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Design and implementation of cemented rockfill at the Ballarat Gold Project

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Abstract

Cemented rockfill (CRF) has been implemented at the Ballarat Gold Project to allow pillarless recovery of the narrow vein gold deposit. The stoping extraction strategy requires both vertical and horizontal CRF exposures to remain stable and prevent excessive dilution.

This paper outlines a program of initial laboratory testing and numerical modelling to ensure safe and efficient CRF exposure design. A novel numerical modelling approach has been developed to accurately simulate the particulate nature of CRF material. The stability of CRF exposures have been determined by conducting a series of three-dimensional numerical models that incorporate extraction, filling and the exposure sequence of the CRF filled stopes.

1 Introduction

The Ballarat Gold Project (Ballarat) is located in the city of Ballarat, approximately 100 km due west of Melbourne, Victoria, Australia. Gold was discovered in Ballarat in 1851. At this time, mining was completed through underground shafts and small scale stoping operations. Today, Castlemaine Goldfields Ltd continue mining of the original Ballarat Goldfields deposit extending workings further north and deeper (~690 m) in the Llanberris and Brittania compartments. A combination of stoping methods are used to recover narrow vein gold mineralisation (generally 2-5m width) with an annual production target of 50,000 oz.

A CRF backfill system is currently being implemented to allow pillarless recovery of the deposit. Due to the variable nature of run-of-mine waste and limited control over mixing quality, detailed analysis of the geomechanical behaviour of CRF material is often overlooked in lieu of conservative binder addition. As discussed by Stone (2007), every mine is unique and needs to develop its own strategy and rationale for the target strength of CRF. Otherwise, millions of dollars in cement may be wasted in fills that are overdesigned.

2 Background

2.1 Geological setting

The main rock types at Ballarat are sandstone, siltstone and quartz that have been weakly metamorphosed and tightly folded about north trending axes. The inter-bedded sediments are intensely weathered to a depth of at least 100 m below surface. Below this depth, the degree of weathering decreases and intact rock strength increases. However, extremely weathered rock can persist at depth associated with major geological structures (cross course faults).

Typical orezones consist of a stockwork of quartz veining or massive quartz lobes hosted within the sediments. The quartz can be highly fractured, particularly surrounding major geological structures, and can resemble sugar cubes in intensely fractured zones.

A vertical to horizontal stress ratio of approximately 2:1 has been measured at Ballarat. Squeezing ground conditions have been observed and monitored down to a vertical depth of approximately 670 m, predominantly in the north–south oriented development and where major structures, i.e. west dipping faults, cross course faults or bedding parallel faults, are in close proximity to, or intersect the development.

2.2 Mining geometry

The mining operation extends for approximately 3 km north of the portal position reaching a maximum depth of approximately 690 m below surface. Gold resources have been defined in the Victoria, Llanberris, Sovereign and Britannia compartments and these will form the principal mining fronts through 2014. Drive dimensions are typically 5 m wide by 5.3 m high.

An empirical stope assessment based on the Mathews stability method for the Llanberris 648 NOD Stopes provides an N value of 2.9 for the hangingwall, 4.6 for the crown and a maximum unsupported span of 11 m (limited by the hangingwall). Based on this assessment, vertical rib pillars have previously been left in the stoping horizon to provide stability to the hangingwall as illustrated in Figure 1. This requires the sterilisation of a significant amount of the resource.

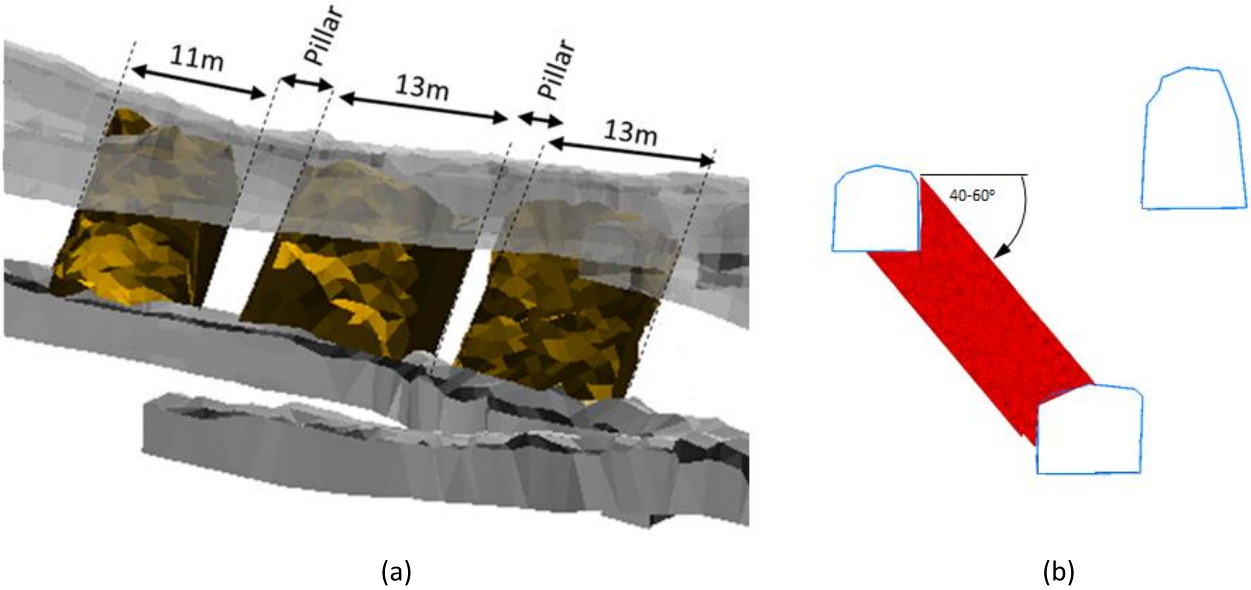


Figure 1 Historical development and stopes in the Llanberris compartment

In order to improve the efficiency of the extraction strategy, CRF will be used for the continuation of mining along strike, initially in the Llanberris compartment.

3 Implementation of CRF

CRF is a mixture of run-of-mine waste rock mixed with cement slurry. Sump mixing with a loader offers the lowest cost form of exposable backfill available for small narrow vein stoping operations. Due to the variable nature of run-of-mine waste and limited control over the sump mixing process CRF is generally not suitable for underhand exposure in man-entry stopes.

The backfill delivery requirements at Ballarat have been estimated to be 224 m^3 per shift. This rate is consistent with current operational efficiencies, equipment and labour availability. Waste headings typically generate 93 m^3 of waste each cut. This equates to approximately 2 ¼ waste headings per shift required for CRF backfilling. In order to minimise any backfilling delay, a stockpile of loose rockfill is maintained underground in close proximity to each stope.

The variability of the CRF material is limited by using only good quality waste rock that has no clay component and by screening particles greater than 400 mm from the waste. Ongoing quality control and assurance is critical to the safe and efficient implementation of CRF. A thorough quality assurance/quality control (QA/QC) procedure has been developed that includes inspection of waste material, sampling of the cement slurry, reconciliation of cement consumption, sampling and laboratory testing of CRF material and visual inspection of exposure performance.

The cement slurry pre-mix is mixed with the waste rock underground at sumps located within close tramming distance to the stope requiring backfilling. The cement slurry is pre-mixed to a water cement ratio of 0.8 at a batch plant on the surface and transferred to the CRF mixing sump by an underground agitator. Based on the backfilling requirements, a maximum of four agitator loads per shift are required.

Using a loader with a 7 m^3 bucket capacity and 80% bucket utilisation, the simple mix designs illustrated in Figure 2 have been developed for 3 and 5% CRF materials.

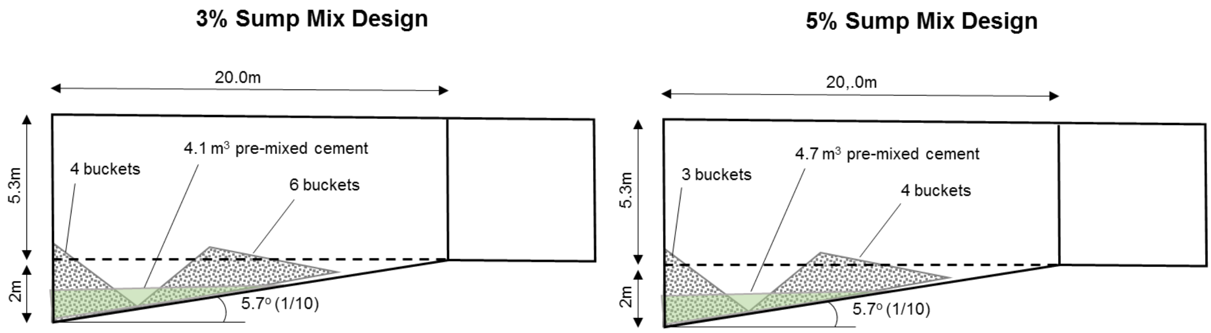


Figure 2 Design of sump mixing system for 3 and 5% mixes

The direct cost savings with reduced CRF cement addition can be easily accounted. However, there are significant additional operational efficiencies associated with reduced cement content in a small sump mixing CRF operation with fixed equipment and limited workforce.

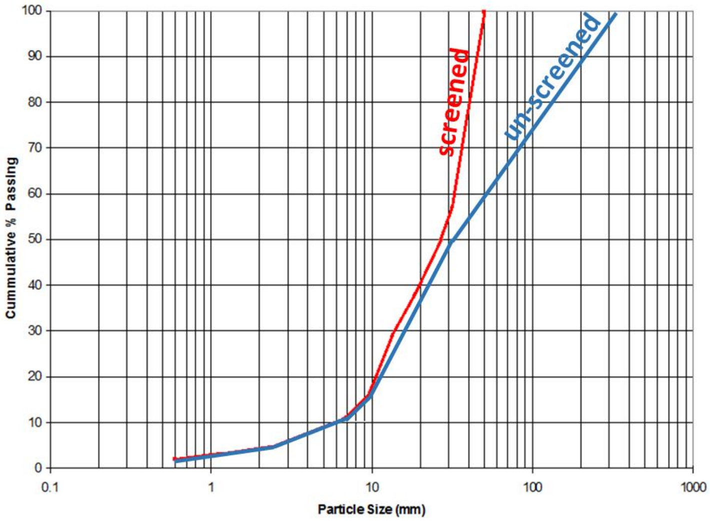
4 Laboratory investigation of CRF strength and deformation behaviour

Routine laboratory testing is an essential element of any backfill quality control procedure. Investigation of the geomechanical properties of CRF provides an improved understanding of the critical factors influencing the strength, deformation and post-failure response of CRF material. The results from both dedicated laboratory investigations and routine quality control strength testing are essential in delivering an improved level of safety and efficiency in the design of CRF exposures.

Due to the variable nature and relatively large maximum particle size (200-400 mm) of typical run-of-mine waste, laboratory testing of representative CRF poses various challenges. Without testing of multiple large scale (~500 mm diameter) specimens, it is difficult to obtain a precise measure of CRF strength and deformation behaviour. However, significant insight can still be obtained by conducting routine tests on small scale (~150 mm diameter) specimens with a modified particle grading curve to minimise the obvious scale effects.

An initial condensed laboratory testing program was designed to investigate the effect of curing time and binder content on the unconfined compressive strength (UCS) of CRF at the Ballarat Mine. Typical run–of–mine rockfill was sampled and screened to remove particles greater than 50 mm. This provided a maximum sample diameter particle size of 3:1. It is understood that this ratio would provide a significant scatter of results in the preliminary testing program. Additional large scale (600 mm diameter) tests are planned as part of an ongoing QA/QC procedure. Figure 3(a) illustrates the in situ sedimentary waste material while Figure 3(b) presents the particle grading curve of the rockfill material used throughout the testing program. The UCS of the typical siltstone/sandstone intact rock particles ranges between 50–100 MPa.

(a)



(b)

Figure 3 In situ rockfill material (a); particle grading curve of rockfill used in testing (b)

A description of the UCS testing program is presented in Table 1. Tests were conducted on 152 mm diameter specimens with height to diameter ratios of both 1:1 and 2:1. The test samples were prepared in PVC cylinder moulds that were wrapped with plastic wrap to prevent dehydration.

Figure 4 illustrates the UCS test results. A clear increase can be observed between the 3 and 5% cement specimens. Although significant scatter is evident in the limited number of test results a general increase in UCS with an increase in curing time from seven to 28 days can be observed. As expected, the strength of the 2:1 height to diameter specimens are approximately 70% of the 1:1 test specimens.

Table 1 UCS testing program

Cement content (% wt)	Curing time (days)	Sample diameter (mm)	Height/ diameter ratio	UCS (kPa)	Young's modulus (MPa)
3	7	152	1	881	44
3	14	152	1	1,442	88
3	14	152	1	1,259	60
3	28	152	1	1,576	87
5	7	152	1	2,026	111
5	14	152	1	4,190	274
5	14	152	1	3,645	105
5	28	152	1	3,613	148
3	14	152	2	857	55
3	14	152	2	988	52

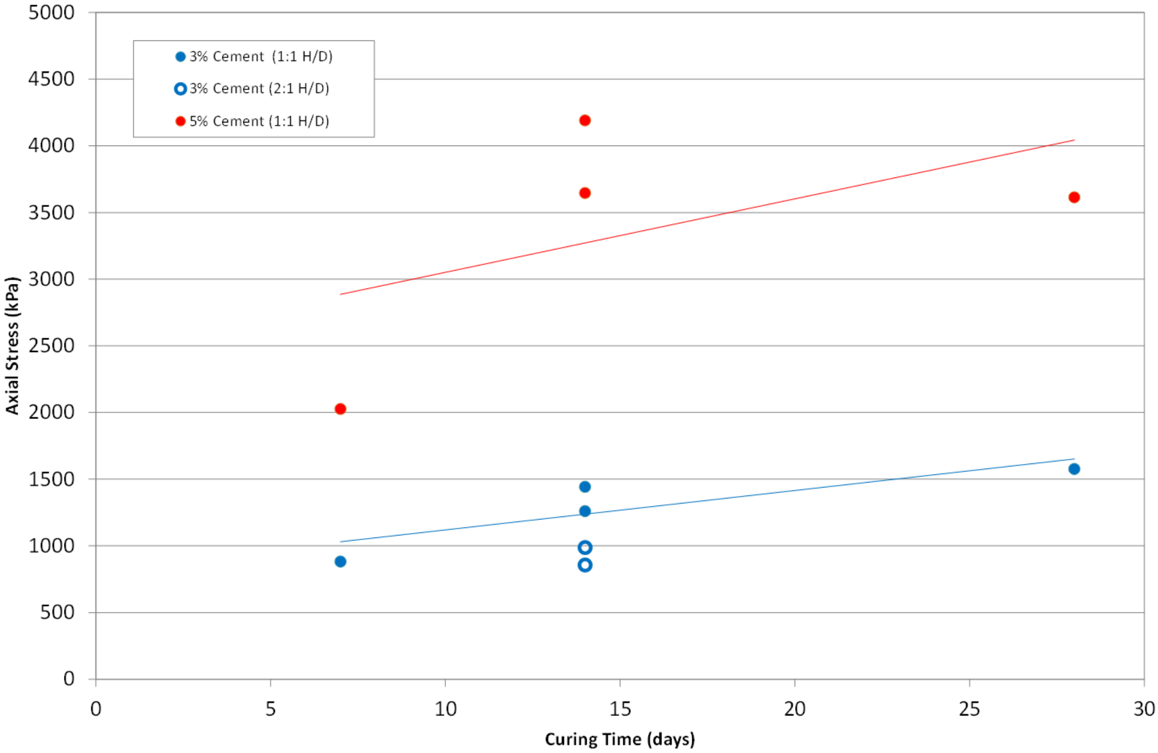
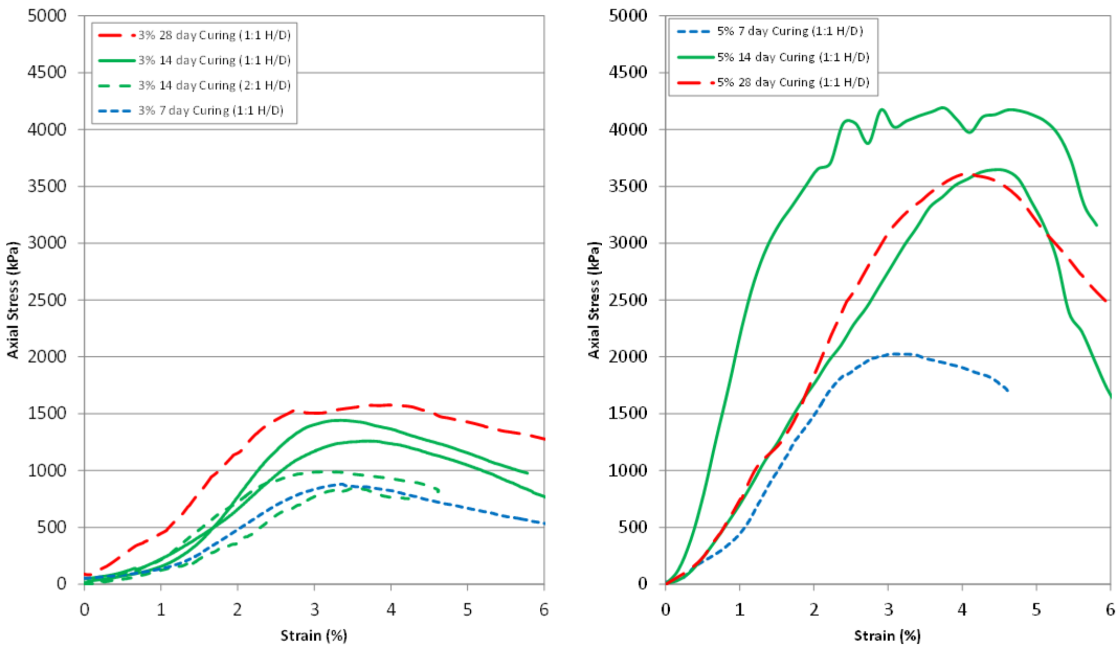


Figure 4 UCS test results

The full stress–strain response of each UCS test is illustrated in Figure 5. As shown, all test results display a relatively ductile post-peak response. Figure 6 illustrates the response of the 14 day, 3% cement, 2:1 height to diameter specimen. During the early stages of loading, cracking of the cement bonds was clearly audible. With increased load the sample entered the brittle/ductile transition phase where the rockfill particles were observed to rotate and interlock. In the post-peak phase, the interlocking particles could be observed to begin crumbling in a controlled manner while the sample maintained approximately 80% of its peak load.



(a) (b)

Figure 5 Stress–strain response of 3% cement tests (a); stress–strain response of 5% cement tests (b)

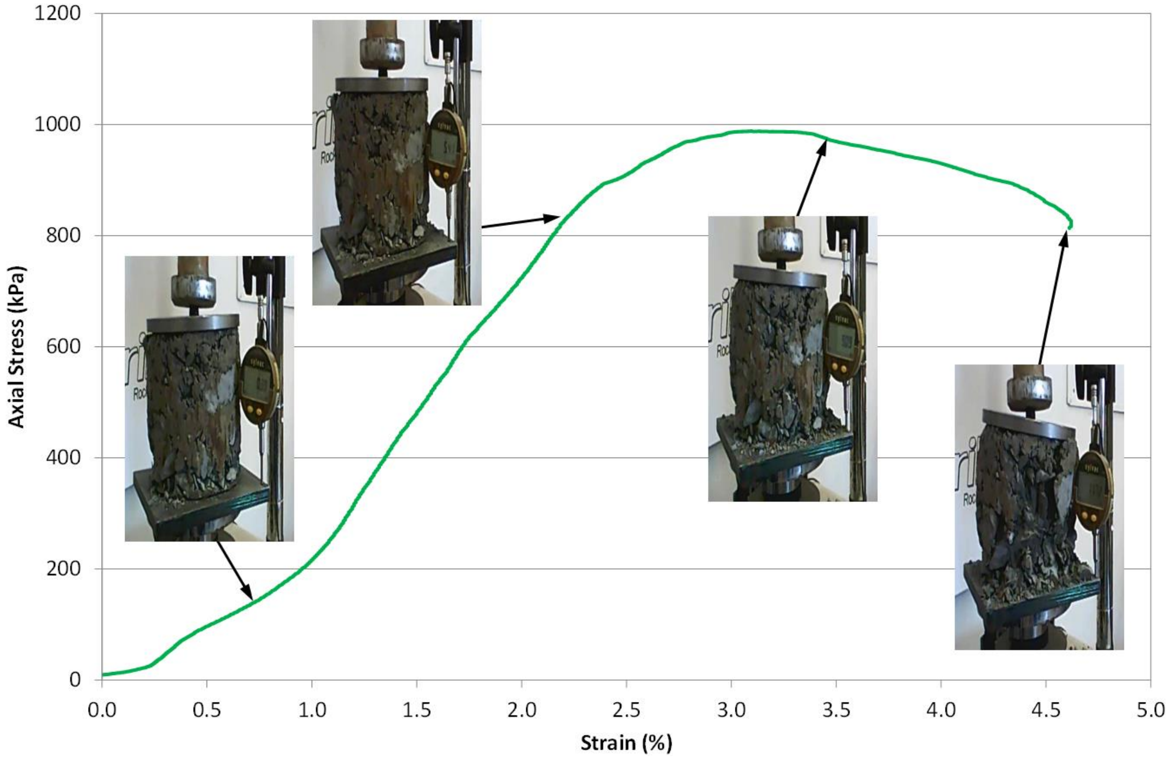


Figure 6 Typical CRF response during UCS testing

It is essential that geomechanical laboratory testing is seen as an iterative process that is used in conjunction with geomechanical analysis/modelling, in situ observation and monitoring. Although only a limited number of UCS tests were conducted within the initial testing program, valuable insight into the effect of binder content and curing time and the post-peak response of the CRF has been obtained. Future testing is planned to investigate the large scale UCS response, shear strength and tensile strength of the CRF material.

5 Analysis of CRF exposure stability

Several analytical and empirical techniques are available to assess the vertical and horizontal exposure of cemented fill masses. Based upon physical modelling of tailings-based cemented fill, Mitchell et al. (1982) developed a series of analytical solutions to assess the exposure of simplified vertical fill exposures. Mitchell and Roettger (1989) later developed a series of two-dimensional analytical solutions to the main failure modes of horizontal (or underhand) fill exposure.

Belem and Benzaazoua (2008) report, that in the absence of numerical modelling, many mine engineers rely on two-dimensional limit equilibrium analyses along with a calculated Factor of Safety to determine fill exposure stability. The typical result is an over-conservative estimate of limiting or critical strength (Stone 1993), which increases backfill operational costs. Modelling within continuum based numerical methods has been successfully employed by many practitioners to overcome the many assumptions, limitations and geometrical constraints associated with these analytical solutions (Caceres 2005; Swan & Brummer 2001). Connors (2001) reports that numerical modelling of underhand CRF exposures at the Murray Mine in Nevada showed that a significant reduction in CRF cementation could be achieved.

In order to simulate the interlocked particulate nature of CRF that controls the ductile/dilatational post−peak response observed in laboratory testing, a modelling methodology has been developed with the three-dimensional distinct element code 3DEC (Itasca Consulting Group, Inc. 2013). 3DEC allows simulation of an assemblage of discrete polyhedral blocks that interact at their contacts. The explicit in-time solution allows large displacement and rotation to be simulated. The program is well suited to the simulation of rockfill material. Taghavi and Pierce (2011) report on the successful use of 3DEC to simulate the flow behaviour of caved rock material in a block cave drawpoint.

To illustrate the capability of the 3DEC program to simulate the flow of rockfill material, a simple model was developed to demonstrate the flow behaviour of a cubic sample of loose rockfill material which is allowed to settle under gravity loading on a flat surface. Figure 7 illustrates the evolution of the rock particle displacements under gravitational loading.

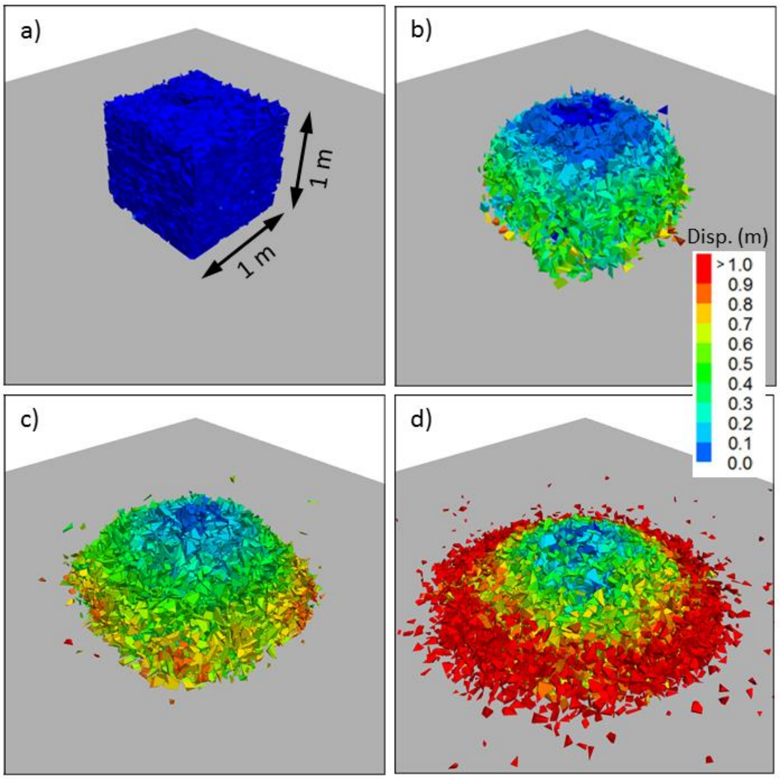


Figure 7 Evolution of particle displacement from a cubic rockfill sample under gravity

A series of simulated UCS and triaxial loading experiments were conducted in 3DEC to calibrate the block and contact material properties to match the stress–strain response recorded in the laboratory. Figure 8 illustrates the simulated and laboratory stress–strain response for 1 MPa CRF material.

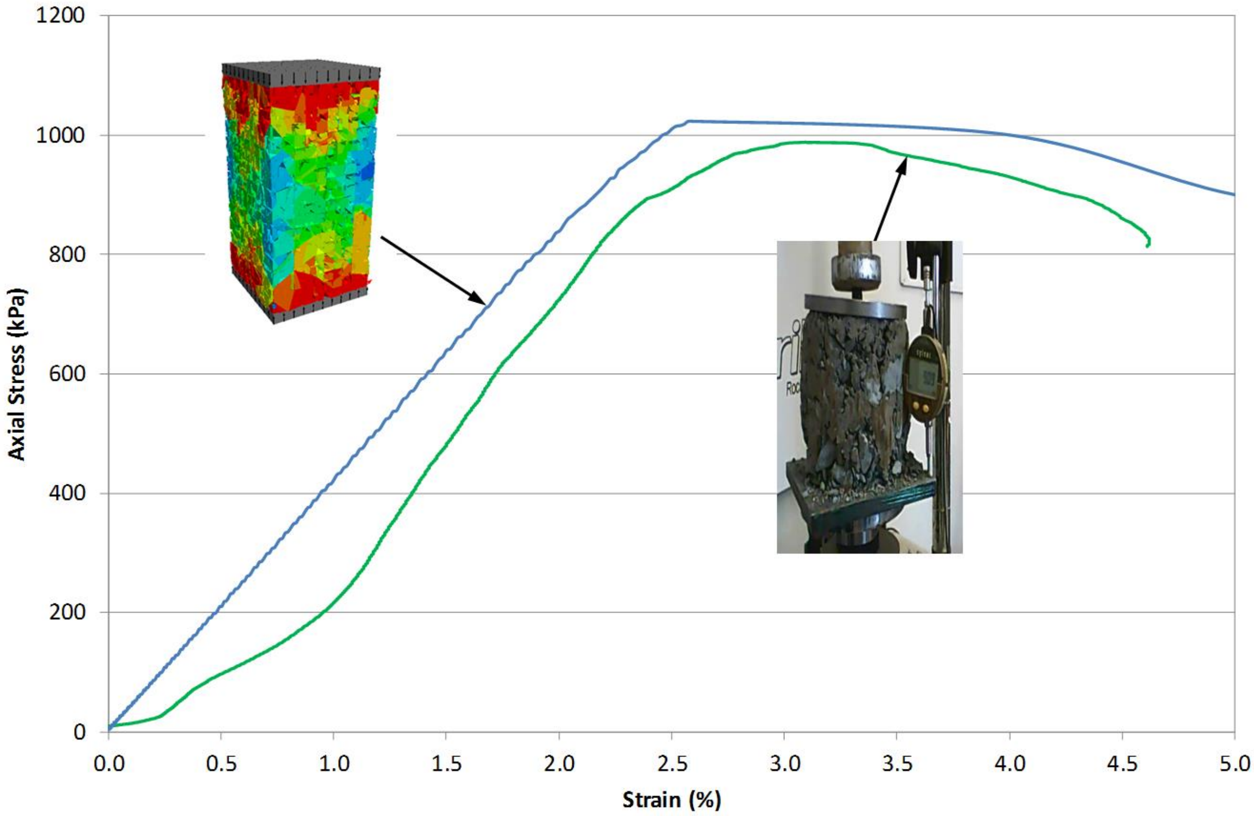


Figure 8 Comparison of numerical and laboratory stress–strain response of 1 MPa CRF material

The material properties used to simulate the 1 MPa CRF is presented in Table 2. In order to simulate the inherent variability caused by the simple sump mixing system, the contact cohesion and tensile strength has been simulated with a normal distribution.

Table 2 3DEC block and contact properties

Simulated UCS (kPa)	Block properties E (GPa)	ν	kn (GPa/m)	ks (GPa/m)	Contact properties c (kPa)	ϕ (deg.)	σ_t (kPa)
1,020	50	0.2	80	40	500 +/- 50	30	250 +/- 25

To determine the required CRF strength for vertical and underhand exposure, a simple 3DEC model of a single stope was constructed, as illustrated in Figure 9. Filling of the CRF stope was simulated by placing the rockfill in 2 m layers to ensure representative internal stress distribution within the fill mass. Figure 10 illustrates the magnitude and orientation of the major principal stress along a cross-section through the centre of the stope after placement of the rockfill. To simulate the delayed hydration of the cement bonds, the contact cohesion and tensile strength was set to zero during the filling process.

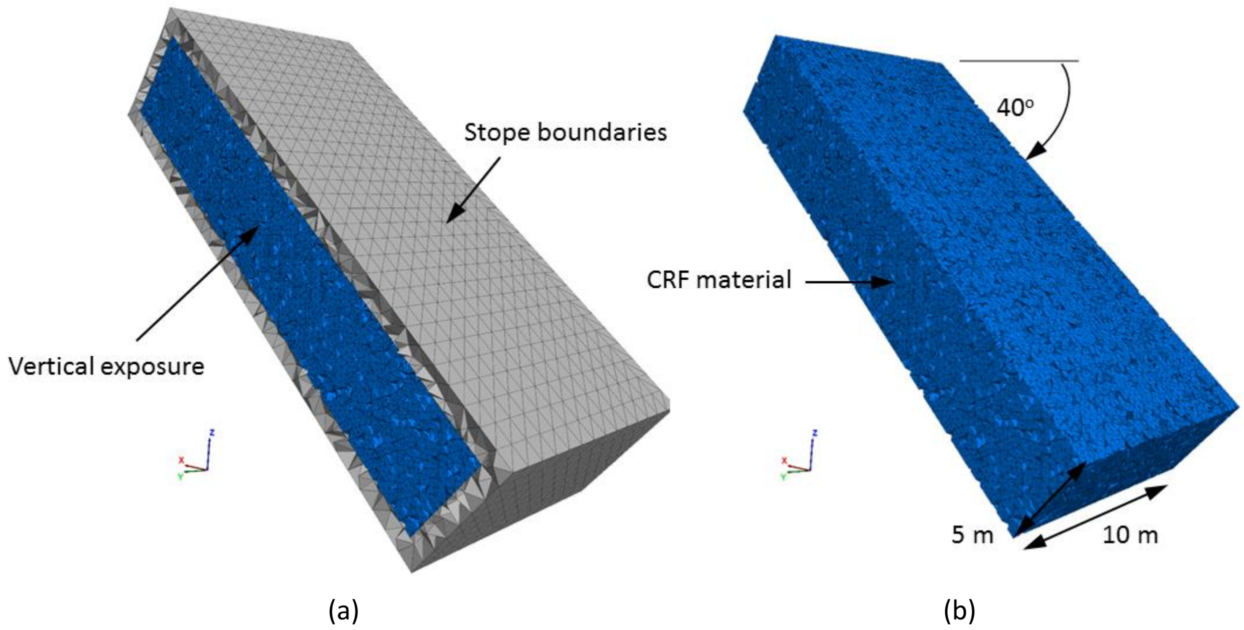


Figure 9 Geometry of CRF stope analysed

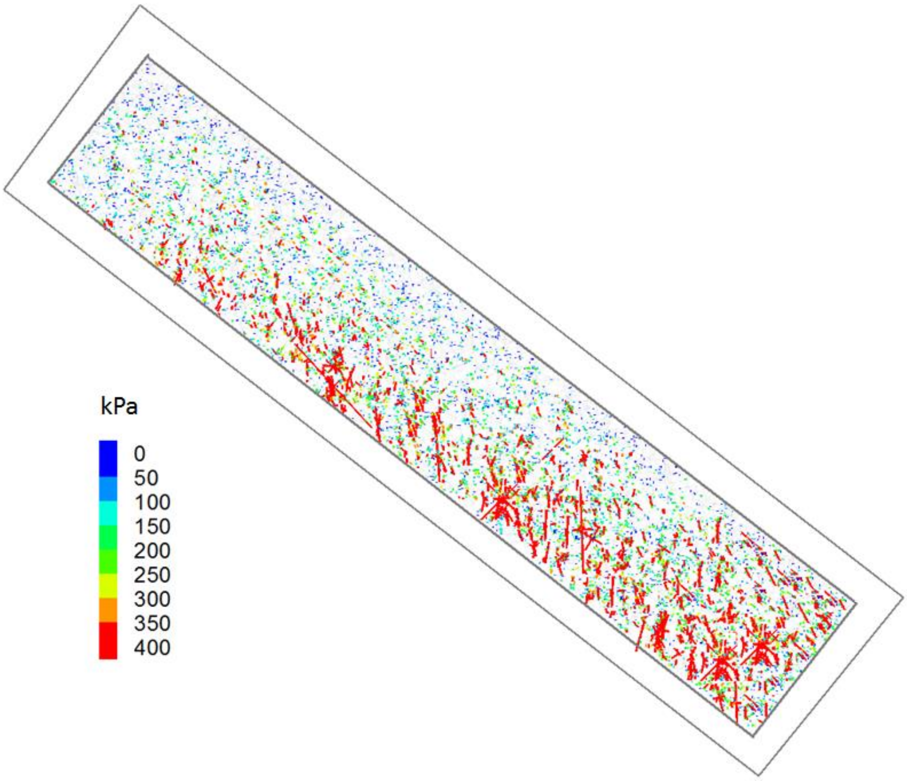


Figure 10 Stress distribution throughout fill mass

After filling of the CRF stope, vertical exposure is simulated by progressively removing the blocks that simulate the vertical stope boundary. A series of analyses were conducted to assess the minimum CRF strength required to maintain stability of the vertical exposure. Figure 11 illustrates the total displacement (max. 500 mm), velocity (m/step) and displacement time history of a point in the centre of the exposure. Only minimal cementation is required to lock the rockfill particles together. As shown, the minimum strength required to maintain stability is approximately 40 kPa. Laboratory testing conducted on 3% CRF material at Ballarat indicates a strength of approximately 620 kPa after seven days.

Figure 12 presents the response of a series of analyses conducted to assess the minimum CRF strength required to maintain stability of an underhand exposure of the simple stope geometry. As illustrated, the minimum strength required to maintain stability is approximately 120 kPa. Laboratory testing conducted on CRF material at Ballarat provides large scale strength estimates of 1,420 kPa after seven days.

Based on the exposure stability modelling, a significant Factor of Safety against stope failure is provided by the current design cementation levels (3 and 5%). Initial stope performance observations will provide scope for cementation optimisation studies in the future.

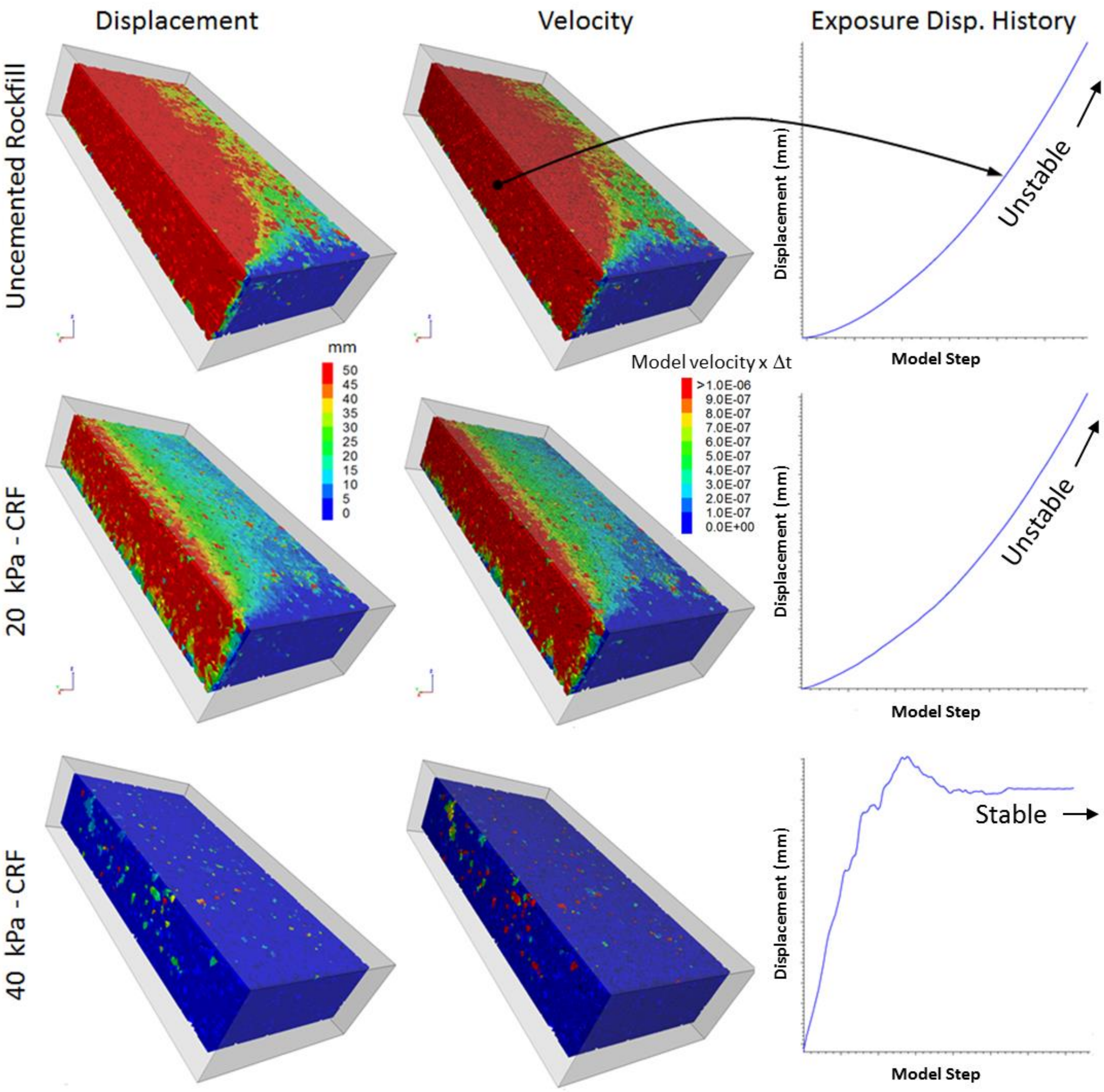


Figure 11 Analysis of vertical exposure stability

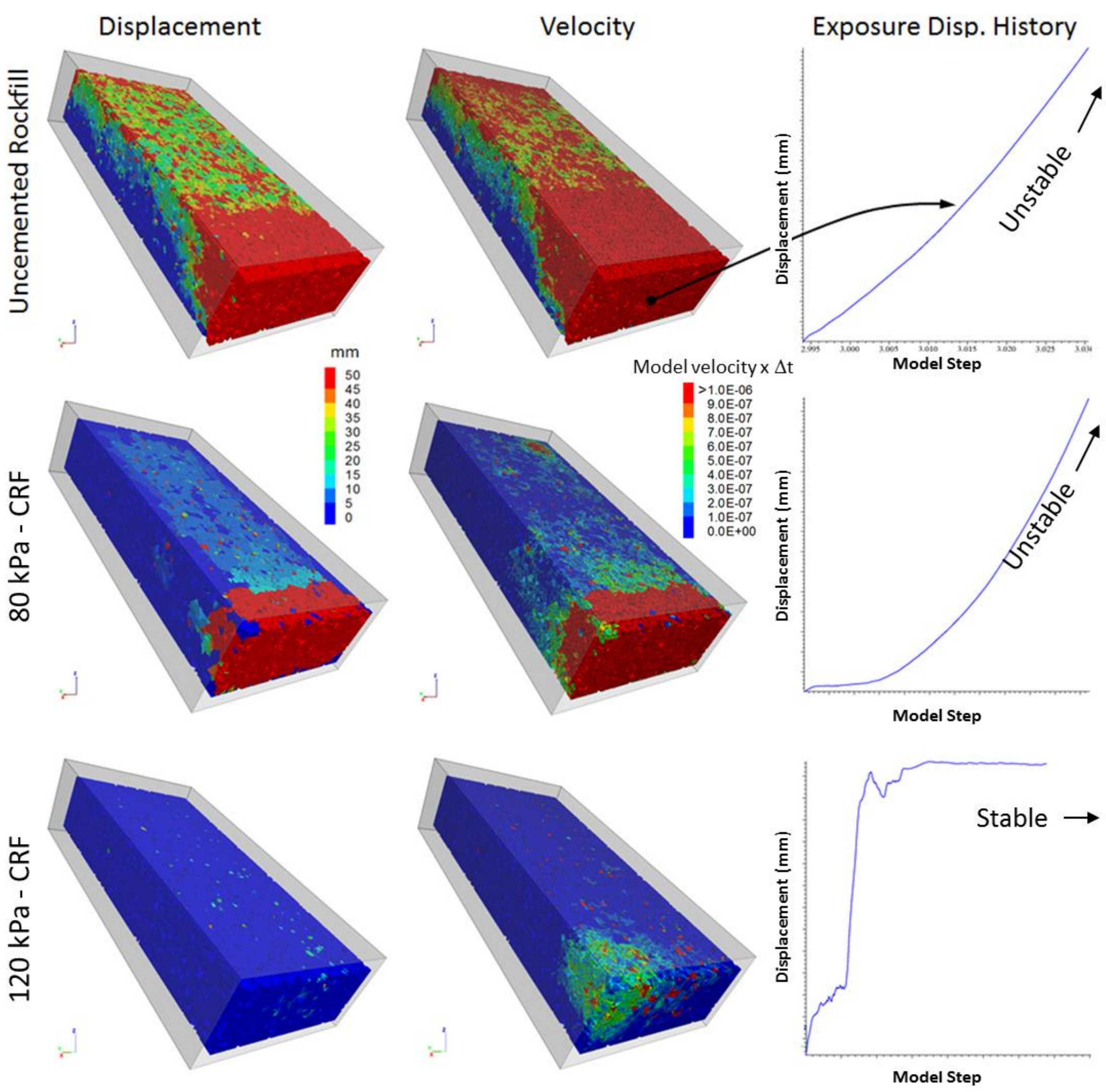


Figure 12 Analysis of underhand exposure stability

6 Initial vertical CRF exposure performance

The initial CRF stopes at Ballarat have been placed with 3%$_{wt}$ cement and a water cement ratio of 0.8. Figure 13 illustrates a vertical exposure of CRF in the Llanberris Compartment after 16 days curing time. As expected, the exposure was observed to remain stable with only very minor, blast-induced dilution.

7 Conclusions

A CRF backfill system is currently being implemented to allow pillarless recovery at the Ballarat Gold Project. A program of initial laboratory testing and numerical modelling has been conducted to ensure safe and efficient CRF exposure design. Based upon the initial laboratory test results, modelling of the simple exposure geometries demonstrate that there is significant scope to optimise the CRF cement addition and still maintain an adequate Factor of Safety for the non-entry stopes. An interactive approach to CRF design at Ballarat is planned for the future that includes stope performance observations, laboratory testing and exposure stability modelling. The direct cost savings with reduced CRF cement addition can be easily accounted. However, there are also significant additional operational efficiencies associated with reduced cement addition in a small sump mixing CRF operation with fixed equipment and limited workforce.

Figure 13 Initial vertical CRF exposure

Acknowledgement

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