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Investigation of the geomechanical criteria for safe and efficient crown pillar extraction beneath stabilised rockfill at the Crusader Mine

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The established crown pillar extraction method at Gold Fields Australia Ltd.'s Crusader Mine, leads to the significant dilution and poor recovery of ore due to caving of the overlying loose rockfill. The application of selectively injecting specifically developed 'FB200' ettringite (calcium sulphoaluminate hydrate) type cement grout into loose rockfill to form a stabilised rockfill material, enables an artificial crown pillar to stabilise the surrounding rock mass and prevent caving of the overlying loose rockfill during crown pillar extraction. Investigation of the geomechanical criteria for crown pillar extraction beneath stabilised rockfill has enabled the safe and efficient extraction of two crown pillars at the Crusader Mine.

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Introduction

At Gold Fields Australia Ltd.'s (formerly WMC Resources Ltd.) Crusader Mine, significant resources have been sterilised due to the placement of loose rockfill above the crown pillars. Potential exists for the recovery of such crown pillars via the application of selectively injecting low viscosity cement grouts into the overlying loose rockfill to form an artificial stabilised rockfill crown pillar.

Due to the recent global turndown in the resource sector, and increasing social pressures to maximise resource recovery, significant benefits are to be gained by the Australian mining industry via the development of improved guidelines for the extraction of such sterilised mine pillars.

The Crusader Mine

The Crusader Mine is owned and operated by Gold Fields Australia Ltd (formerly WMC Resources Ltd.). The mine is located approximately 700 km north-east of Perth, Australia, and 23 km west of Leinster in the Eastern Goldfields region of Western Australia.

The orebody is associated with a flexure in the contact between an ultramafic and basalt unit which dips to the west at 50-60° and plunges to the north at 20-30°. The contact is highly sheared with a thickness of between 0.2 to 1.5 m. Splay structures come off the hangingwall and extend into the hangingwall ultramafic. These structures have been observed to contribute to local failure of the hangingwall.

Mining Methods

Overhand Cut and Fill and Post Pillar Cut and Fill mining methods have been employed at the Crusader Mine. The orebody is divided into 25 m lifts. A 5 × 5 m drive is driven along the orebody and then backfilled with loose production mullock rockfill. Three flat-back lifts are then extracted and backfilled, each 5 m high, leaving an 8 m crown pillar as displayed in Figure 1. The fourth flat-back drive is not backfilled to provide access to the overlying crown pillar.

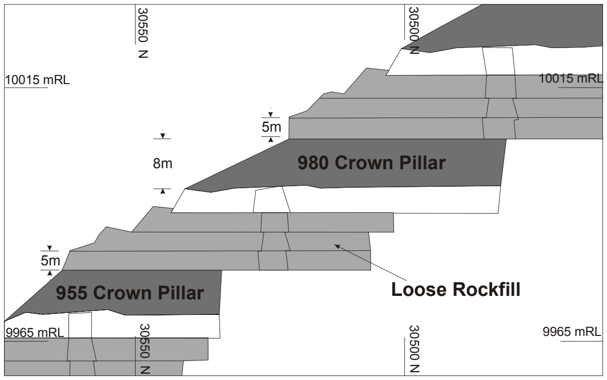

Figure 1 Long section view of typical Crusader Mine cut-and-fill layout (looking east).

Established Crown Pillar Extraction Method

Traditionally, crown pillars at the Crusader Mine have been extracted beneath loose rockfill, allowing the rockfill and significant amounts of the weak hangingwall ultramafics to cave and dilute the blasted ore. Figure 2 displays the open stope created by the extraction of the 1005 Crown Pillar beneath loose rockfill. As observed, all of the above lying rockfill has caved while a significant amount of the ultramafic hangingwall has also caved, significantly diluting the ore extracted from the crown pillar while also eliminating the passive support provided by the loose rockfill. Typical reconciliation of crown pillars extracted beneath loose rockfill, results in only 70% recovery with approximately 200% dilution.

To prevent excessive ore loss, dilution and production delays, the practice of placing cemented rockfill in the bottom 5m lift was adopted to form a cemented crown pillar once the crown pillar is extracted. The process of placing these is explained in detail by Finn and Dorricott (2002). However, a number of stopes had already been mined and waste backfill placed without the cemented rock fill pillars being placed. Extracting these pillars would result in significant dilution and ore loss, unless a safe and efficient engineered backfill solution could be implemented.

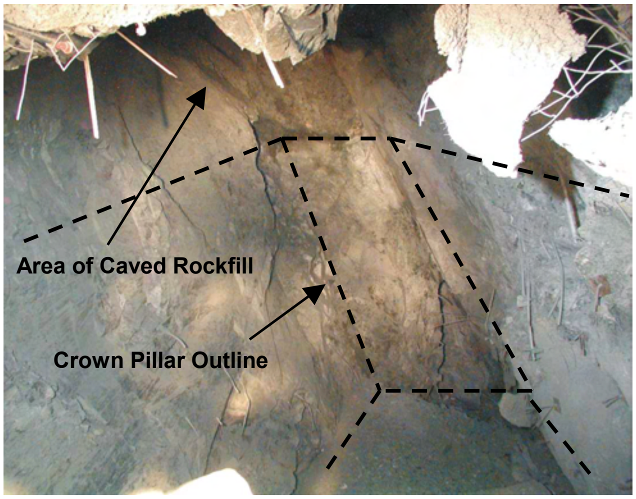

Figure 2. Open stope created after extraction of loose rockfill along with crown pillar ore (looking south).

Stabilised Rockfill

Stabilised rockfill is produced by injecting a binder material into loose rockfill in order to produce an exposable backfill material.

A low viscosity cement grout has been developed by Minova Australia Pty. Ltd. (formerly Fosroc Chemfix Pty. Ltd.), specifically for the stabilisation of extremely fractured rock. ‘FB200’ cement grout is based on a calcium sulphoaluminate cement which forms the mineral ettringite $(CaO . Al_2O_3 . SO_3 . 32H_2O)$ on reaction with water. As a result, the material can be placed at a water / powder ratio of between 2 : 1 and 4 : 1 to produce a dimensionally stable cement grout, unlike ordinary Portland cement which would exhibit excessive shrinkage at the same ratios.

Geomechanical Testing of Stabilised Rockfill

In order to minimise the technical risks associated with the construction of an artificial stabilised rockfill crown pillar, a series of unconfined compressive strength (UCS) and unconsolidated drained triaxial laboratory tests were conducted to investigate the critical parameters influencing the strength and behaviour of a stabilised rockfill matrix with FB200 cement grout. The factors investigated include; sample size and shape, particle size distribution, curing time, water quality, cement : water ratio and the confinement effect. The results of the laboratory testing program are discussed in detail by Sainsbury, Cai and Thompson (2001).

The stress-strain behaviour observed in unconsolidated drained triaxial compression demonstrated that the stabilised rockfill material behaves as a Mohr-Coulomb material. Under a confining pressure of 1 MPa, strengths of 7 MPa were obtained. No post peak drop in axial stress was recorded, as displayed in Figure 3.

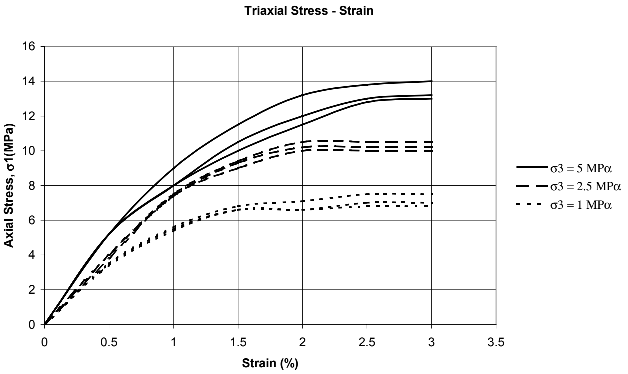

Figure 3 Unconsolidated drained triaxial stress-strain behaviour of stabilised rockfill.

The laboratory measured cohesion and friction angle for the stabilised rockfill are 690 kPa and 44^o respectively for a confining pressure between 0 – 1 MPa.

The optimum UCS obtained in the laboratory using FB 200 cement grout is 4.45 MPa. This is obtained in the laboratory with a well graded particle size distribution between 0.001 and 50mm, a cubic sample size of 150 mm, a water cement ratio of 2:1 and a curing time of 28 days. The average Young's modulus obtained in the laboratory is 0.45 GPa.

Figure 4 illustrates a 300 mm cubic sample tested in uniaxial compression to 12% strain. As observed, the interlocking particles along the perimeter of the sample have been squeezed out towards the area of zero confinement, while interlocking particles in the centre of the sample have begun to grind together and rupture.

Figure 4 Large-scale laboratory unconfined compressive strength test.

Evaluation of the Penetration Capability of FB200 Cement Grout

The primary technical risk associated with the formation of stabilised rockfill is the ability of the binder material to penetrate the rockfill matrix to form a stable fill mass with near zero porosity. Unlike traditional cemented rockfill backfill, whereby the rock particles need only be coated with cement prior to placement, stabilised rockfill requires the complete penetration of all voids within the rockfill matrix to ensure there are no zones of uncemented rockfill within the fill mass which form planes of weakness.

A 3.6 m wide trench was excavated to a depth of 1.8 m, and a length of 11.4 m in laterite cap rock on the surface nearby the Crusader Mine and filled with representative loose rockfill. Four polypropylene injection lines were inserted into the rockfill at various depths to act as injection points. Approximately $6m^3$ of FB200 cement grout, mixed at a water / powder ratio of 2 : 1, was pumped through the injection points and allowed to cure for approximately 8 days. Following excavation of the stabilised rockfill trench, it was evident that the FB200 cement grout had percolated through the rockfill matrix to the trench floor from each of the four injection points. The FB200 cement grout self levelled within the rockfill for the entire length and width of the trench. From inspection of the stabilised rockfill excavated from the bottom of the trench it is clear that the viscosity of the FB200 cement grout permits penetration of the smallest voids of the rockfill matrix.

Numerical Investigation of Stabilised Rockfill Pillar Stability

In order to design safe and efficient artificial stabilised rockfill crown pillars, development of a numerical modelling methodology is essential in understanding the behaviour and failure mechanisms of undermined horizontal exposures of stabilised rockfill crown pillars.

Artificial stabilised rockfill crown pillars are required to be of sufficient strength to minimise dilution of the underlying ore, while preventing the inrush of overlying uncemented backfill and water in previously mined stopes.

Numerical investigation of the regional effects of crown pillar extraction conducted with the three-dimensional boundary element code Map3D is not discussed herein.

Numerical Modelling of Backfill with PFC2D

PFC2D models the movement and interaction of circular particles by the distinct element method (DEM). More complex behavior can be modeled by allowing the particles to be bonded together at their contact points such that, when the inter-particle forces acting at any bond exceed the bond strength, that bond is broken. Parallel bonds are applied to the PFC particles to simulate the injection of FB200 cement grout within the void spaces of a loose rockfill matrix. A series of biaxial tests were simulated in PFC2D to calibrate the PFC microproperties to the macroscopic behaviour of the stabilised rockfill observed in laboratory triaxial testing. The details of the biaxial simulations and the representative PFC microproperties are discussed by Sainsbury, Cai and Hebblewhite (2002).

The PFC2D modelling approach allows the initial stress distribution and arching within the loose rockfill to be explicitly modelled, while the evolution of failure and progressive caving of undermined stabilised rockfill can be representatively modelled.

The economic viability of crown pillar recovery beneath stabilised rockfill is controlled by the amount of cement grout required to form a stable exposure of stabilised rockfill. A series of analyses was conducted to investigate the behaviour and failure mechanisms of artificial stabilised rockfill crown pillars of 1, 3 and 5 m height.

The behaviour of a 5 m high artificial stabilised rockfill crown pillar is illustrated in Figure 5. As observed, progressive failure and caving is predicted along tensile failure planes in the de-stressed lower part of the stabilised rockfill, however, due to the inclined nature of the fill mass, compressive forces are able to arch over the upper part of the stabilised rockfill, impeding further yielding.

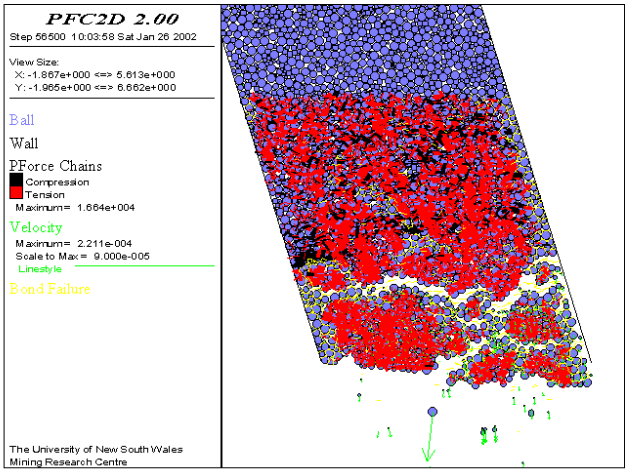

Figure 5 Predicted behaviour of 5m high artificial stabilised rockfill crown pillar.

Numerical modeling was also conducted with the explicit finite difference code FLAC, in order to confirm the mechanisms observed with the PFC2D modeling approach.

Based upon these observations, the artificial stabilised rockfill crown pillars at the Crusader Mine were designed to be 5 m high for typical 5m wide, 70° dip stopes.

Implementation of Artificial Stabilised Rockfill Crown Pillars

The 980 and 955 Crown Pillars at the Crusader Mine were identified as high-grade mining reserves that would realise significant increases in recovery, and reductions in dilution, if an artificial stabilised rockfill crown pillar was created via the injection of cement grout above the crown pillars. As detailed below, several technical and practical challenges needed to resolved in order for implementation of the artificial stabilised rockfill crown pillars to be conducted safely and efficiently.

Drilling of Injection Holes

A trial was conducted using a percussion drill rig to establish downholes into the loose rockfill. The rig was capable of drilling through the rockfill. Whilst the drill rods were able to be withdrawn without too much difficulty, the hole collapsed immediately. In light of this, the method of placing a polypropylene injection pipe directly into the hole was eliminated.

The concept of using a diamond drill to drill through loose rockfill underground is relatively untested. The primary difficulty with drilling through loose rockfill with existing diamond drill equipment is that the rig needs to be set up on top of the backfill, and therefore there is no means of anchoring the drill rig. MacMahon Underground Pty Ltd. were contacted and asked to devise a modified system to address this problem. The solution was to mount the Longyear 400 Series Drill Frame on a Cubex Megamatic 5200 Longhole Rig, this eliminated stability issues and also reduced set up time. The modified Cubex Rig is shown in Figure 6.

Figure 6. Cubex with Longyear 400 Series Feed Frame.

Due to the abrasive nature of the loose rockfill, it was decided to use a 60 mm diameter very hard, abrasion resistant diamond bit, which extended the life to an acceptable level. As a result of this change the drill rate when coring through large rocks in the fill matrix was decreased. It was found that drilling the hole without the inner tube, the target depth could be achieved and the rock fill would push up into the drill barrel. The drill string would then be retracted and approximately 0.5 m of the hole would be lost, the inner tube could then be replaced and the remaining 0.5 m could be recovered.

Once the hole reached the required depth the bit was cleared using a spear attached to the wire line, in preparation for running the polypropylene injection casing. The injection casing consisted of 40 mm outside diameter polypropylene pipe with clusters of holes drilled in the bottom 5 m which formed the exit points for the cement grout. Barbs were cut into the end of the pipe to hold it in place while the drill rods are retracted. The injection casing was fed inside the drill string, and the drill string then retracted, leaving the injection casing in the hole.

Injection holes for the FB200 grout were spaced approximately 10 m apart, as illustrated in Figure 7.

Due to the low viscosity of the cement grout, required for the penetration of the rockfill void spaces, grout curtains were designed to prevent the flow of cement grout behind the below lying crown pillars.

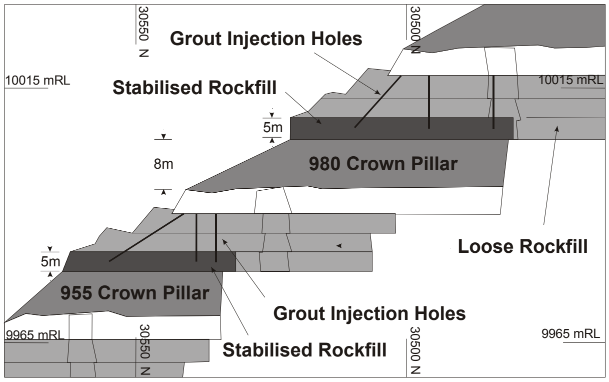

Figure 7. Long section view of Grout Injection Holes (looking east).

Mine water has been observed to run down the orebody, through the waste rock fill and accumulate above the crown pillars. This water has the potential to dilute the cement grout, weakening the artificial stabilised rockfill pillar. The water was drained by drilling up from the level below, through the crown pillar into the bottom of the rockfill.

Placement of FB200

Due to the large volumes of cement grout required, a 3 tonne capacity steel hopper was fabricated in order to facilitate the use of 1 tonne bulk cement bags to significantly reduce the labour required to deliver the cement to the mixing-pumping units. The hopper enabled the use of dual mixing-pumping units which effectively doubled the pumping capacity. Figure 8 displays the mixing and pumping process whereby a Cat IT 28 unit was used to transport the cement underground and position the bag above the hopper.

A pneumatically powered, and an electric powered placer pump unit were used to mix and pump the cement grout via 1 in. ID poly pipe to the previously inserted injection sleeves at a rate of approximately 3 t/hr (dry cement).

A total of 42 tonnes of FB200 was placed above the 980 Crown Pillar. Above the lower 955 Crown Pillar, 75 tonnes of FB200 was placed. In both pillars this was far less than the original estimates of the amounts required. It was obvious that the void ratios were much less than had been used for these estimates, an actual figure of 15% as opposed to the estimated 30%. This was due to compaction of the backfill due to the action of the load-haul-dump as the loose backfill is placed.

After curing for approximately 7 days, probe holes were drilled to confirm the penetration of the FB 200 cement grout.

Figure 8. Cement Hooper and Pump Configuration.

Extraction of the 980 Crown Pillar

Inspection of the stope, from beneath the crown pillar following two ring firings revealed spalling off the weak hangingwall, however the stabilised fill was observed to remain stable. Further inspection of the stope following the firing of a further four rings revealed a small failure of the hangingwall (approximately 3m deep) along with failure of the stabilised rockfill, as displayed in Figure 9.

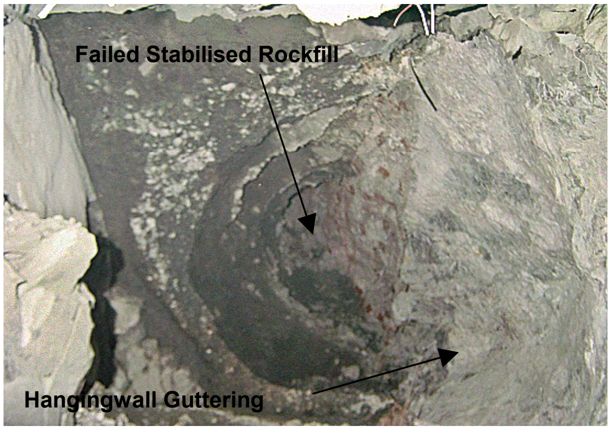

Figure 9: View from Beneath 980 Stabilised Fill Pillar.

Within the exposure of the failure stabilised rockfill, the FB200 could be seen in layers, this was also evident from a large block of grouted fill observed in the ore stockpile. The failure occurred due to the hangingwall shear guttering up past the bottom of the pillar resulting in the lower layer of the FB200 being left to support the fill above in a cantilever configuration. The layering and poor penetration observed in this area is a result of the blockage of the third injection hole. Upon reconciliation of the extracted crown pillar, the ore recovery was 100% while 125% dilution (tonnage increase) was recorded.

Extraction of the 955 Crown Pillar

The extraction of the 955 Crown Pillar was conducted progressively as a longhole retreat from the southern end of the pillar towards the 955 Level central access drive. Figure 10 displays the intact stabilised rockfill from beneath the brow of the crown pillar.

Reconciliation of the 955 Crown Pillar reported 100% recovery with 5% dilution, significantly increasing the recovery and reducing the dilution associated with the extraction of crown pillars beneath loose unconsolidated rockfill.

Figure 10: View from Beneath 955 Stabilised Rockfill Pillar.

Cost and Revenue Analysis

Historically 70% of ore had been recovered mining with the established crown pillar extraction method, whilst dilution had been 200%. These figures were used to compare the revenue and costs with the crown pillar extraction beneath stabilised rockfill. A gold price of US$280/oz was assumed and an exchange rate of AU$0.50 to US$ was used.

Table 1 shows the financial comparison of the 955 Crown Pillar if mined conventionally and the actual recoveries and dilution.

As observed, significant economic benefits were gained by implementation of stabilised rockfill crown pillars at the Crusader Mine.

Table 1. Financial Comparison of mining with and without stabilised rockfill for the 955 Crown Pillar.

	955 Loose Rockfill	**955 Stabilised Rockfill**
In-situ Grade and Tonnes	6231t @ 31.34g/t	6231t @ 31.34g/t
Stope Dilution	200%	100%
Costs Haulage & Milling	AU$239,000	AU$167,000
Costs Diamond Drilling	-	AU$81,000
Cost of Grouting	-	AU$62,000
Total Costs	AU$239,000	AU$310,000
Recovery	70%	100%
Gold Price & Exchange Rates	US$280 @ 0.5 US$:AU$	US$280 @ 0.5 US$:A$
Revenue	AU$2,461,000	AU$3,516,000
Net Benefit		**AU$1,100,000**

Conclusions

The 980 and 955 Crown Pillars at the Crusader Mine were formed beneath loose rockfill. The extraction of such crown pillars has traditionally resulted in significant dilution and loss of ore.

Investigation of the geomechanical criteria for safe and efficient crown pillar extraction beneath stabilised rockfill has lead to the successful extraction of the two crown pillars. Reconciliation of the 980 Crown Pillar reported 100% recovery with 125% dilution, while the 955 Crown Pillar reported 100% recovery with 100% dilution, significantly increasing the recovery and reducing the dilution associated with the extraction of crown pillars beneath loose unconsolidated rockfill.

Laboratory testing of the strength and deformation characteristics of stabilised rockfill material, field testing of the penetration capabilities of FB200 cement grout, and the numerical investigation of the failure mechanisms and behaviour of undermined exposures of an artificial stabilised rockfill crown pillar, have solved the technical risks associated with the proposed extraction method. However, several practical challenges needed to be resolved prior to implementation. These included; drainage of accumulated mine water above the crown pillars, placement of grout injection pipes via diamond drilling methods and the placement of grout curtains to limit the flow of the low viscosity FB200 cement grout.

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