Improved Ground Control Using Hydro Scaling and In-Cycle Shotcrete

P A Jenkins [1], J Mitchell [2] and B Upton [3]

ABSTRACT

The use of hydro scaling and in-cycle shotcrete to replace conventional jumbo scaling mesh and bolting as the primary method of ground control for run of mine development has been investigated through extensive trials at the Waroonga mine, Agnew Gold Mining Company. These trials have progressed from investigating the productivity aspects of the method through to a three month mine-wide trial, which may yet lead to the adoption of this potentially best practice ground control technique at Agnew. Overseas trials and research have shown that hydro scaling results in a significant improvement in the shotcrete-rock bond strength. Good adhesive bond strength ensures that the shear strength of the shotcrete layer rather than it's flexural or tensile strength is fully mobilised as rock mass reinforcement. This maximises shotcrete ground reinforcement capability and it is suggested that a bolt-less fibrecrete support design is feasible using the hydro scaling technique.

INTRODUCTION

The use of a high pressure water jet for scaling has been the subject of trials in both mining and civil tunnelling environments in Sweden. Experimental research has also been undertaken in North America at the Colorado School of Mines (CSM) to establish the optimum water jet pressures for hydro scaling. Using hydro scaling prior to the application of shotcrete improves adhesion of shotcrete to the rock surface. Three to fourfold increases in bond strength were achieved at the Kiruna mine and CSM, compared to conventional surface preparation methods.

At Gold Fields Australia's Agnew Gold Mining Company, hydro scaling has been integrated into the development cycle for the first time on a mine-wide basis in trials at the Waroonga mine. A modified Normet Spraymec shotcreter was used to hydro scale the freshly blasted cut and then apply fibrecrete, thus releasing the drilling jumbo from the mechanical scaling and mesh installation tasks that it would normally perform. These trials have demonstrated that improved ground control can be achieved using the Hydro Scaling and In-Cycle Shotcrete (HS-ICS) technique.

The Waroonga trials and the emergence of hydro scaling are documented in recent papers by Jenkins, Mitchell and Upton (2004) and Clements, Jenkins and Malmgren (2004). Although these papers cover the Kiruna trials and CSM research in some detail, this work is summarised again briefly here as it provided the confidence and justification for the use of hydro scaling in the in-cycle shotcrete trials at Agnew. However, some recent work at the CSM that compares hydro scaling and manual scaling is described in more detail as this substantially quantifies the effectiveness the two methods. Observations from the Waroonga trials, where hydro scaling replaced mechanical scaling, support the findings of this CSM work although are much more limited and qualitative in nature.

This paper focuses on the practical aspects of implementing HS-ICS at Waroonga, with particular emphasis given to the ground support improvements as well as the potential productivity benefits and limitations of the method.

HYDRO SCALING TRIALS AND RESEARCH

The Swedish Standard SS 13 72 43 (1987), gives a standard test method for determining the *in situ* adhesion strength or bond strength between the shotcrete and the rock surface. A 70 mm diameter cored hole to be drilled through the shotcrete layer and at least 20 mm into the wall rock, with a larger and parallel cored slot, drilled into the shotcrete layer to a depth of only 20 mm. Figure 1 illustrates the steps in this testing method, whereby a friction grip ring is placed over the core stub and attached to a tensioning device mounted in the outer cored slot. Adhesion results from using this method at both Kiruna and CSM have shown significantly improved bond strengths for shotcrete sprayed onto hydro scaled surfaces as opposed to manually or mechanically scaled surfaces.

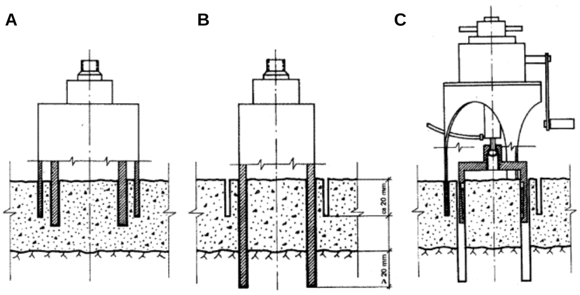

FIG 1 - Shotcrete adhesion testing arrangement, showing (**A**) drilling of the outer slot with the double core bit, (**B**) the inner core stub, and (**C**) the tensioning device (Swedish Standard, SS 13 72 43, 1987).

Kiruna mine trials

Water jet scaling was first trialled in the 1980s in Sweden by LKAB and Boliden. LKAB continued these trials through the 1990s at their Kiruna iron ore mine where shotcrete was used extensively. Poor adhesion had been identified as the main cause of the observed shotcrete failures, though also significant was the fall out of rock and shotcrete, see Figure 2.

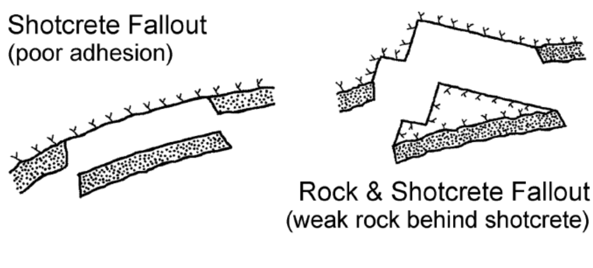

FIG 2 - Shotcrete failure modes at Kiruna (Malmgren and Svenson, 1999).

1. Dempers and Seymour Pty Ltd, PO Box 2323, Warwick WA 6024. Formerly: Agnew Gold Mining Co Pty Ltd, Gold Fields Australia.
2. Jetcrete Australia Pty Ltd, Sydney Office, 30 Milba Road, Carringbah NSW 2229.
3. Byrnecut Mining Pty Ltd, 130 Fauntleroy Avenue, Redcliffe WA 6105.

Trials were conducted to compare shotcrete adhesion in water jet scaled areas with adhesion where normal surface preparation had been used. A prototype rig water jetted at a nozzle pressure of 2900 psi or 20 MPa, whereas normal surface preparation at Kiruna consisted of scaling with a hydraulic pick hammer and washing down the rock surface with water at low pressure, 100 psi or 0.7 MPa.

In the Kiruna trials, adhesion testing of two-day-old shotcrete demonstrated a threefold increase of average bond strength from 0.2 MPa for areas with 'normal' surface preparation to 0.6 MPa for the water-jet scaled areas. It was concluded by Malmgren and Svenson (1999) that the blast fractured immediate wall rock was more effectively cleaned by the water-jetting and also, importantly, the adhesion tests on these areas showed that less failure occurred in rock behind the interface. This inferred that the water-jetting caused less damage to the wall rock than the pick scaling.

Colorado School of Mines research

At the Colorado School of Mines an experimental study of water-jet scaling was initiated as part of a mining safety research program to investigate alternative methods of scaling. The objective was to reduce the exposure to rock falls of personnel engaged in manual scaling operations. The scaling effectiveness of water jet pressures that ranged from 100 - 6000 psi were tested on both rock walls and concrete panels at the CSM experimental mine site, Kuchta (2001, 2002). It was found that:

- at around 3000 psi (or 20 MPa) there was a notable increase in the size of rocks removed, with fist sized loose and larger rocks starting to be dislodged;
- at 6000 psi (40 MPa) a sandblast effect resulted in the operator being peppered with rock fragments.

Adhesion tests were performed on all the rock and concrete panels after they had been shotcreted. The results from the rock panels were inconclusive due to the failure of the majority of cores at weak partings in the partially weathered gneiss wall rock; which only indicated that the shotcrete bond strength was greater than the tensile strength of the gneiss parting planes. However, for the concrete panels there was a clear increase of adhesion strength from 0.5 MPa for water 'washed' surfaces (at 100 psi) to 2 MPa for surfaces water jetted at 3000 psi; with no significant further strength increase for panels treated with higher water jet pressures.

Hydro scaling versus manual scaling

Further research at the CSM experimental mine was conducted to compare the volume and size gradation of material scaled by water jetting and hand scaling, that was reported in a paper on the importance of surface preparation before shotcrete application by Kuchta, Hustrulid and Lorig (2003). After removing the blasted rock from advancing a 3 m by 3 m tunnel, a tarpaulin was laid on the floor and the material scaled by water jetting and by hand scaling of the backs was collected for analysis. In four of the five experiments water jetting of the backs at 2500 psi pressure for 30 minutes was followed by hand scaling with the scaled material separately collected, weighed and screened in each case. Sounding of the backs after each pass of water jetting indicated there was no loose or drummy material, although subsequent hand scaling removed up to half as much rock again as had been hydro scaled.

Figure 3 shows the results of the five experiments. In the last experiment hand scaling was done first, followed by water jetting and then a further pass of hand scaling. After the initial hand scaling, more than half this weight of material was removed by subsequent hydro scaling and then almost the same volume again by further hand scaling.

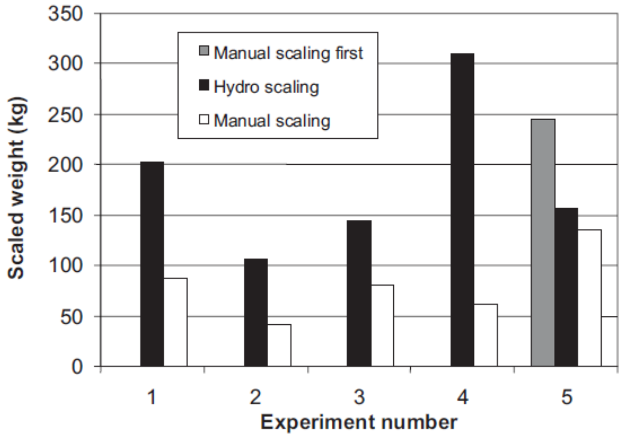

FIG 3 - Material removed by hydro scaling and manual scaling in CSM experiments (after Kuchta, Hustrulid and Lorig, 2003).

In conclusion, it was suggested that many of the semi-loose rocks pried out after hydro scaling would, for immediate subsequent shotcrete application, have been better left in place as their removal would tend to reduce the overall wall rock stability. But that 'if shotcrete is not applied, then clearly these rocks should be removed or supported'. The weight of material removed by secondary hydro scaling in the fifth experiment was considered surprising and the similar weight removed again in the hand scaled third pass illustrative of 'the dilemmas with trying to quantify the effectiveness of a scaling operation…that the longer one scales, the more material is removed'.

The contrasting effectiveness of the two scaling methods is also well illustrated by the screening analysis of the total volume of scaled material for each case, see Figure 4.

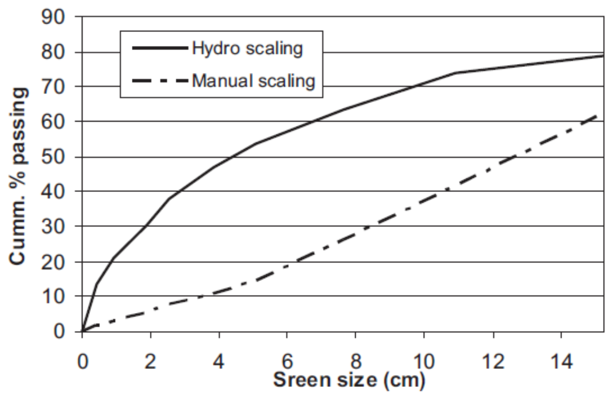

FIG 4 - Size gradation of hydro scaled and manually scaled material in CSM experiments (after Kuchta, Hustrulid and Lorig, 2003).

The water jet scaled material contains a significantly higher proportion of fines than that removed by hand scaling. This is because it has effectively cleaned all the smaller loose rock particles, dust, grease, etc from over the entire surface area scaled; rather than, in the case if hand scaling, removing rock only at the individual impact points.

WAROONGA TRIALS – BACKGROUND

Prior to the HS-ICS trials at Waroonga the use of ICS alone had previously been considered to improve development rates by replacing mesh with fibrecrete, thereby releasing the drill jumbo from the task of installing mesh and increasing its face boring availability. However, an ICS trial was only implemented when the potential for this to compete with mesh and bolts on an economic basis became more realistic. That is, when Byrnecut Mining, the underground contractor, in conjunction with Jetcrete Australia, proposed the combined use of hydro scaling; thus releasing the drill jumbo from scaling as well as mesh installation. An additional motivation was that mechanical scaling or rattling incurs maintenance costs and downtime additional to that incurred for the design purpose of the rig.

Waroonga operations

The Waroonga site is located 370 km north of Kalgoorlie and 30 km west of Leinster, where the mine's predominantly fly-in/fly-out workforce is based. There has been sporadic mining and exploration activity at Waroonga for more than 100 years with several phases of underground exploitation prior to the mining of the Emu pit by WMC from 1986 to 1990.

WMC commenced the current phase of operation in 2001 with the Waroonga cutback of the existing Emu pit. This cutback was completed by Gold Fields in early 2003, following acquisition of the Agnew and St Ives Gold Operations in December 2001. Underground mining at Waroonga resumed with portal establishment in early 2002 and decline development to access the Kim Lode, under the northern end of the pit.

Underground ore was first delivered from Kim Lode in late 2002 with development towards the Main Lode ore bodies, below the southern end of the pit and the old underground workings, commencing early the following year. There is potential to extend the current three-year reserve at Waroonga to a ten-year plus mine life, with ongoing exploration drilling.

Development support

Ground conditions and support profiles

All the main access development at Waroonga is located in the hanging wall rock mass that consists of well bedded, metamorphosed sandstones and siltstones, dipping at 65° to the West. This rock mass is competent but can be fairly blocky and slabby, particularly when development runs parallel to the strikes. However, there is nothing unusual about these ground conditions or the stress environment that demands the use of shotcrete or any other exceptional support design.

As such, the standard support practice at the Agnew, as at many Australian mines, is to install mesh with friction bolts up to the face in development headings. This work is done by the development jumbo as part of the development cycle, after scaling or 'rattling' the freshly exposed walls. Figure 5 illustrates the standard support profile for a 6 m × 6 m arch decline at Agnew with mesh to 3.5 m from the floor and spot bolts.

The orientation of the Main Lode decline, parallel to strike in the hanging wall sandstones, is adverse and the time dependant loosening of bedding slabs was experienced on both sidewalls, either by sliding or toppling, in the early stages of its development. Hence, before the initial HS-ICS trial took place here, the support design in Figure 5 was upgraded with an additional sheet of mesh on each sidewall to contain the slabby conditions encountered.

Limitations

The rattling process, i.e. mechanical scaling with the drill jumbo, is effective but in most ground conditions can lead to overbreak and unnecessary impact damage to the surrounding wall rock, as well as the jumbo. Scaling is not a design function of the jumbo and so increases wear and tear and maintenance costs.

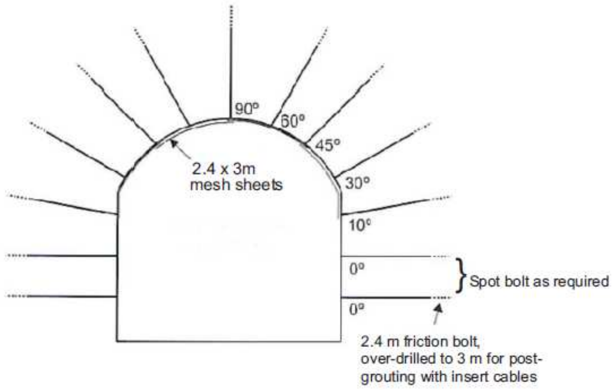

FIG 5 - Standard ground support profile for a 6 m × 6 m arch, Agnew Gold mine.

Due to the ease of split set type friction bolt installation with a jumbo there is also a tendency for this type of bolt to be relied upon for long-term ground support, a purpose for which it is not inherently suited. To increase the life-span and capability of jumbo installed mesh and bolts, the grouting of friction bolts is undertaken by some mines and the current practice at Waroonga is to over-drill the split sets for later grouting with cable inserts. This is intended to stiffen the split set support, increasing the long-term support capability and providing some protection against corrosion of the galvanised friction bolts. This is not an entirely satisfactory process as it is difficult to ensure effective quality control of the post-grouting and insert cabling. Also as a second pass in the ground support process, it tends to be done on a campaign basis and is rarely completed within the desired timeframe.

Depending on the environment and required life span, corrosion of ground support elements and/or deterioration of wallrock conditions is likely to necessitate some degree of rehabilitation of the ground support. Figure 6 illustrates the result of time dependant loosening or relaxation in the Main Lode Decline sidewall, before upgrade of the support design noted above. Mesh and bolts may contain rather than prevent this type of deterioration, which is likely to require rehab at some future time. Further illustrating this limitation of mesh and bolts, it is significant to note that the cost of decline rehabilitation at Agnew's Redeemer mine, which closed in early 2001, prohibited the extension of mining to exploit the deeper identified resource there.

Objective of HS-ICS trials

Initial single heading trial

Before attempting to prove the productivity benefits of hydro scaling and in-cycle fibrecrete by incorporating them into the development cycle on a mine-wide basis, a single heading trial was first undertaken with the objective of demonstrating:

- the suitability of hydro scaling, from both a safety and ground control perspective; and
- successful integration of this scaling technique and the required equipment into the development cycle.

This initial trial was conducted over an 11-day period in the Main Lode Decline in March 2003. Time and motion studies were conducted to evaluate the productivity and financial impacts of the method, with adhesion tests undertaken to ensure that adequate shotcrete bond strengths were achieved.

A detailed financial analysis of the initial trial results was necessary to show that the productivity benefits of the method

FIG 6 - Time dependant loosening of wallrock in the Main Lode Decline.

could be harnessed without an adverse cost implication. This analysis indicated that the establishment of an on-site batch plant and use of a site-sourced aggregate would be necessary to minimise the cost of the fibrecrete product. Before the mine-wide trial a small scale trial to test the suitability of aggregate derived locally from the sandstone waste rock was conducted, as well as a limited trial to assess the applicability of hydro scaling without subsequent shotcrete. The aggregate trial was successful, but not that of hydro scaling only, as will be discussed later.

Extended mine-wide trial

When the extended mine-wide trial was conducted, over a three month period from mid-November 2003, the expectation was that it would provide:

- an improved long-term ground support, with less check scaling, rework and rehabilitation required in the long term;
- increased jumbo availability/productivity;
- increased development advance; and
- reduced jumbo operating costs.

These objectives had been shown to be realistic in the initial trial and so it was important to demonstrate that HS-ICS could be successfully integrated mine-wide and that it was feasible from a cost perspective. Again, this trial was closely monitored with time and motion studies, that also attempted quantify some of the less tangible benefits of the method.

HS-ICS TRIAL IMPLEMENTATION

Development cycle

Table 1 outlines the steps in the normal development cycle for meshing and bolting and the changes in the cycle for integrating HS-ICS.

TABLE 1
Change of development cycle for HS-ICS trials.

Normal cycle	Trial cycle
Fume clearance period after firing of heading	
Re-entry and watering down for dust suppression	
Bog the heading	Bog heading to grade line
Jumbo set up and delivery of mesh and bolts	Hydro scale with modified Spraymec
Rattle backs and walls	Agitator truck to decline and spray fibrecrete
Bolt and mesh	Jumbo re-enters to set up, delivery and installation of bolts
Rattle the face	Rattle down the face and bore top down
Scratch-back	Re-bog to the floor and scratch-back
Mark up, bore face bottom-up	Finish boring
Hand scale, charge and fire the heading	Charge and fire the heading

Hydro scaling equipment

For the Waroonga trials, Normet fitted a Dynaset HPW 470/50 water pump and additional nozzle to a Spraymec 6050 shotcreter, to modify this for hydro scaling prior to fibrecrete placement. This pump is capable of delivering 50 L/min at a pressure of 6000 psi or 41 MPa. However, the 62 kW rating of the engine on this Spraymec was insufficient to operate the boom and run the pump at full power. Hence the pump and nozzle were pre-set to deliver at a maximum pressure of 3000 psi or 20 MPa, which is at around the optimum nozzle pressure established in the previous hydro scaling studies. Figure 7 shows hydro scaling in progress with the operator controlling the boom and nozzle from the control unit, 'worn' at waist height and mounted from a shoulder harness, as for shotcrete spraying.

FIG 7 - Hydro scaling in progress.

All Spraymec units supplied by Normet are now fitted with the HPW 470/50 pump and future units imported to Australia will have an engine specification of 88 kW, to allow the pump to be operated at full capacity, Clements, Jenkins and Malmgren (2004). The overall cost of modifying a Spraymec rig for hydro scaling is approximately $A25 000.

Fibrecrete product

The wet mix fibrecrete product for the initial trial was supplied from a batch plant in Leinster, 30 km away, with delivery by agitator truck direct to the Spraymec hopper at the work location. This was a standard 32 MPa shotcrete mix design with synthetic fibres, see Table 2.

TABLE 2
Fibrecrete mix designs.

Shotcrete mix component	Initial trial mix	Mine-wide trial mix
GP cement (kg/m^3)	420 kg	440 kg
7 mm aggregate (kg/m^3)	550 kg	460 kg
Coarse sand (kg/m^3)	360 kg	
Fine sand (kg/m^3)	770 kg	820 kg
Crusher dust, -3 mm (kg/m^3)		500 L
Synthetic fibres (kg/m^3)	7 kg	7 kg
Water (L/m^3)	175 L	175 L
Accelerator, Sigunit L50AF (L/m^3)	16 L - 25 L	
Accelerator, SA160 (L/m^3)		17 L
Rheobuild 1000 superplasticiser (L/m^3)	3 L	3 L
Pozzolith 370C (L/m^3)	18 L	18 L
Delvocrete stabiliser (L/m^3)	3 L	3 L

In addition to the standard shotcrete quality assurance and control measures undertaken through the batching process and product application, adhesion tests were attempted during the initial trial. As discussed in the Fibrecrete adhesion section, alternative equipment to that specified by the Swedish Standard was sourced for these tests, which were only successfully completed some five months after the product had been sprayed. These adhesion tests were not repeated during the mine-wide trial, for which the minimum fibrecrete product specification was:

- Compressive strength 32 MPa
- Flexural strength 5 MPa
- Tensile strength 20 MPa
- Adhesion/bond strength 1.5 MPa
- Product life expectancy 10 years

As previously noted, it was necessary to establish a batch plant on site, using aggregate sourced from run-of-mine waste rock crushed at the Agnew mill, to minimise the cost of the product for the mine-wide trial. An initial trial of the locally derived aggregate, using a similar mix to the standard design in Table 2, only just satisfied the strength specification above leaving little room for variation. A revised mix design, also given in Table 2, was used in the mine-wide trial and found to be successful.

Re-entry and support design

On completion of fibrecrete spraying, a nominal strength gain of 1 MPa was set as the re-entry requirement before bolting commenced. A hand held Meyco needle-type soil penetrometers was used to help confirm the 1 MPa strength gain, that generally coincided with the stage at which visible signs of fibrecrete curing, or 'white tips', could be seen. At this stage, generally 40 - 60 minutes, it was considered safe for bolting to commence and personnel re-entry was only allowed after the friction bolts had been installed. As such, the friction bolts were employed as temporary support.

For the initial trial a nominal fibrecrete thickness of 75 mm was specified for the backs and walls down to the grade line. The bolting pattern remained the same as for the normal development support profile. This enabled mesh to be installed if there were any unacceptable delays in fibrecrete delivery or if there were product quality issues. Figure 8 shows the revised decline support profile for the mine-wide trial, in which the fibrecrete on the walls is brought down to 1.0 m from the floor and reduced to a 50 mm thickness.

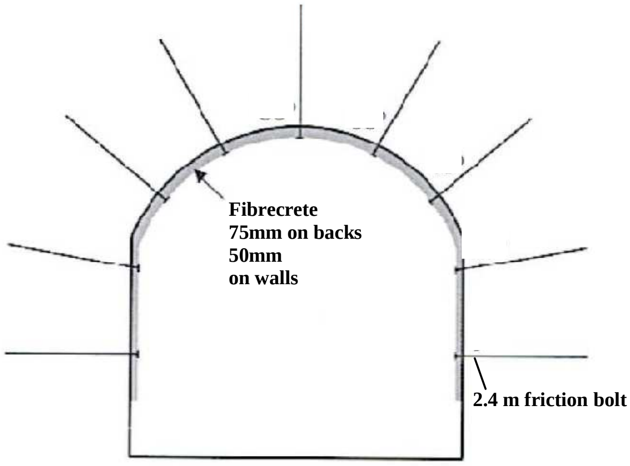

FIG 8 - Decline ground support profile for the mine-wide trial.

The support profiles recommended have been compared to the available design guidelines, as reviewed by Langille (2001); and with the deterministic methods proposed by Barrett and McCreath (1995), who comment that 'shotcrete's full potential as a method of ground support is rarely exploited and frequently it is not properly integrated into the excavation-support cycle'.

The thickness of the shotcrete layer was tested during spraying by probing with a depth gauge attached to the end of the spray nozzle.

Personnel

An important aspect in the success of the trials was gaining acceptance of the HS-ICS method from the work force, as well as their confidence in the procedures and the final product. Both the main HS-ICS trials at Agnew were introduced with a healthy amount of forethought, discussion and consultation with the workforce beforehand. All parties were fully committed to the trials and in this environment they stood every chance of success.

As well as establishing the batch plant, an additional three two-man shotcrete crews and a supervisor were integrated into the workforce. When not required for shotcrete related activities they were used as additional labour in the service crews.

WAROONGA TRIAL RESULTS

Hydro scaling

Loose material removed by hydro scaling was generally of scat size and smaller, with a maximum dimension of up to 300 mm. However, the mobility of the robotic arm of the Spraymec and its skilled operation is important as the water jet needs to be directed into the cracks and joints to create the pore pressure required to propagate cracks and dislodge blocks. It was observed that some larger slabs, up to 1 m long and weighing up to 800 kg were also dislodged.

It is inferred that the water jetting tended to remove only the looser, blast fractured material from the sidewalls. In comparison, mechanical jumbo scaling dislodged blocks of up to 1.5 m x 1.5 m x 0.5 m or approximately 4.5 tonnes. There were no large or overhanging slabs that could not be removed by hydro scaling and it was not necessary for the jumbo to further scale the backs and walls of the decline in the trial section. These observations are in agreement with the experimental work at the CSM detailed in the hydro scaling versus manual scaling section. Prior to the mine-wide trial the use of hydro scaling to replace jumbo scaling with mesh and bolts installation attempted. However, it was fairly conclusively shown that there was no benefit from doing this, as significant additional scaling was necessary when the jumbo re-entered the heading. This also agrees with the CSM findings of Kuchta, Hustrulid and Lorig (2003). It is concluded that hydro scaling under Waroonga-type hard rock conditions and using water pressures of around 3000 psi are only appropriate for use where an active surface support, i.e. shotcrete or a thin skin liner, is applied after scaling.

Profile control

One of the more dramatic outcomes of the initial trial was the improvement in the arch profile of the Main Lode decline and reduction in overbreak, as Figures 9 and 10 demonstrate. The average overbreak before the trial section was 26 per cent; this was reduced to six per cent during the trial and subsequently increased again to 13 per cent.

FIG 9 - View looking down the Main Lode Decline from before the start of the trial section.

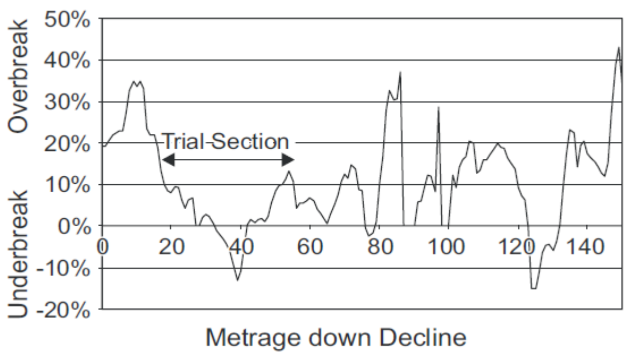

FIG 10 - Design profile compliance in the Main Lode Decline before, during and after the initial trial.

This trend was repeated, although less dramatically during the mine-wide trial. Overbreak in the waste ends mined during the trial averaged three per cent with variation between one to four per cent only for each set of headings as measured per monthly broken tonnage. In comparison, for the six months prior to the trial the average overbreak was six per cent and varied over a much larger range, from -8 per cent to 13 per cent.

Cycle times

Time and motion studies conducted during the initial trial analysed the HS-ICS development cycle as well as conventional mesh and bolt development end for comparison purposes. Apart from ground support activities, all other activities are assumed to take the same amount of time to perform. The summarised results of this study are:

- Conventional bolts and mesh (six sheets)

Time to jumbo scale	33 minutes
Time to bolt and mesh	158 minutes
Total support time	191 minutes

- Hydro scale and in-cycle fibrecrete

Time to hydro scale	21 minutes
Time to fibrecrete	37 minutes
Time to bolt (av 23 bolts)	59 minutes
Total support time	117 minutes

The average cycle time per cut for ground support was reduced by 38 per cent for HS-ICS, a 74-minute saving over the average time for the comparable six sheet mesh profile installation. It was estimated from this that jumbo availability for face boring could be increased by five hours per day, equating to a potential 25 per cent increase in jumbo productivity on a mine-wide basis. Teething problems with the new aggregate during the first few weeks of the mine-wide trial resulted in average the HDS-ICS times of 80 - 90 minutes. This was due to oversize material being picked up when transporting crushed aggregate from the mill to the batch plant, causing frequent interruptions to spraying and nozzle blockages. However, towards the end of the trial period the average cycle time for ICS had been reduced to 52 minutes. The presence of ammonia gas in the headings after ICS spraying and on re-entry also caused some concerns and minor delays. The ammonia was produced by reaction of the shotcrete with Anfo and although not toxic this did cause discomfort to some personnel; and those affected were advised to withdraw. Improved ventilation and care in preventing Anfo from being left in the heading after charge-up largely eliminated this issue.

Fibrecrete adhesion

The shotcrete adhesion tests were extremely difficult to perform. An air driven, single bit drill mounted on the basket of an elevated work platform used for the *in situ* coring. This was not the most stable arrangement and it took many attempts on several occasions to get the 11 cores that were successfully tested with the Swiss-made Dyna Pull-off Tester Z16. Even then, none of the cores penetrated to the required 20 mm depth into rock as required by the Swedish Standard. In most cases the core stub was destroyed before full penetration of the shotcrete layer and the greatest depth of penetration into rock achieved was 10 mm. By the time these tests were completed, the fibrecrete was 150 days old.

As such, the limited results given in Table 3 cannot be considered a valid direct comparison with the previous studies at Kiruna and the CSM, which were produced under very different conditions. Nevertheless, summary results from Kiruna and CSM are included with the Waroonga tests graphically presented in Figure 11. The achievement of some significantly high bond strengths for mature-age fibrecrete at Waroonga is indicated, although it is possible that eccentric loading has contributed to the values reported, as well as the destruction of many of the cores during drilling. As is the case with material property testing of rock from drill core, it is likely that only the strongest intact specimens are recovered and the results obtained skewed towards the higher values.

Difficulty in achieving successful shotcrete coring for the underground adhesion tests at Kiruna has also been commented upon by Malmgren (2004). There the double bit core drill was actually bolted onto the rock wall to provide the necessary stability.

Installed fibrecrete support

During the initial trial the actual thickness of fibrecrete sprayed was variable, generally greater than the 75 mm specified and up to 130 mm thick. This was due to a minimum product delivery constraint of 5 m^3 for shotcrete sourced from Leinster, which resulted in the full delivered amount being sprayed in each cut.

After the initial trial it was proposed that the maximum benefit from the use of HS-ICS would be gained if the full potential of shotcrete as ground support were realised. Despite the difficulty in obtaining adhesion test results, these demonstrate bond strengths that exceed the generally accepted industry standard of 1 - 2 MPa. The achievement of bond strengths exceeding 1.5 MPa is a key support design assumption and ensures that the shear strength of the shotcrete layer rather than its flexural or tensile strength will be fully mobilised as rock mass reinforcement, Barrett and McCreath (1995).

Given these results it was considered possible to develop the HS-ICS method to the stage where a boltless fibrecrete support design was feasible. To achieve this would require knowledge of and appropriate quality control to establish:

- the shear- and early-strength gain of the fibrecrete, to determine safe re-entry times; and
- adequate specification and achievement of design cover thicknesses of fibrecrete.

These issues are discussed in more detail by Jenkins, Mitchell and Upton (2004) and it was not considered prudent to attempt a boltless fibrecrete regime for the extended trial. Nevertheless, the support strategy recommended utilised the fibrecrete layer as the principal component of the permanent support system, with friction bolts principally used in a temporary support capacity. The spacing of the bolts, not now constrained by mesh size, was increased to a 1.5 m staggered pattern.

In short-term excavations the fibrecrete on the walls generally extended down to 3.0 m above the floor. However, this is not considered advisable for longer term excavations as it is likely that the unsupported or spot-bolted sidewall below the mesh will be undermined due to time dependant effects and possible impact damage, thereby destroying the integrity of the fibrecrete support regime.

In practice, it was found that fibrecrete sprayed on the lower sidewalls right up to the face was usually damaged during subsequent mucking operations. Therefore, shotcrete on the lower sidewalls was carried two to three cuts behind the advancing face.

TABLE 3

Waroonga adhesion test results.

Scaling method	Shotcrete thickness (mm)	Location of failure				Tensile strength (MPa)
		Bond	Rock	Pull cap	Shotcrete	
Hydro	10		X		X	5.8
Hydro	70	X				3.98
Hydro	75	X				3.18
Hydro	30	X				2.7
Hydro	50				X	9.6
Hydro	75			X		11.3
Hydro	70	X				2.83
Average hydro scaled strength						5.63
Jumbo	80	X				4.27
Jumbo	35	X				4.77
Jumbo	45	X				4.37
Jumbo	120			X		6.3
Average jumbo scaled strength						4.93

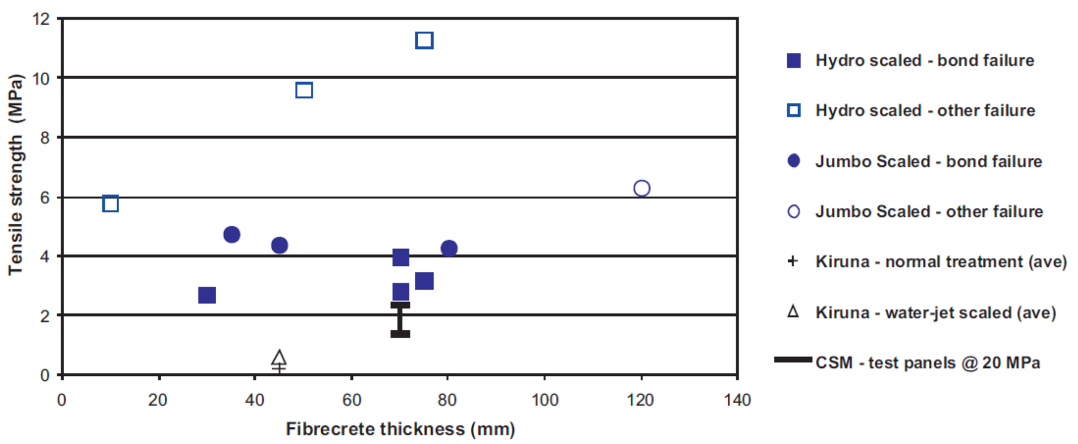

FIG 11 - Waroonga adhesion test results, compared with average Kiruna and CSM results.

Financial evaluation

Initial trial

During the initial trial the delivered cost of fibrecrete sourced from Leinster was $583/m3 and inclusive of equipment and labour, the cost was $919/m3. The crushing of run of mine waste from Waroonga at the Agnew mill and its evaluation as a part of a revised mix design indicated that the material cost of fibrecrete could be reduced from $583/m3 to $313/m3. This is obviously still far higher than the cost of meshing and bolting. However, with the vision of fully integrating the method into all development activities on the mine, there are many other factors to be considered in evaluating the costs and benefits.

Byrnecut's initial estimate for this over a three year underground contract life, for the development component only, indicated a cost increase of six to eight per cent depending on the size of the excavation. However, for the overall contract this equated to a 4.8 per cent cost increase.

Further detailed review of all aspects of the supply, application and integration of HS-ICS on a mine-wide basis was undertaken by the Contract Innovation Committee, which included representatives from Agnew, Byrnecut and Jetcrete. This indicated that compared to the base case with no hydro scaling and ICS, a near-cost neutral or better financial result appeared feasible; and it was resolved to undertake a further extended mine-wide trial.

Mine-wide trial

The three month extended trial could not be considered a success as the main purpose – that of realising the potential productivity benefits offered by hydro scaling and ICS – was not achieved. In fact, the Powerclass Jumbo used for waste development was under-utilised as it had less work to do. It was disappointing that four headings were available on only a few days towards the end of the trial, with mostly only two available. The optimum availability to give the trial a fair chance would have been four or five headings being consistently available. Largely as a result of this, the average long-term additional cost of the trial (compared to the rate for conventional mesh and bolts) was around $400/m.

CONCLUSIONS

Despite some initial teething problems with the on-site batching of fibrecrete, the technical side of the mine-wide trial was a success. However, the potential productivity benefits were never realised due to severe constraints on heading availability. There were several contributing factors causing the lack of available headings for ICS, most prominent was the lack of Main Lode heading availability that was still only a single heading for the duration of the trial. Since the initial trial progress in the Main Lode Decline had been slowed down by the intersection and ingress of significant quantities of water; before the planned pumping capacity infrastructure had been established. During the course of the extended trial there were rarely four headings available for ICS during any 24-hour period; whereas four or five headings consistently being available would have utilised the equipment fleet and personnel to maximum effect.

The hydro scaling was considered to be very effective for the ground conditions encountered and combined with in-cycle fibrecrete, successfully integrated into the development cycle. All operators readily accepted the changes brought about by the trial and HS-ICS was shown to be capable of achieving all of the perceived benefits identified, namely:

- Increased jumbo availability and reduced damage to both equipment and wall rock;
- improved tunnel profile with overbreak minimised;
- improved long-term ground support, quality and duration;
- an improved underground environment with reduced ventilation airflow resistance;
- reduced check scaling requirements;
- reduced personnel exposure;
- reduced future ground support re-work and rehabilitation; and
- development of intersections was faster and tidier than with conventional techniques.

The Waroonga trials have successfully demonstrated the benefits of this technique, which is a potentially best practice development for the mining industry. Lack of heading availability prevented a successful economic outcome to the extended mine-wide trial. However, it is still possible that the method will be adopted on a mine-wide basis at Waroonga when there is sufficient heading availability.

Hydro scaling is considered to be highly advantageous for any long-term shotcrete or fibrecrete application under most ground conditions. The development of a boltless fibrecrete ground support regime is thought to be possible with good surface preparation (i.e. hydro scaling); although the shear strength gain and achievement of adequate fibrecrete cover thickness are quality controls required for this, in particular to minimise re entry times.

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