INVESTIGATION OF A CALCINATED CLAY PRODUCT FOR SHOTCRETE SUPPORT

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ABSTRACT

This paper presents research results for three shotcrete mixes that include up to 50% cement replacement by calcinated clay. The results are part of a multi company research project under way at the WA School of Mines and show that a 25-30% saving can be achieved. In addition, a large amount of CO_2 reduction (up to 40%) can be realized by replacing the cement within a conventional shotcrete mix. Additionally, large gains in early strength can lead to higher productivity. Also, the long-term strength is significant, and the failure mechanism is compatible to soft response to violent loading, likely to minimize shotcrete ejection.

1 INTRODUCTION

Shotcreting is a ground support technique in which a specially designed concrete mix is sprayed at high speed, onto rock excavation surfaces to improve rock mass integrity and assist load carrying capacity at the rock surface. Shotcrete minimizes time-dependent rock deformation, slabbing and violent rock ejection of highly stressed rock, thus improving the safety of the underground mining excavations, where equipment and mining personnel are exposed. In Australia, the use of shotcrete has continued to grow in the mining industry since the late 1980s due to its success in stabilising excavations driven in difficult conditions. The future use of shotcrete will continue and is likely to increase further as mines attempt development within the higher stress regimes and more difficult conditions that generally accompany mining at depth (Villaescusa et al., 2023).

A typical mining tunnel development (5m W by 5m H) advances 3.5 m at a time with 5-7 m^3 of sprayed concrete used to achieve a 50-75 mm thick surface support layer. Thus, for a typical wet mix, the cement component of a 1 m^3 of shotcrete ranges from 400-450 kg of cement. Additionally, for a typical underground mine, the usage of cement from shotcreting activities typically ranges from 2,000 to 20,000 t/year, depending upon the mining method.

In addition to material and transport cost of the cement to the remote mine site locations in Australia, an excessive amount of CO_2 is being emitted during the production of clinker, the main component of cement. This is due to burning of the limestone ($CaCO_3$) during cement production. Historically, to limit the emissions, the cement manufacturing process has improved the fuel efficiency of the burning process and included supplementary cementitious materials such as silica fume and fly ash. Nevertheless, 60% of the emissions are due to the use of limestone. Recently, a sustained effort to quantify and reduce CO_2 emission has started within Australia at large and the mining industry in particular. Consequently, the Western Australian School of Mines (WASM) has started a multi-company research project to investigate the replacement of a significant portion of the cement being used in the mining industry. The cement is being replaced by calcinated (activated) clay which is a low cost (and abundant), supplementary cementitious material.

2 CLAYSTONE DEPOSIT

The clay material being investigated is sourced from a deposit located within the late Archaean Eastern Goldfields Superterrane (EGS) of the Yilgarn Craton, Western Australia (Ambrose, 2023). The Kalgoorlie Clay (KalClay) Project mining and exploration leases are located adjacent to the sealed Yarri Road, approximately 10 km northeast of the city of Kalgoorlie and 7 km southwest of the Kanowna Belle Gold Mine (Figure 1).

Within the project area deep weathering and the chemical characteristics of the underlying sedimentary units have contributed to the significant thickness (average 50 m) of a clay layer. The underlying stratigraphy is dominated by felsic-derived immature sediments, with most exploration holes ending in very fine-grained siltstones and mudstones. The exploration drilling to date has shown an abundance (footprint 8 km by 2 km) of clay mineralisation probably associated with weathering of the Black Flag Beds. Overall, very thin, typically less than 1 m thick, young, transported sediments cover the greenstone stratigraphy. The underlying sedimentary-dominated stratigraphy is extremely weathered with the base of complete oxidation generally occurring at 45 – 65m depth in all holes. The clays comprise predominantly silica, kaolin and mica (interpreted in XRD as muscovite). A typical chemical analysis of samples obtained above the base of complete oxidation is shown in Table 1.

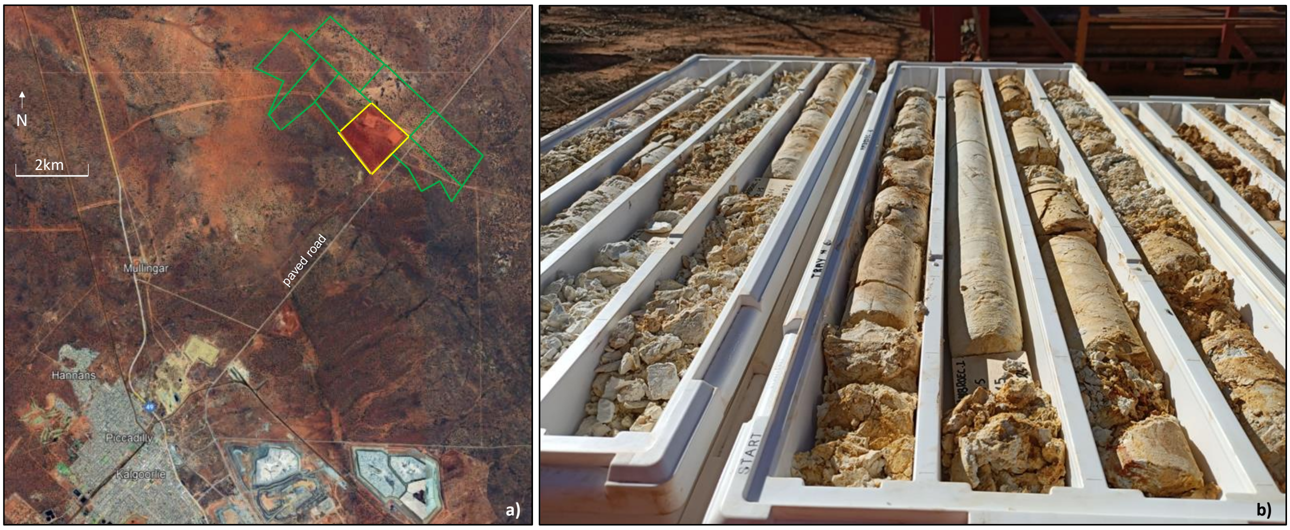


Figure 1: Details of KalClay project showing a) mining (yellow) and exploration leases with respect to Kalgoorlie and b) typical claystone drilling results

Table 1: Chemical analysis of the KalClay material

Material	Composition	%
Mica	$X_2Y_{4-6}Z_8O_{20}(OH,F)_4$	23
Silica	SiO_2	52
Kaolinite	$Al_2Si_2O_5(OH)_4$	23
Halite	NaCl	<1
Rutile	TiO_2	1

3 SHOTCRETE SUPPORT

Two conflicting requirements can be identified for a shotcrete mix. Firstly, it must have the rheological properties of a fluid to be pumped and sprayed. Secondly, it must have the mechanical properties of a solid to create a stabilising structural layer. The rheology of the mix depends on the fluid/solid constituents, their particle size distribution which in turn affect the mechanical properties of the in-situ paste, its hardening, and the mechanical properties of the final hardened layer.

An infinite variety of possible loadings and equally large numbers of possible boundary configurations exist. However, two main mechanisms are considered here, firstly a stress-controlled deformation mechanism and secondly, a structurally controlled deformation mechanism. The total response and total capacity can be a combined response mode comprising a limited number of fundamental responses including:

- Compression
- Tension

- Shear
- Torsion
- Flexural
- Combinations

The typical response modes are illustrated in Figures 2 with examples in Figure 3. Each fundamental response mode has an associated capacity (in terms of force and displacement) or mechanical properties such as strength (in terms of compressive, tension, shear and flexure) in elastic and plastic phases. The mechanical properties can be determined from different laboratory test arrangements.

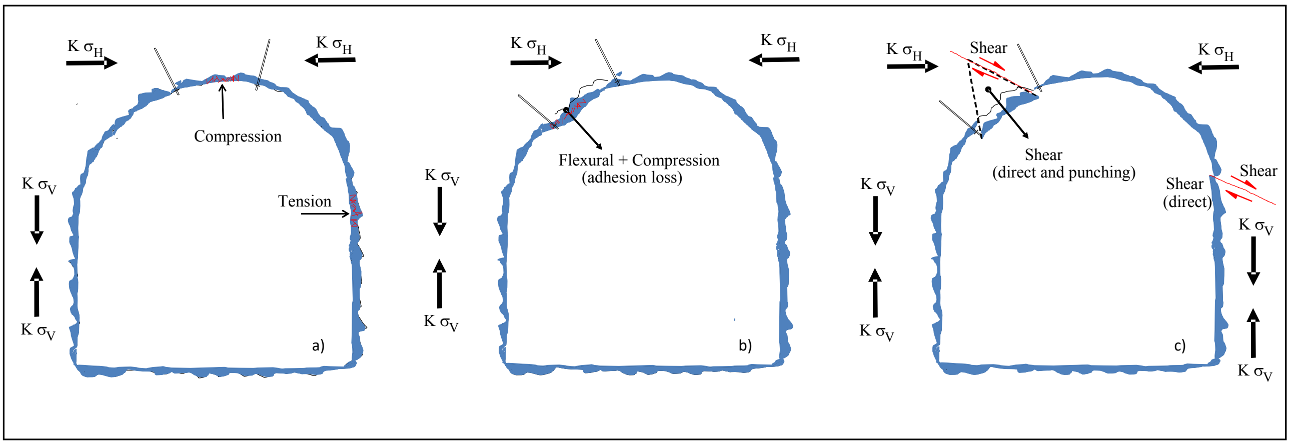


Figure 2: Modes of response for excavation with filled roughness and covered to a minimum shotcrete thickness a) Compression and tension, b) Flexural and compression and c) Shear modes of failure (Modified after Windsor, 1999)

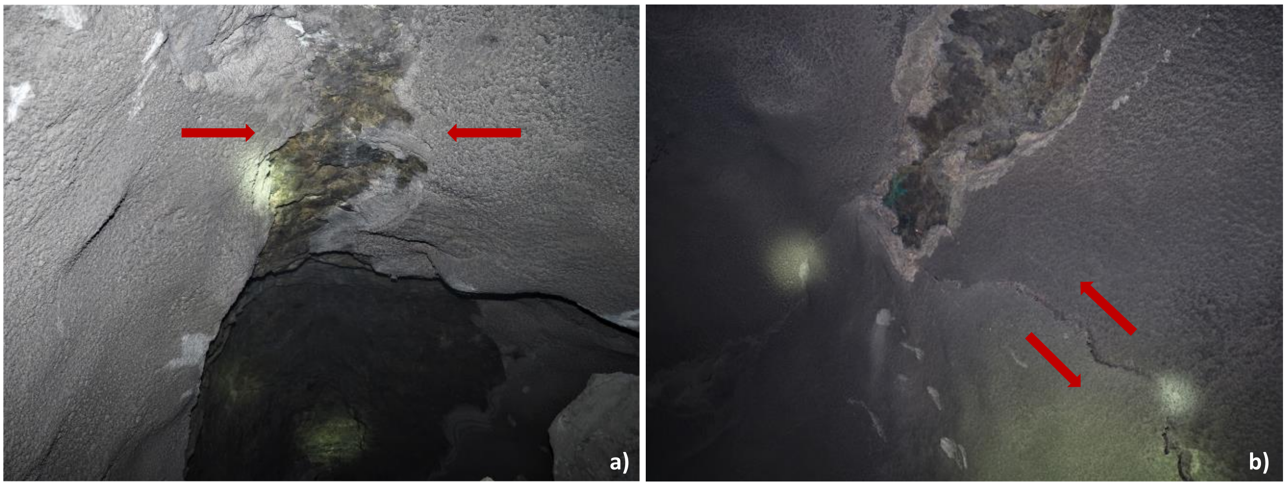


Figure 3: Examples of shotcrete failure a) compression and b) shear and punching

3.1 SHEAR STRENGTH OF FRESHLY SPRAYED SHOTCRETE

Prior to hardening, the mechanical properties of the paste are dictated by the cementitious matrix comprising the cement, mineral additives, chemical admixtures, and the water. After hydration, the shotcrete should possess the mechanical properties of the hardened matrix plus some additional strength due to the presence of coarse aggregate particles, mesh reinforcement and fibres. It is important to note that these mechanical properties improve with hydration from those of the wet paste, to the stiff paste, to the hardened paste and finally to the fully hardened and cured shotcrete. Consequently, the mechanical properties of freshly sprayed shotcrete are those associated with the cementitious matrix. Therefore, it is predominantly the changes with time of the curing shotcrete paste that will indicate the mechanical response of freshly sprayed shotcrete.

The yield strength of the fresh shotcrete pastes for the research described here was determined using a purposely constructed and calibrated vane shear test apparatus (Figure 4). During the mixing period the hydration products in the shotcrete pastes are in the fluid gel state. After approximately 1.5 to 2 hours curing time, the hydration products start transforming into a solid gel state and its shear strength can then be readily determined using conventional uniaxial or triaxial compression test methodologies.

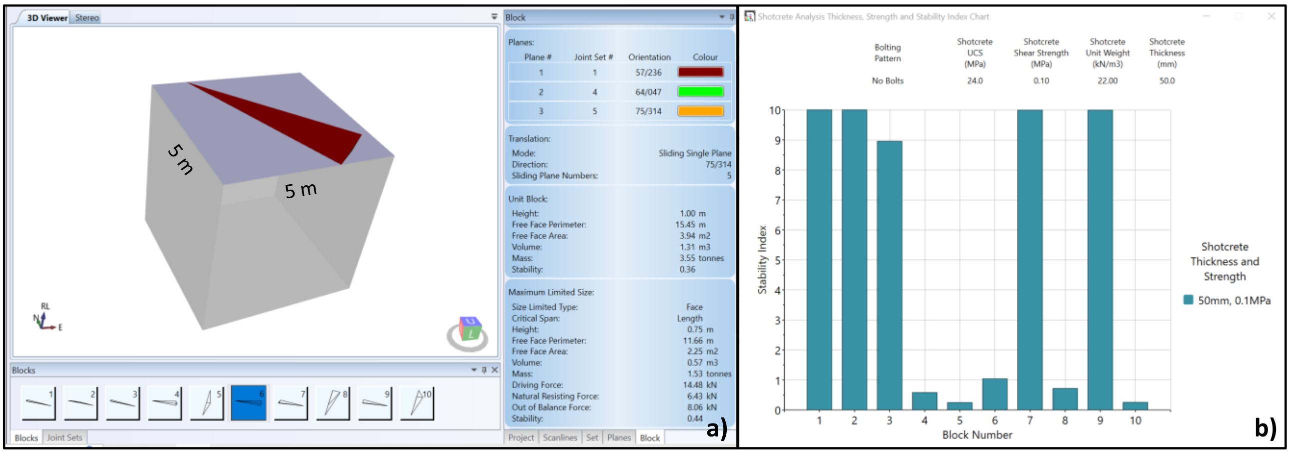
Figure 4: A large-scale viscometer used to determine yield stress of full shotcrete mixes

Two structural requirements can be identified for a freshly sprayed shotcrete layer. Firstly, it must support its own mass within minutes of being applied to the surface and, secondly, it must support the superimposed mass of an estimated unstable volume of rock. In the first instance, the shotcrete supports its own mass by development of an adhesive bond strength (comprising adhesion and mechanical interlock) between itself and the substrate and by development of intrinsic shear strength.

The minimum shear strength required for shotcrete to support its own weight is typically about 4 Kpa (Villaescusa et al., 2013). In almost all cases, where bond and shear strength develop simultaneously after spraying, both laboratory investigations and in situ experience have shown that the required strength levels for shotcrete to support itself are easily achieved.

During service, the shotcrete must be capable of supporting the mass of loose rock blocks that may become unstable and represent a risk to personnel that enter an excavation. The specific arrangement of excavation span, stress and structural geology associated with each excavation will be different and the specification of unstable volume of rock are linked to the potential block shapes that can form due to the geological discontinuity array at a particular location. The computer program SAFEX can be used to show that within a few hours of spraying, shotcrete is quite capable of supporting a significant volume of unstable rock. Figure 5 shows a 5 m y 5m tunnel back with a potential 1.5-ton block shape (0.75 m apex). The calculations show that block can be stabilized by having a 50 mm thick shotcrete layer that has developed a 100 Kpa shear strength. That is, it can be noted that for Block Number 6, the Stability Index (safety factor) increases from 0.44 to 1.0 with the addition of the shotcrete layer. Similarly, each potential block geometry having a Stability Index less than 1 needs to be analysed separately to determine if its occurrence is likely in terms of mass, depth of failure and tunnel profile construction.

Saw (2015) indicated that freshly sprayed shotcrete stability can be determined using a known volume or mass of unstable rock in conjunction with the layer thickness and time after spraying. Saw (2015) provided examples in which a 2.7 mass of instability (i.e., a 1 metre cube block) would be supported by 50 mm of shotcrete having developed a 97 KPa shear strength at approximately 3 hours and 50 minutes after spraying, for a conventional shotcrete mix with accelerator, synthetic fibres and aggregates. It must be noted that the volume of loose rock that may become unstable is naturally minimised during blasting by waves that vibrate the excavation surfaces and by subsequent mechanical or hydro-scaling procedures that clean the excavation surfaces. Consequently, a 100 KPa shear strength is usually sufficient for safe re-entry time in most cases of slab type instability.



Planes:

Plane #	Joint Set #	Orientation	Colour
1	1	57/236	🟥
2	4	64/047	🟩
3	5	75/314	🟧

Translation:
Mode: Sliding Single Plane
Direction: 75/314
Sliding Plane Numbers: 5

Unit Block:
Height: 1.00 m
Free Face Perimeter: 15.45 m
Free Face Area: 3.94 m2
Volume: 1.31 m3
Mass: 3.55 tonnes
Stability: 0.36

Maximum Limited Size:
Size Limited Type: Face
Critical Span: Length
Height: 0.75 m
Free Face Perimeter: 11.66 m
Free Face Area: 2.25 m2
Volume: 0.57 m3
Mass: 1.53 tonnes
Driving Force: 14.48 kN
Natural Resisting Force: 6.43 kN
Out of Balance Force: 8.06 kN
Stability: 0.44

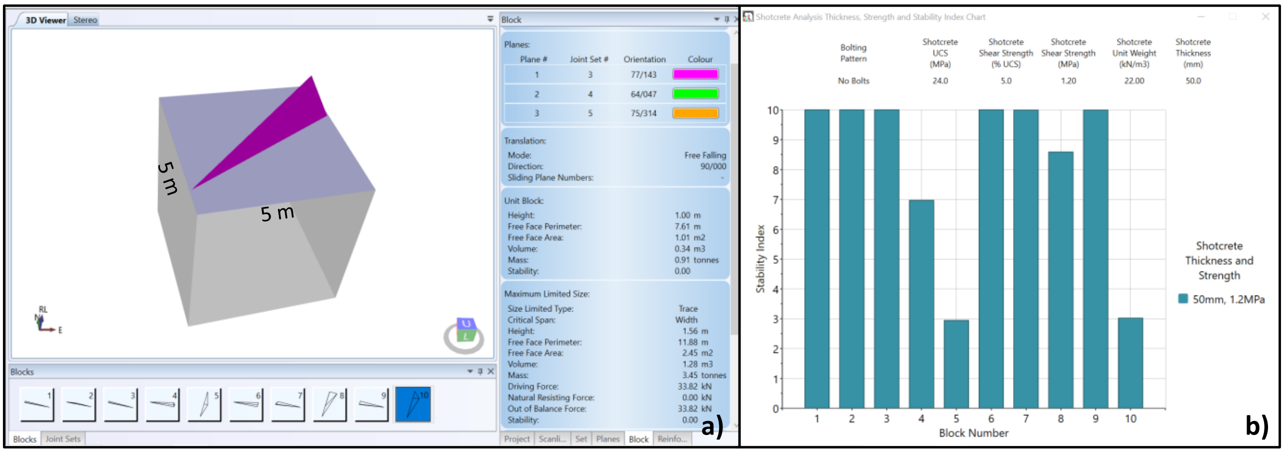
Bolting Pattern	Shotcrete UCS (MPa)	Shotcrete Shear Strength (MPa)	Shotcrete Unit Weight (kN/m3)	Shotcrete Thickness (mm)
No Bolts	24.0	0.10	22.00	50.0

Figure 5: Example of shotcrete design for a) potentially unstable block geometry and b) stabilized using a shotcrete layer

3.2 PERFORMANCE OF CURED SHOTCRETE

The physical properties of the hardened layer that are important are its density, void ratio and permeability. However, the mechanical properties of a shotcrete layer that are most significant in rock support action include its strength (compressive, tensile, shear and adhesion) and its stiffness (flexural, biaxial and shear). These mechanical properties are dictated by the rheology of the paste, the hardening mechanism of hydration and the underground environmental conditions (i.e. temperature and moisture) during hydration and curing.

The SAFEX program can be used to show that a modest amount of shear strength is sufficient to stabilize most potentially unstable blocks (Figure 6). The calculation (for the same block geometry shown in Figure 5) shows that a block of nearly 3.5 tonnes and having 1.5 m apex height, exposed at a 5 m tunnel back, can easily be stabilized using a 50 mm thick layer of shotcrete having 1.2 MPa shear strength. For a conventional bolting pattern (1-1.2m by 1-1.2m), such unstable weight would be at the upper limit of possible unstable geometries (within the bolting pattern). That is, when an instability becomes significant, it is likely to first mobilize the reinforcement elements (Villaescusa et al., 2023).



Planes:

Plane #	Joint Set #	Orientation	Colour
1	3	77/143	🟪
2	4	64/047	🟩
3	5	75/314	🟧

Translation:
Mode: Free Falling
Direction: 90/000
Sliding Plane Numbers: -

Unit Block:
Height: 1.00 m
Free Face Perimeter: 7.61 m
Free Face Area: 1.01 m2
Volume: 0.34 m3
Mass: 0.91 tonnes
Stability: 0.00

Maximum Limited Size:
Size Limited Type: Trace
Critical Span: Width
Height: 1.56 m
Free Face Perimeter: 11.88 m
Free Face Area: 2.45 m2
Volume: 1.28 m3
Mass: 3.45 tonnes
Driving Force: 33.82 kN
Natural Resisting Force: 0.00 kN
Out of Balance Force: 33.82 kN
Stability: 0.00

Bolting Pattern	Shotcrete UCS (MPa)	Shotcrete Shear Strength (% UCS)	Shotcrete Shear Strength (MPa)	Shotcrete Unit Weight (kN/m3)	Shotcrete Thickness (mm)
No Bolts	24.0	5.0	1.20	22.00	50.0

Figure 6: Example of a) potentially unstable block geometry b) stabilized with a modest amount of shear strength development

4 REPLACEMENTS OF CEMENT FOR IGO LIMITED SHOTCRETE MIXES

The WASM research to date has considered shotcrete mixes that include up to 50% cement replacement by the KalClay product. The variables studied to date include sand and aggregate grading, the water/solids, the chemical admixtures (retarder, water reducer and accelerant), the yield stress and the resulting slump. Some of the results are as follows.

Aggregate is the granular material, such as sand, crushed stone and gravel used with a cementing medium to form hydraulic-cement concrete or shotcrete (ASTM C125 – 10a). It occupies at least three quarters of the total volume of a given shotcrete mix and thus, its properties greatly affect the properties of the fluid and hardened concrete or shotcrete. Figure 7 shows the particle size distribution for three IGO Mine sites including a comparison with the typical combined grading used in Australia (Villaescusa et al., 2023). A cross section view of a typical 100 m diameter specimen can be seen in Figure 8 showing the effects of each particle size distribution.

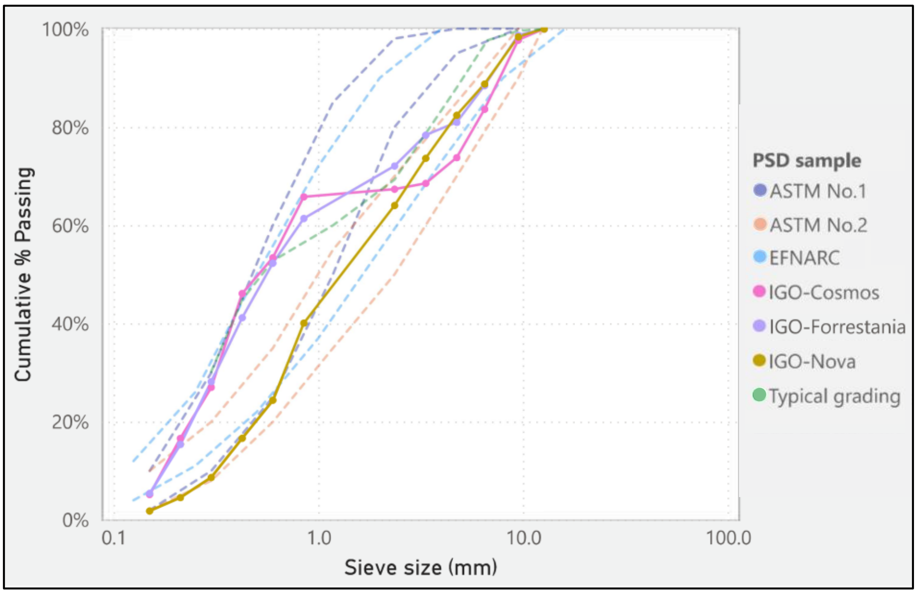


Figure 7: Grading limits for three IGO shotcrete mixes

Figure 8: Cross section of view of UCS specimen following testing for a) Cosmos, b) Forrestania and c) Nova Mines

Figure 9 shows the early strength development for several mixes for three mine sites at IGO Limited. The data shows that for mixes having 50% of the cement replaced by the KalClay material, the 100 Kpa shear strength capacity is achieved in less than 2 hours. Comparatively, the conventional mixes can not reach the 100 Kpa shear strength within the first 4 hours of curing time.

Figure 10 shows a plot of long-term strength for the conventional mixes used at several of the IGO Limited operations. These results can be compared with the data shown in Figure 11, where 50% of the cement component within the mix has been replaced by the KalClay product. The data indicates that the cement-KalClay mixes produce a more uniform strength development of sufficient engineering capacity. That is, the block theory calculations using SAFEX indicates that the cement-KalClay mixes develop sufficient shear strength to stabilize any block formed with a typical bolting pattern. Also, the failure mode of cement-KalClay is more plastic, which is important if shotcrete ejection or large time dependent deformations are likely to occur under high stress (Villaescusa et al., 2023).

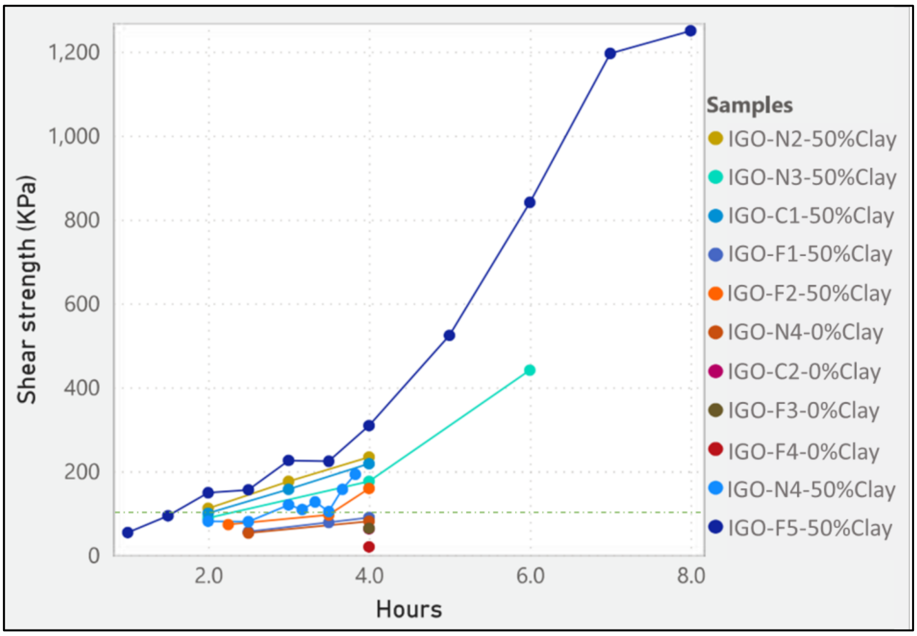


Figure 9: Early strength of shotcrete for several mixes at IGO Limited

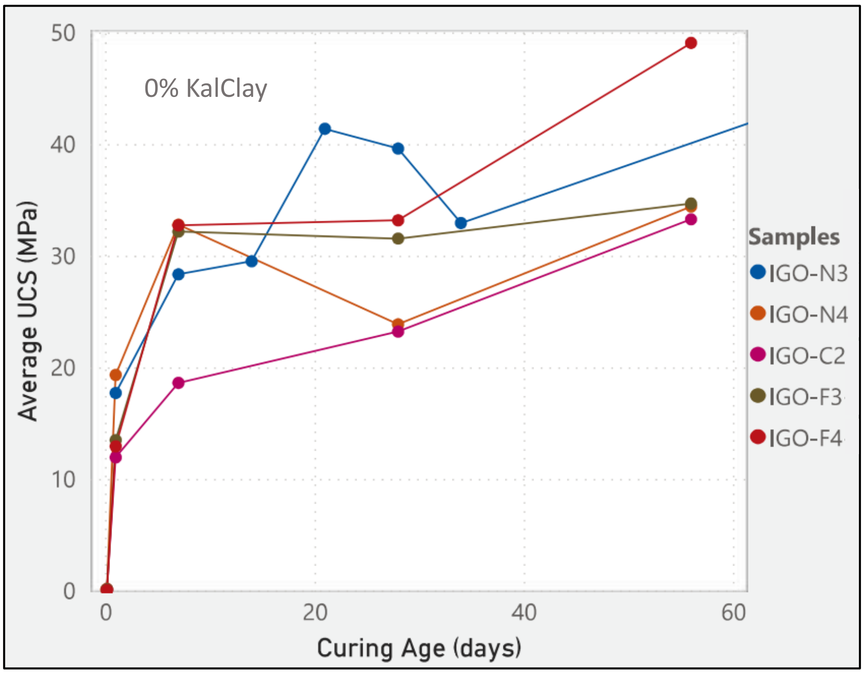


Figure 10: Long term strength of shotcrete for conventional mixes at IGO Limited

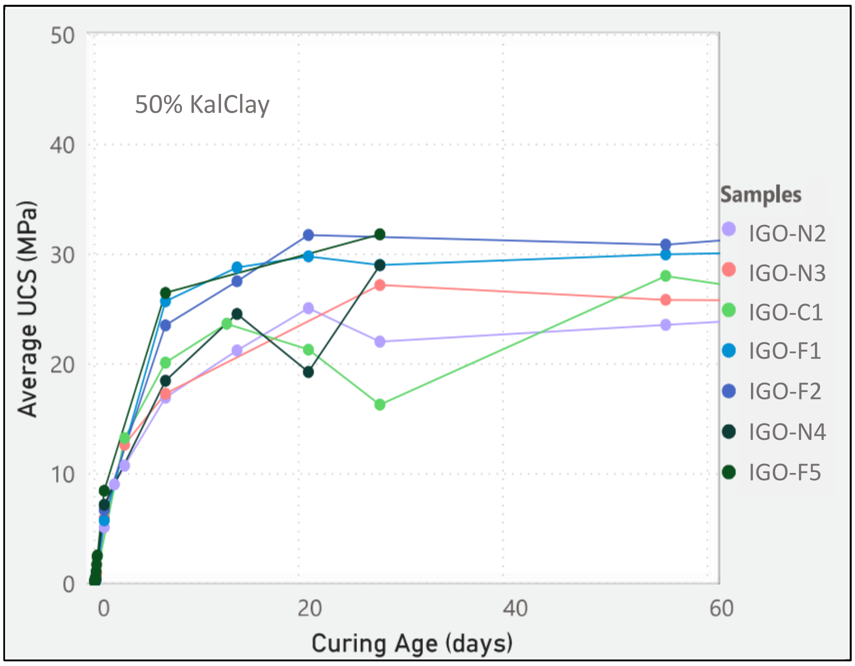


Figure 11: Long term strength of shotcrete for cement-KalClay mixes at IGO Limited

6 CONCLUDING REMARKS

The research results presented here indicate that a significant proportion of the cement component of a shotcrete mix can be replaced by the KalClay material. The percentage of replacement can vary according to the expected rock mass demand of early and long-term strength for a particular shotcreting application. The cost saving for a 50% replacement is estimated in the range of 25-30% with a 40% CO_2 emission reduction.

Also, for a similar curing age, the early strength for a shotcrete mix having equal proportions of cement-KalClay is greater than a conventional mix using cement only. This presents an opportunity for productivity improvement due to a decreased re-entry time. The re-entry time can be safely engineered using block theory calculations that rely on shear strength.

The long-term strength for a shotcrete mix having equal proportions of cement-KalClay provides sufficient shear strength capacity for ground support schemes that incorporate a typical rock bolting pattern. In addition, the strength development is uniform, and the failure mechanism is a soft, non-violent failure with much less micro-seismicity, as shown in Figure 12. This is important to minimize shotcrete ejection during large violent rupture following a seismic event while mining under high stress.

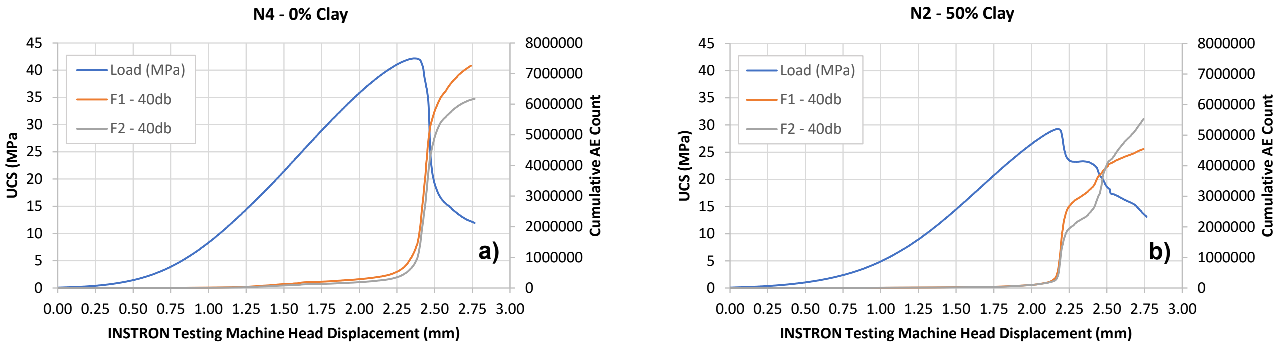


Figure 12: Micro-seismic response during sample loading a) conventional cement mix and b) 50% KalClay component

7 ACKNOWLEDGEMENTS

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