the Owner (and/or his agent) were responsible for Quality Assurance and verification of performance. The supervising engineer was given authority to stop work if a significant non-compliance was observed, such as contamination of the site by fines carried by flood.

In overview, the following quality initiatives were taken for some of the most critical processes as described in Section 2, above:

- 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 the cleanliness of the individual plums, were assessed, approved and signed off jointly.
- Mortar Intrusion. As described in Section 2.16.
- Scabbling of Dry Face of exposed Concrete Segment. On completion of this work, the acceptability of the face conditions was inspected and approved by the supervising engineer.

***** Maximum pressure available from test pump.

- High Point Injection and Grout Tightening. Each hole was brought to refusal on the basis of attaining the maximum injection pressures described in the Method Statement. Contemporary construction records were maintained by the Contractor and signed off retrospectively by the supervising engineer. Random spot checks of these operations were, however, conducted by the supervising engineer during the works.

For each process, non-compliances with the specification had to be recorded and their potential significance assessed, with appropriate remedial measures if required.

3.2 QA/QC procedures during mortar intrusion

High standards of material handling and storage were observed. Bearing in mind that an acceptable grading curve "envelope" had been established for the doubled washed sand, random samples from discrete sources and deliveries were tested for compliance. The moisture content of the sand, as stockpiled, was tested hourly during batching, but results were of doubtful accuracy due to the malfunction of the test instrument used. As a consequence, sand was sampled on three different occasions during mortar intrusion for moisture content determined by oven drying. Reliance was therefore placed on the data from the hourly testing of the mortar density. Hourly pH readings of the mixing water were also taken to ensure compliance.

As a check point before mortar intrusion could commence, the placement, location and condition of all pipework and coarse aggregate had to be inspected, approved and signed off by representatives of the supervising engineer and the Contractor.

At the batching plant, all materials were weight batched. The accuracy of the load cells was checked with calibrated weights before and after the mortar intrusion. A pre-programmed electronic controller was used to assure correct component proportioning and permitted minor adjustments, on water weight, to maintain batch fluid properties within acceptable limits. The rate at which batches were produced was readily judged from the computer output, both in real time and retrospectively in hard copy. Based on experience gained during the intrusion of the experimental plug it became routine practice to discard at the plug site the first batch mixed (due to its higher than acceptable water content which resulted from residual cleaning water in the system).

During mortar intrusion, the tests shown in Table 1 were conducted on samples taken at the batch plant.

Table 1. 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 2 hours
Strength/ Rate of Gain of Strength	100mm cubes	3 cubes every 2 hours

Data were recorded on specially developed Mortar Quality Control Sheets.

The mandated routine sequence of pipe intrusion was observed full time by the supervising engineer to assure efficient full and progressive filling of the aggregate porosity, while at the conclusion of segment injection, a quick comparison between theoretical and actual mortar volumes was conducted to check the reasonableness of the operation's records. At this time, a tally was made of cement bags used, to quickly confirm the results of the computer-based records.

In early segments, two 210 litre drums containing preplaced plums were intruded using lances. One drum was filled using representative plum sizes, the other with smaller plum sizes. The samples were then cured underground for 28 days before being taken to CSIR Miningtek for unconfined compressive strength testing. Unfortunately, the roughness of the top and bottom surfaces of the samples made it impossible to obtain realistic results and this initiative was therefore soon discontinued.

Records covering surveyed dimensions of the segment, mortar constituents, mortar intrusion, quality control test results, batch controller printouts, temperatures during curing, high point injection and plug tightening were forwarded by the Contractor to the supervising engineer for assessment and approval. On completion of each segment, an as-built construction report was prepared and signed off by the representatives of the client, supervising engineering Contractor and members of the IRP.

3.3 Construction Statistics

The data from the as-built reports were compiled into a project database which comprised six tables:

(i) Geological and site investigatory drilling.
(ii) Site preparation, as related to permeability testing and pregrouting, where appropriate.
(iii) Construction data, including QC tests on sand, mortar and water as well as information on the volume and rate of mortar intruded.
(iv) Thermocouple data, on the curing mortar.
(v) Mortar strength data, from the 100mm cubes.
(vi) High point injection and tightening data.

This section provides information on the data collected in Tables (iii) to (vi).

3.3.1 Construction data

The compliance of the constituent mortar materials to the Method Statement was confirmed. For the fluid mortar, Figure 1 shows the specific gravity readings (by Salter Scale) for each segment. Although three segments recorded values below the specified range, other key properties, specifically bleed and strength, were acceptable. The individual computer records generated during batching confirmed compliant water/cement ratios and sand/cement ratios.

Figure 2 shows the apparent variation in segment porosity to mortar. The average of 52.9% compares closely with the 52.4% figure calculated from 210 liter drum injections, and the 51.3% obtained in the Experimental Plug. Significant variations from the average (e.g., as low as 41.7% and as high as 63.7%) were considered due to variations in the plum size gradations and/or in inherent inaccuracies in the calculation of the segment volumes prior to placing the plums.

3.3.2 Mortar curing temperature data

For all segments, the typical profile was a very rapid temperature rise peaking typically 1 to 4 days after intrusion (e.g., Figure 3), although some segments took several days longer to reach maximum temperature. Initial temperatures within the aggregate ranged from 25 to 39ºC, being consistently higher in the level 58 plugs (33 to 39ºC). Peaks of 60 to 82ºC indicate a range of temperature rises from 30 to 50ºC, average 40ºC. Readings between each pair of thermocouples in each segment were generally in good accordance, with only 3 examples of a significant difference (up to 11ºC) in the amount of temperature rise measured by each pair. Such discrepancies most probably reflect instrument malfunction. For comparison, the average increase as measured by thermocouples 1 and 2, was 39.3º and 40.5º, respectively.

Day 28 temperatures varied from 28 to 54ºC, following slow and steady decline. These represented drops of between 17 and 42ºC (average 28.5ºC) relative to the peaks recorded. The average difference between peak and 28-day temperatures for thermocouple 1 and 2 was 29.3º and 27.6º, respectively.

No clear relationship is apparent between intruded volume, or porosity and the subsequent temperature development.

3.3.3 Mortar strength data

Overall, the mortar cube strength development with time can be summarized as shown in Figure 4. The key acceptance criterion – a minimum of 25MPa at 28 days – was met, on average by every segment of every plug, the overall average being 35.6MPa. The average figures are based on the testing of at least three cube samples.

It may also be observed that the 28-day strengths of the first 7 segments intruded (excluding the experimental) ranged from 25.5 to 40.8MPa (average 32.9MPa), whereas the corresponding data for the subsequent segments ranged from 32.3 to 41.4MPa (average 37.1MPa). This is indicative of progressively improving standards of batching with time and a progressive reduction in the water/cement ratio.

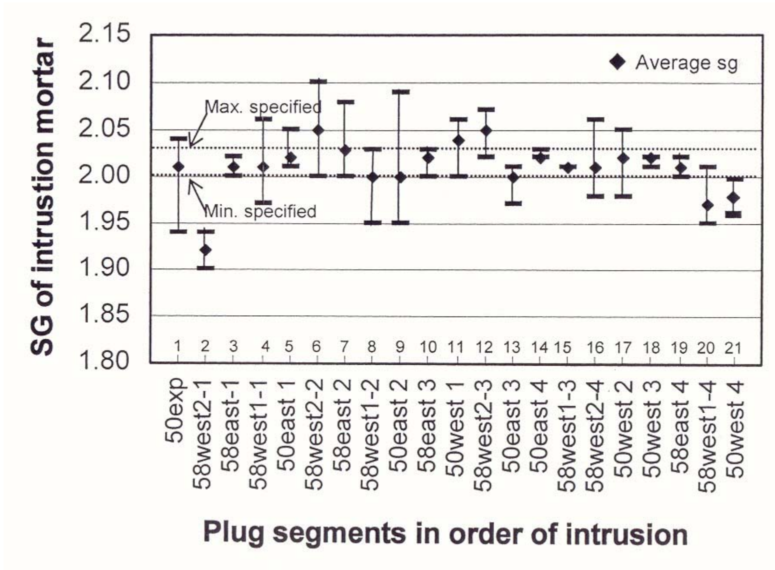

Figure 1. Salter SG Values in Order of Segment Intrusion

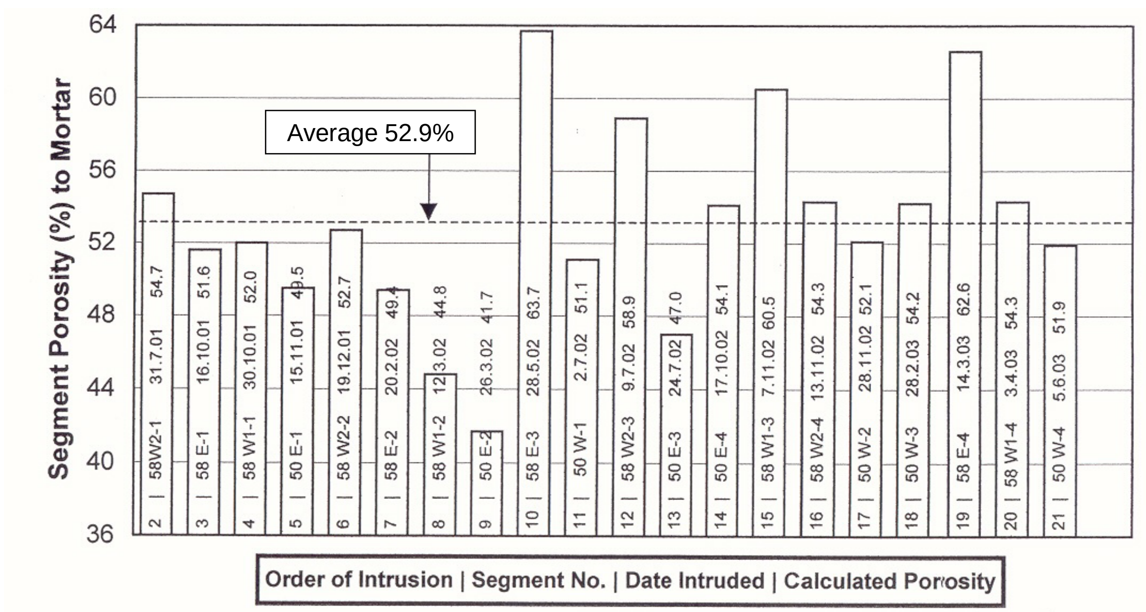

Figure 2. Details of Plug Porosities by Order of Segment Intrusion (excluding Experimental Plug).

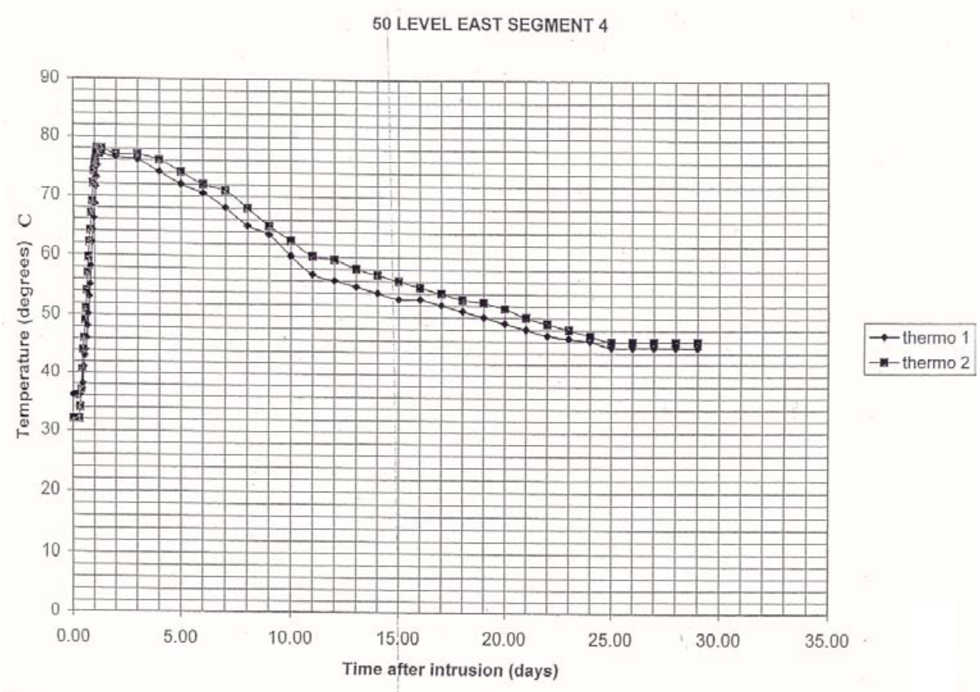

Figure 3. Temperature after intrusion.

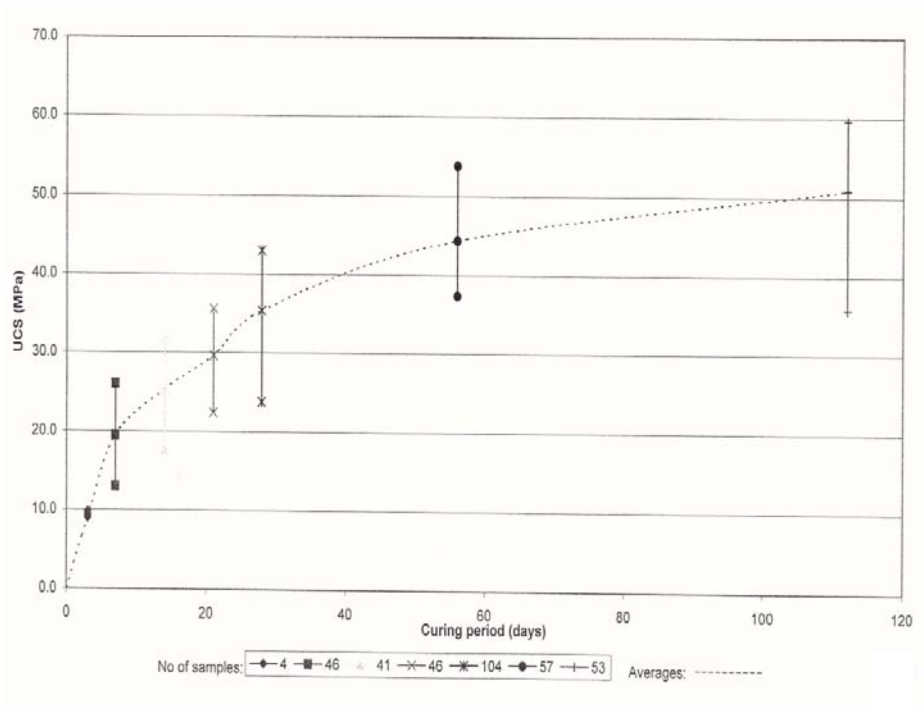

Figure 4. Range and average of mortar cube strengths based on individual segment averages.

3.3.4 High point injection

Each production segment was subjected to high point injection after the mortar had stopped bleeding. For the production plugs 325 to 600kg (average 448kg) of cement at a water/cement ratio of about 0.50, was batched. After making allowance for wastages, volumes of 0.25 to 0.44m^3 (average 0.31m^3) were estimated to have been injected compared to the total volume of mortar injected, the high point void space was remarkably low and consistent (0.38 to 0.73%, average 0.53%). However, considering that the high point void space (assumed to be created by bleed water) would only have developed from batches placed in the last two hours of intrusion, then the ratio should more appropriately be calculated over approximately 15 to 25% of the total volume intruded. In this way, estimated high point proportions should be factored up by 4 to 7 times. The resultant proportion (probably 2 to 5%) therefore much more accurately reflects the true in situ conditions at the time of injection and the range of batch bleed vales established on samples during intrusion (Section 3.3.1).

3.3.5 Tightening

Table 2 summarizes the volumes of tightening grout injected, compared to the measured segment volumes. The percentages in the 50 level segments were uniformly low (1.40 to 3.16%), average 1.75% (West) and 2.02% (East). However, the three largest ratios were found in 58 West 2 which averaged 4.42% whereas the response of 58 West 1 and 58 East were close to that of 50 level (average 1.92% and 2.61%, respectively). This distribution of takes strongly suggests a geostructural control and is consistent with the data recorded in the project database Tables (ii) and (ii). It would seem that 58 West 2 was relatively the most permeable and fissured of the sites selected for plug construction.

Table 2. Summary of Grout Tightening Volumes as a Percentage of Segment Volumes.

Segment	Tightening Grout Volume (m^3)	Measured Volume of Segment (m^3)	Ratio (%)	Plug Average%
50W1	2.150	97.79	2.20	1.75
50W2	1.295	104.02	1.25	
50W3	1.817	99.56	1.83	
50W4	1.619	93.46	1.73	
50E1	3.225	102.19	3.16	2.02
50E2	1.649	117.70	1.40	
50E3	1.659	114.32	1.45	
50E4	1.686	81.53	2.07	
58W2-1*	7.486	118.94	6.29	4.42
58W2-2	4.148	131.17	3.16	
58W2-3	4.492	95.27	5.19	
58W2-4	3.481	114.16	3.05	
58W1-1	2.738	123.98	2.21	1.92
58W1-2	2.994	165.25	1.81	
58W1-3	1.867	123.53	1.51	
58W1-4	2.415	112.09	2.16	
58E1	3.899	133.64	2.92	2.61
58E2	3.251	112.01	2.90	
58E3	3.548	122.38	2.90	
58E4	1.804	106.11	1.70	

* This plug had the lowest UCS values for the mortar

4. CONCLUSION

The successful construction of the 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 the strictures of a strict QA/QC program. It need not be stated that the work was undertaken in arduous and often unpleasant ambient conditions. The technical, logistical and environmental challenges of such 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 essential and totally intertwined.

5. ACKNOWLEDGEMENTS

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