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ABSTRACT

In-Cycle shotcrete is an important component of support for many underground excavations in rock. In particular, the safe re-entry time after shotcrete has been sprayed needs to be considered as it influences the productivity associated with development. It is proposed that the shear strength of the shotcrete matrix is a better parameter to consider than the Uniaxial Compressive Strength of the overall shotcrete material including coarse aggregate. A number of shotcrete paste mixes were prepared and evaluated for strength gain. It was found generally that the shear strengths of shotcrete pastes increase exponentially during the first 4 to 8 hours of curing in all shotcrete mixes except when the pastes included a hydration stabiliser. It was found for shotcrete mixes with accelerator, synthetic fibres and aggregates that an average layer of about 50mm thickness develops sufficient shear strength of about 20kPa within about one hour to support a tetrahedral block with 1m edge lengths and the layer mass. For the same shotcrete layer, it was found that a cubic metre block and the shotcrete layer can be supported within about 3 hours and 50 minutes when the shotcrete shear strength is estimated to be approximately 97kPa.

1. INTRODUCTION

Shotcrete is a surface support technique in which a specially mixed concrete is sprayed at high speed onto rock excavation surfaces to improve rock mass integrity and assist load carrying capacity. The benefits of using shotcrete compared with other ground support techniques have been demonstrated particularly where the rock mass is of poor quality, has short stand-up times and is easily disturbed when attempting to scale or to drill boreholes for the installation of reinforcement and mesh. Wet mix shotcrete is now widely accepted in mines throughout the world, particularly those prone to violent rock failure due to induced stress changes. In Australian mines, the use of shotcrete has continued to grow since the late 1980s due to its success in stabilising excavations. 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. In terms of economics, there is also the necessity to minimise development costs. In particular, faster development rates are required with lower ground support costs and increased safety. All of these objectives may be achieved in certain rock conditions using In-Cycle Shotcrete (ICS).

In the true engineering sense, ICS involves precise mark-up and drilling of face holes (using modern drilling jumbos), blasting (using careful blasting techniques), water jet scaling (using specialised hydro-jetted machines), high quality shotcrete (using modern shotcrete machines) with a timed re-entry into the excavation followed by rock bolting.

Figure 1 shows a typical underground mining process incorporating shotcrete which takes 9 hours and 15 minutes to excavate a 5.3m x 5.5m x 3m (Width x Height x Advance) tunnel (O'Shea, 2005). It can be seen that the re-entry time is a significant component of the toal cycle time.

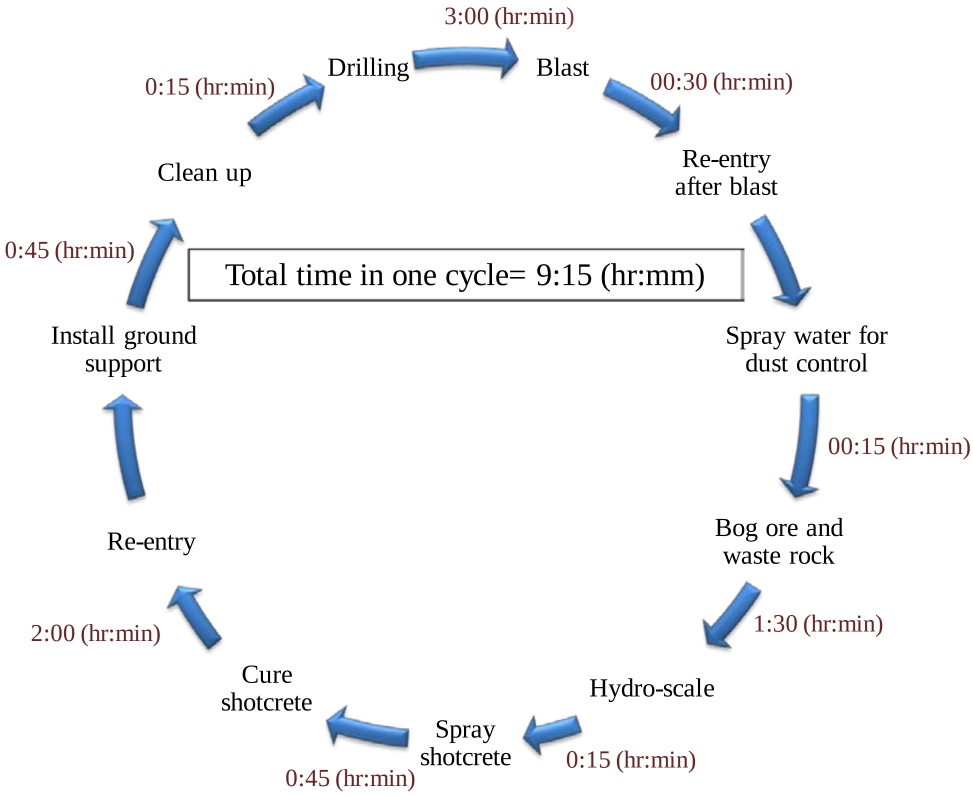


Figure 1. Underground mining process with ICS,
(Width = 5.3m, Height = 5.5m, Advance = 3m. shotcrete thickness = 50mm)
(Modified after O'Shea, 2005).

2. REVIEW OF SHOTCRETE EARLY STRENGTH

Re-entry time presents a conflict between increased productivity and workplace safety. The current literature does not sufficiently address the issue of re-entry time. Currently, re-entry times range from 2 to 4 hours based on the time when the Uniaxial Compressive Strength (UCS) of shotcrete based on penetration resistance reaches 1MPa. Many early strength shotcrete data collected according to ASTM C403 have been published (e.g. Jolin et al., 1999, Rispin, 2003, Clements, 2004, Knight et al., 2006, O'Toole & Pope, 2006 and Bernard, 2008). Figure 2 shows the UCS of shotcrete at various curing times determined by the penetration resistance method published by different authors.

The implication of UCS reaching 1MPa as a benchmark for re-entry time is somewhat confusing. Figure 3 shows a sketch of a shotcrete layer undergoing shear, a combination of shear and compression, and a combination of shear and tension (Windsor, 1999). Based on these mechanisms, it is the shear strength of the shotcrete and possibly its tensile strength and adhesion with the underlying rock that are critical. The shear strength of a fresh (immediately after it has been sprayed) shotcrete is the strength that it can resist subject to shear loading imposed by the rock mass during service.

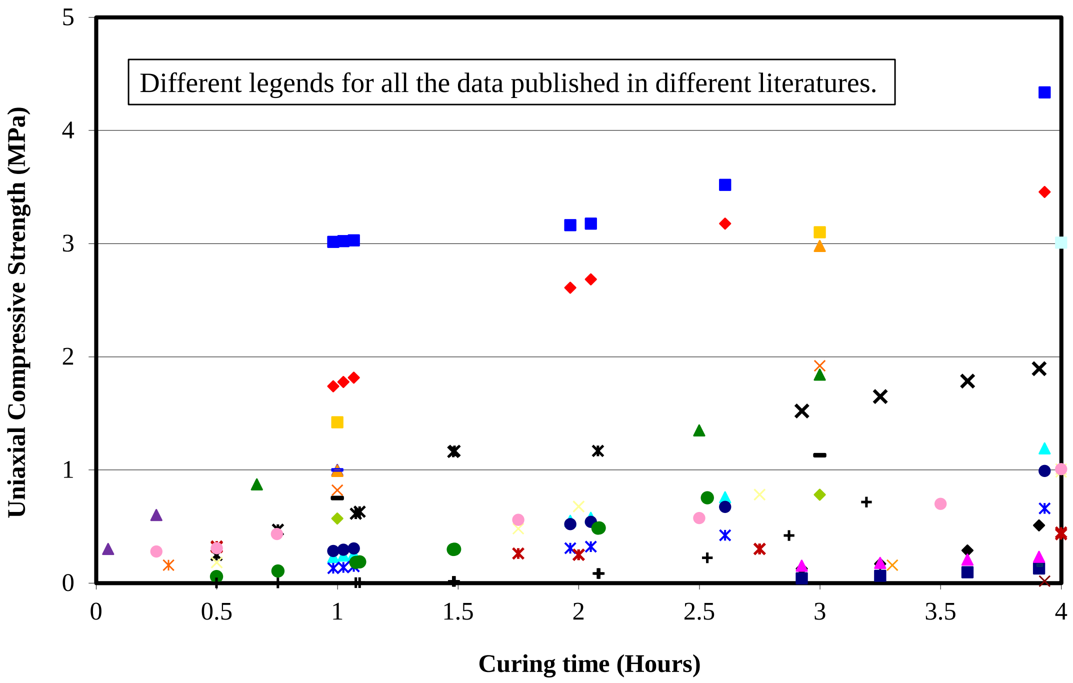


Figure 2. Typical UCS of shotcrete determined by penetration resistance.

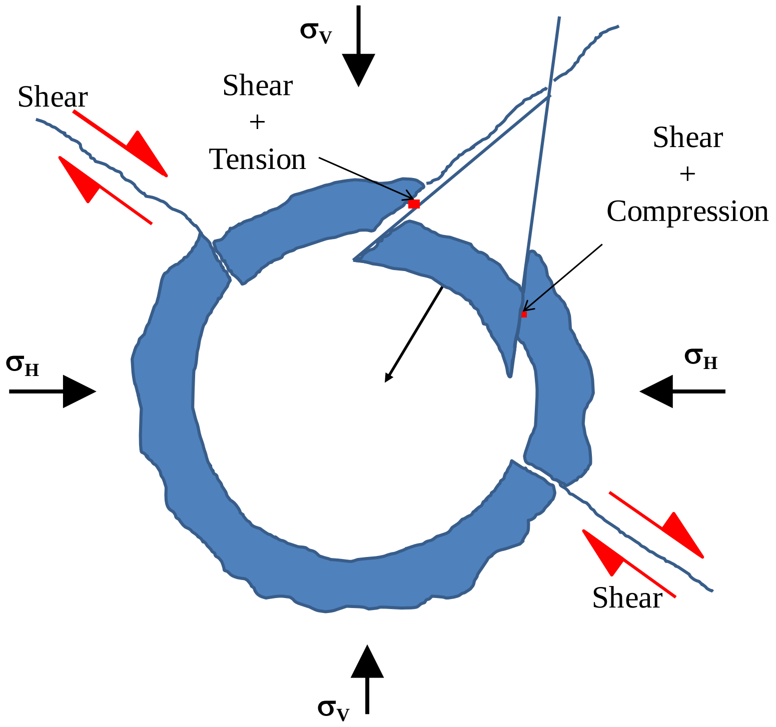


Figure 3. Shotcrete layer undergoing shear, a combination of shear and compression, and a combination of shear and tension (Windsor, 1999).

3. FRESHLY SPRAYED SHOTCRETE

3.1 Constituents

Shotcrete is a designed material which comprises cement, supplementary cementing minerals, fine and coarse aggregates, chemical admixtures, water and commonly includes reinforcing fibres. It consists of separate component solids and fluids which are combined, mixed, pumped and sprayed to form a heterogeneous but uniform layer of solids and fluids that harden into a solid concrete layer. The mechanical properties of shotcrete change as the cementitious materials hydrate from a viscous fluid to a paste and then harden to a solid. The physical, chemical and mechanical properties of each of these constituent materials affect the mechanical properties of the gelling, setting and hardening shotcrete. The constituent materials and their proportions in a typical shotcrete mix used in underground mining operations are listed in Table 1.

Table 1. The range of constituent materials in a typical shotcrete mix.

<table>
<tr><th colspan="2">Constituents</th><th>Dry mix</th><th>Wet mix</th><th>Unit</th></tr>
<tr><td colspan="2">Cement</td><td>400 - 420</td><td>400 - 450</td><td rowspan="7">kg/m^3</td></tr>
<tr><td colspan="2">Fine aggregate (fine to coarse sand)</td><td>1380 - 1510</td><td>1110 - 1180</td></tr>
<tr><td colspan="2">Coarse aggregate (maximum 9 - 12.5 mm)</td><td>235 - 400</td><td>500 - 535</td></tr>
<tr><td colspan="2">Water</td><td>150 - 200</td><td>175 - 200</td></tr>
<tr><td rowspan="3">[1]Mineral additive (supplementary cementing materials)</td><td>Silica fume</td><td colspan="2">20 - 50</td></tr>
<tr><td>Fly ash</td><td colspan="2">20 - 75</td></tr>
<tr><td>Granulated blast-furnace slag</td><td colspan="2">20 - 50</td></tr>
<tr><td rowspan="5">[1 & 2]Chemical admixture</td><td>Air-entraining</td><td colspan="2">0.3 - 0.5</td><td rowspan="5">litre/m^3</td></tr>
<tr><td>Accelerator</td><td colspan="2">20 - 22</td></tr>
<tr><td>Hydration stabiliser</td><td>-</td><td>1- 2</td></tr>
<tr><td>Water reducer</td><td>-</td><td>1 - 2</td></tr>
<tr><td>Superplasticiser</td><td>-</td><td>3 -7</td></tr>
<tr><td colspan="2">□Steel fibres</td><td colspan="2">30 - 40</td><td>kg/m^3</td></tr>
<tr><td colspan="2">[4]Synthetic fibres</td><td colspan="2">5 -8</td><td>kg/m^3</td></tr>
</table>

1. Different types of mineral additive may be used in a particular mix.
2. Chemical admixture dosage should follow manufacturer's guidelines.
3. For steel fibre reinforced shotcrete.
4. For synthetic fibre reinforced shotcrete.

3.2 Physical and Mechanical Properties

There are two conflicting requirements for a shotcrete mix. Firstly, it must have the rheological properties of a fluid in order 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 sizes and proportions which in turn affect the mechanical properties of the in situ paste, its hardening and the mechanical properties of the final solid layer.

The physical properties of the solid layer that are important are its density (void ratio and permeability). However, the mechanical properties of the 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.

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 the coarse aggregate particles 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 or shotcrete paste (hereafter referred to as 'shotcrete paste'). Therefore it is predominantly the changes with time of the curing shotcrete paste that will indicate the mechanical response of freshly sprayed shotcrete.

4. DEVELOPMENT OF SHEAR STRENGTH OF SHOTCRETE PASTE WITH CURING TIME

The shear strength of shotcrete pastes without chemical accelerator can be determined using a standard vane shear test apparatus such as a viscometer (VT550) from 0 to 3 hours curing. During this period the hydration products in the shotcrete pastes are in the fluid gel state. After 3 hours, the hydration products start transforming into a solid gel state and its shear strength cannot be determined with the standard vane shear test apparatus. After about 4 hours, the shear strength of shotcrete pastes can usually be determined using the conventional triaxial compression test method. The shear strength is estimated using the Mohr-Coulomb shear failure criterion. That is:

$$\tau = c + \sigma_n \tan\phi \tag{1}$$

where, (τ) and (σ_n) represent shear stress and normal stress, respectively. The parameters (c) and (ϕ) are assumed to be constants called the cohesion and the angle of internal friction. In reality, 'c' and 'ϕ' change with stress level. In this research, the normal stress (σ_n) is considered to be insignificant. Therefore, the minimum shear strength is essentially its cohesion (c) based on Equation 1.

4.1 Development of shear strength of shotcrete paste with and without the influence of a chemical admixture

Summaries of the shear strength development of shotcrete pastes with and without the influence of chemical admixtures for the first 4 and 8 hours of hydration are presented in Figures 4 and 5, respectively. The chemical admixtures were added at the dosage recommended by the manufacturer of that particular admixture as detailed previously in Table 1.

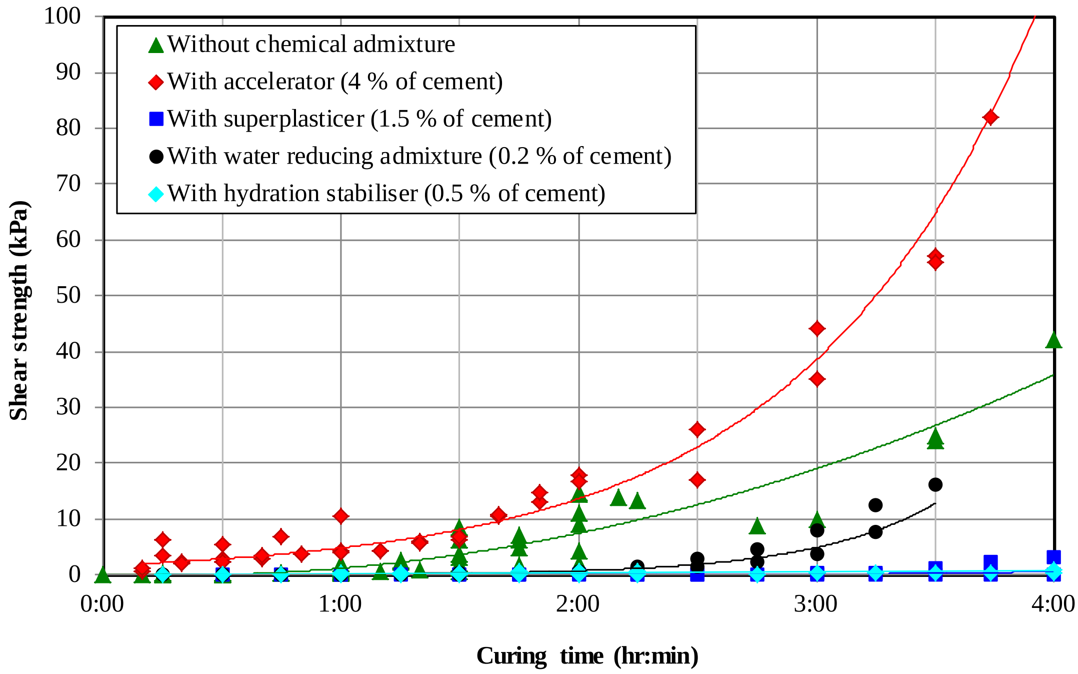


Figure 4. Shotcrete paste shear strength development without and with the influence of chemical admixtures during the first (4) hours of hydration.

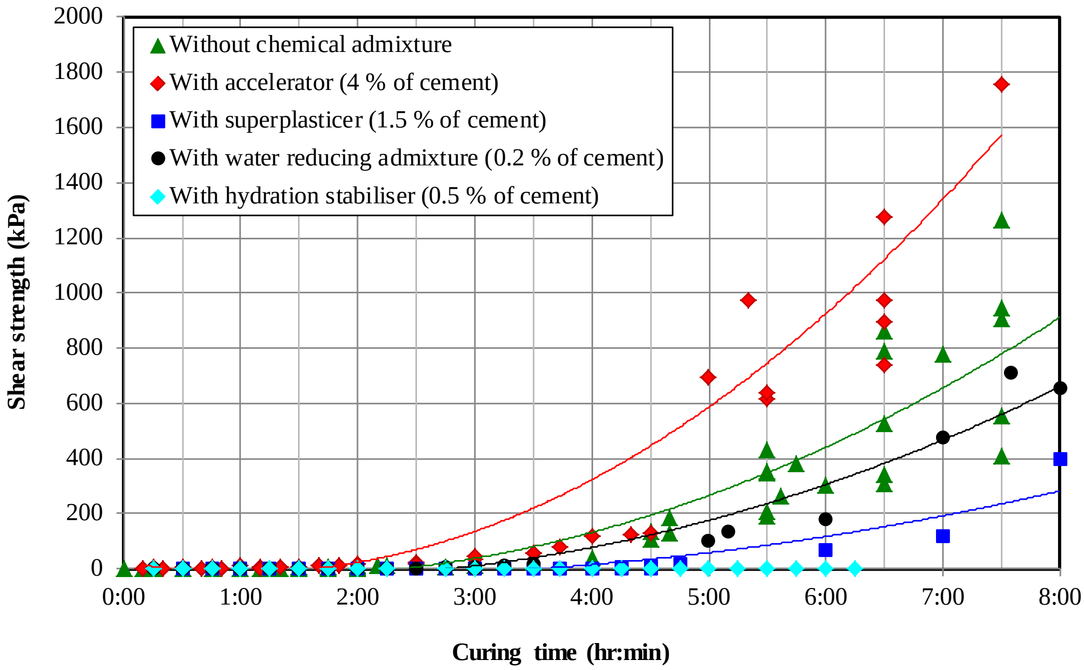


Figure 5. Shotcrete paste shear strength development without and with the influence of chemical admixtures during the first (8) hours of hydration.

The results show generally that the shear strength increases rapidly during the first 4 to 8 hours of curing in all shotcrete paste mixes except for the shotcrete paste mixed with a hydration stabiliser. The shear strengths of shotcrete pastes mixed with accelerator were significantly higher than those of shotcrete pastes mixed without chemical admixtures. The shear strengths of shotcrete pastes mixed with water reducing admixtures were slightly lower than that of shotcrete pastes mixed without chemical admixtures. The shear strengths of shotcrete pastes mixed with superplasticer were significantly lower than those of shotcrete pastes mixed without chemical admixtures. The shear strengths of shotcrete pastes mixed with hydration stabiliser were significantly lower than that of shotcrete pastes mixed without chemical admixtures.

4.2 Pull-out testing of synthetic fibres encapsulated with shotcrete paste

A test method developed by the writers was used to investigate the pull-out strength of synthetic fibres from within shotcrete paste.

The mechanical properties of the Shogun Barchip synthetic fibre used in these investigations are given in Table 2.

Table 2. Mechanical properties of synthetic fibre.

Length (mm)	Width (mm)	Thickness (mm)	Tensile strength (MPa)	* Axial force capacity (N)	*Bond strength required to break the fibre with 24 mm embedment (MPa)
48	0.65	1.22	550	436.15	22.92

Note: * Calculated based on the product information
(Elasto Plastic Concrete, 2011).

The testing procedure comprises:

- A "C" shaped steel pipe of 50 mm diameter was cut in half to simulate a crack.
- A layer of shotcrete paste was cast inside the steel pipe. A single synthetic fibre was installed with the midpoint of the fibre at the simulated crack as shown in Figure 6.
- Another layer of shotcrete paste was cast to cover the fibre.
- A tension test was conducted to determine the pull-out resistance.

The set up for the pull-out test conducted using an Avery Universal Testing Machine is shown in Figure 7 (a). Figure 7 (b) shows a completely pulled-out (24mm) fibre following completion of the pull-out test.

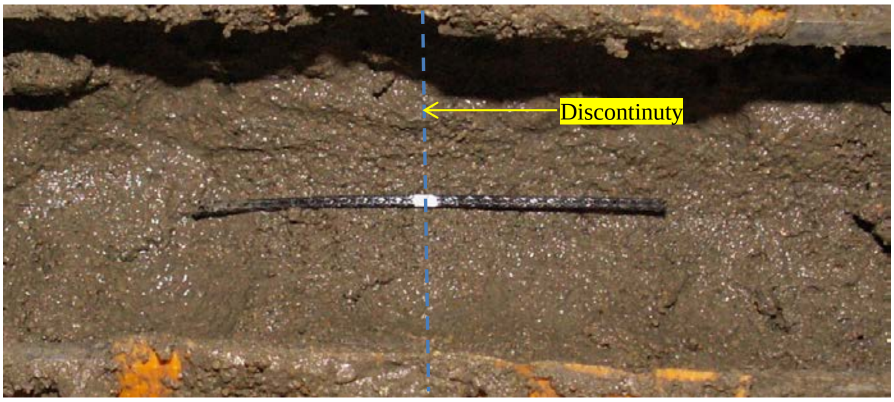
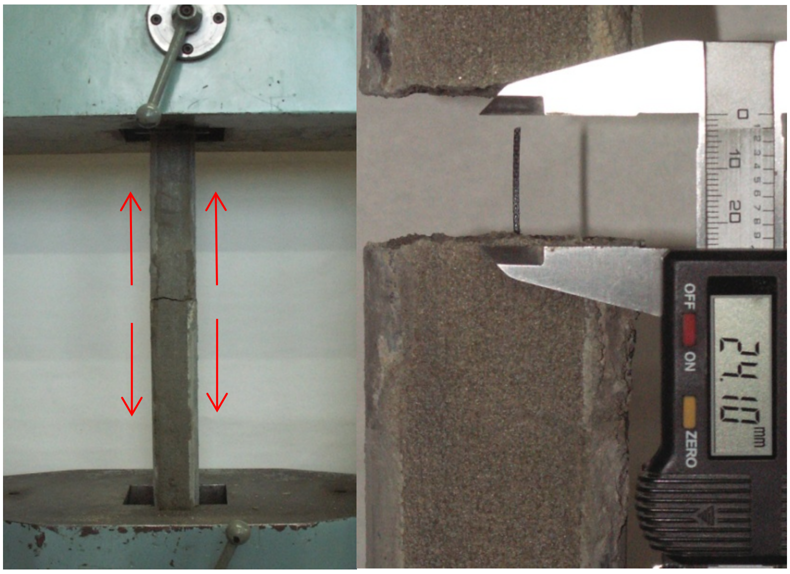


Figure 6. Installation of synthetic fibre across a simulated discontinuity for pull-out testing.



(a) (b)

Figure 7. (a) The fibre pull-out test using an Avery Universal Testing Machine, and,
(b) the fibre after pull-out.

A summary of the pull-out strength test results are presented in Table 3. The results show that the pull-out strengths at ages from 3 to 4 hours and 6.5 to 8 hours range from 0.3 to 0.6MPa and 0.9MPa, respectively. Given that minimum bond strength of 23MPa is required to break the fibre, the early age load transfer of the fibre is insignificant. Therefore, the strength of shotcrete paste comprising synthetic fibres and accelerator is mainly controlled by the shear strength of the shotcrete paste matrix.

Table 3. Synthetic fibre pull-out test results.

Curing time (hour:minute)	Fibre			Pull-out load (N)	Nominal-bond strength (MPa)
	Embedment length (mm)	Width (mm)	Thickness (mm)		
3:30	24	0.65	1.22	23	0.3
4:30	24	0.65	1.22	50	0.6
6:30	24	0.65	1.22	80	0.9
8:00	24	0.65	1.22	80	0.9

4.3 Development of shear strength of shotcrete paste with various combinations of mix components

Figure 8 shows the shear strengths of shotcrete pastes with accelerator, shotcrete pastes reinforced with synthetic fibres and accelerator, and shotcrete pastes reinforced with synthetic fibres, aggregates and accelerator for the first 4 hours for curing. The components were given previously in Table 1. The shear strengths of shotcrete pastes reinforced with synthetic fibre, aggregates and accelerator were slightly higher than those of shotcrete pastes mixed with synthetic fibres and accelerator. The shear strengths of shotcrete pastes reinforced with synthetic fibre, aggregates and accelerator were significantly higher than those of shotcrete pastes with only accelerator. The test results suggest that the addition of aggregates (sand and coarse aggregate) increased the cohesiveness of the paste and resulted in increased shotcrete shear strengths at an early age.

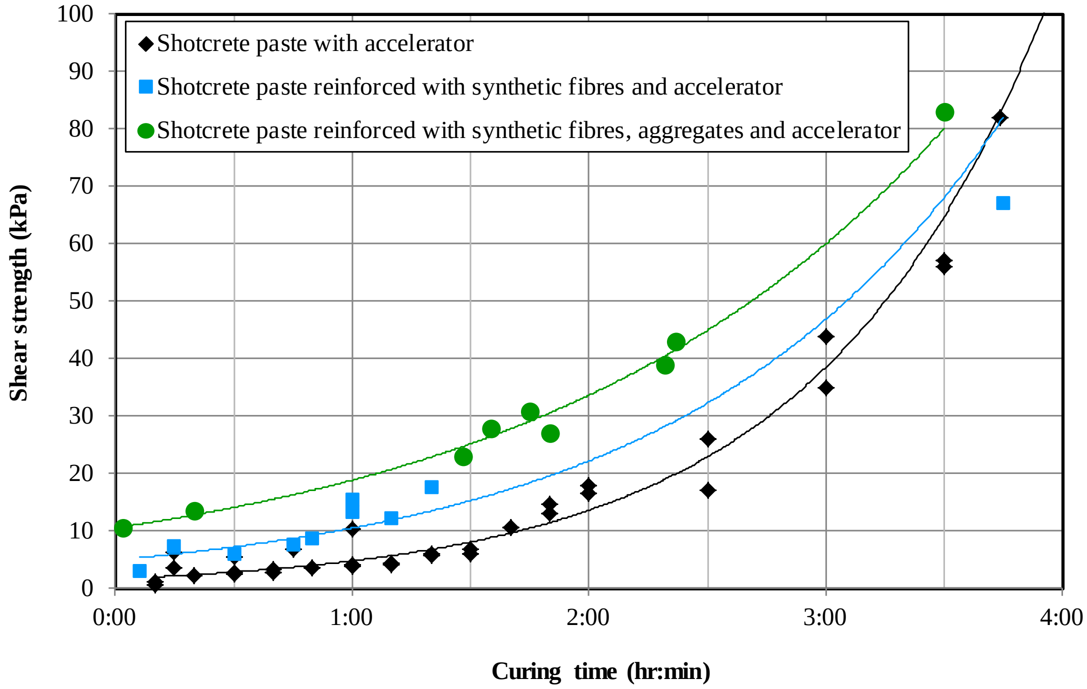


Figure 8. The development of shear strength in shotcrete pastes with accelerator, shotcrete pastes reinforced with synthetic fibres, and shotcrete pastes including coarse aggregate and reinforced with synthetic fibres (all during the first 4 hours of curing).

5. STRUCTURAL REUIREMENTS FOR A FRESHLY SPRAYED SHOTCRETE LAYER

There are two structural requirements 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 superincumbent 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. Consider a one metre square block of rock which could be formed within a typical 1.2 x 1.2 metre rockbolt patten used in the mining industry interacting with a shotcrete layer having a thickness (t_s) and unit weight of (γ_s) as shown in Figure 9.

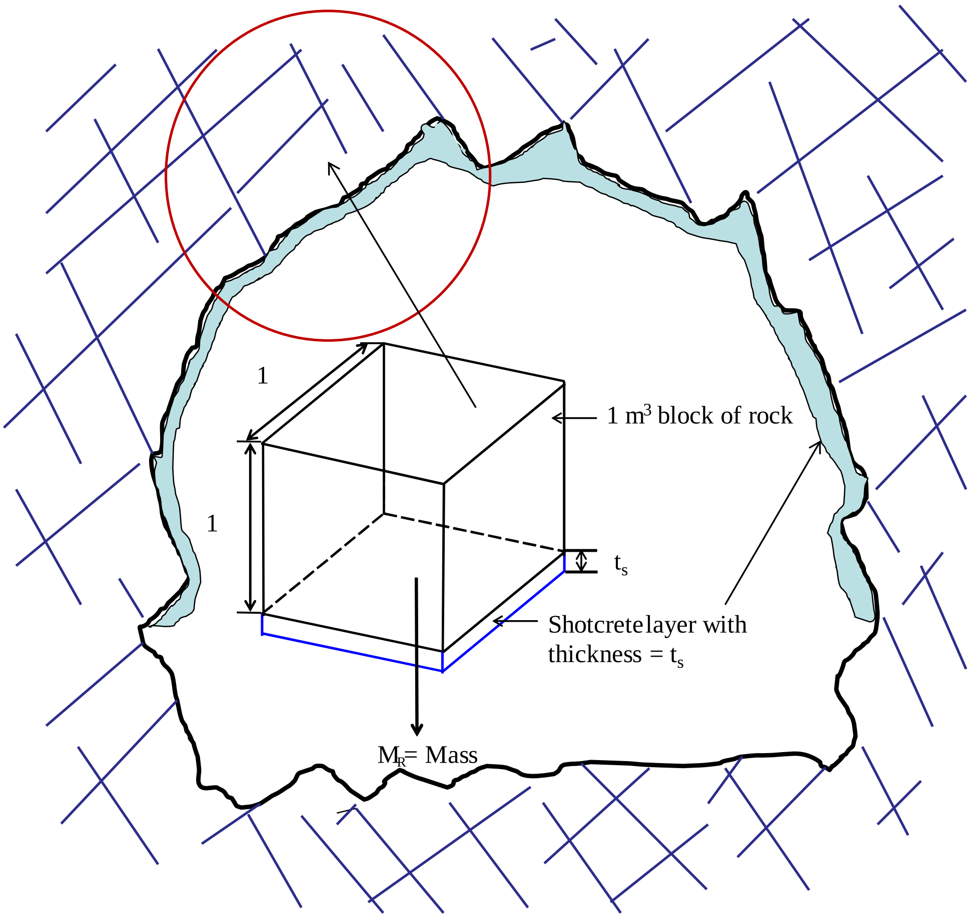


Figure 9. A 1 m^3 block of rock interacting with a shotcrete layer of thickness (t_s).

5.1 Requirements for self support

In the case of zero shotcrete shear strength, the minimum bond strength (σ_{VS}) required for the shotcrete layer is equal to the vertical stress due to its own weight. This may be calculated as

$$\sigma_{VS} = \gamma_S \ t_S \tag{2}$$

A typical unit weight of synthetic fibre reinforced shotcrete is 23kN/m^3. Therefore, the minimum bond strength required for a shotcrete layer thickness measured in mm is about $\gamma_s \ t_s / 1000$ kPa (or about $0.023t_s$ kPa).

Figure 10 shows a shotcrete layer and a potential shear failure plane within the layer.

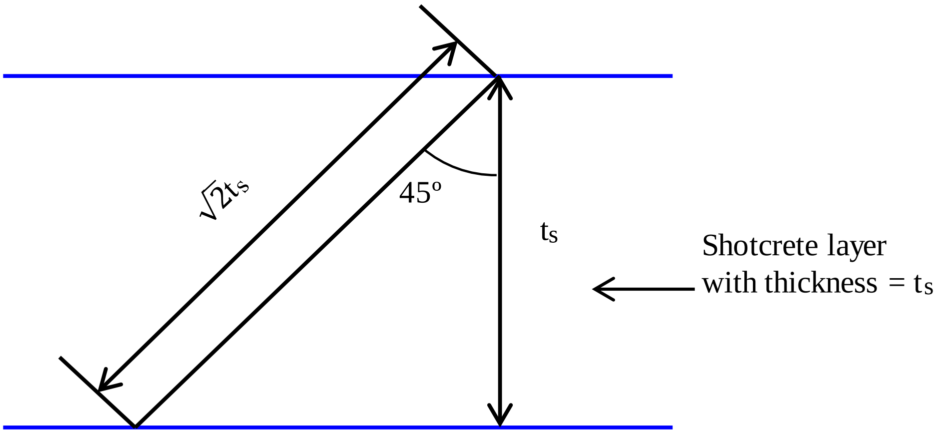


Figure 10. Thickness of shotcrete along the expected shear plane.

In the case of zero bond strength, the minimum shear strength required for shotcrete to support its own weight is calculated from:

$$\tau_S = \frac{F_S}{A_S} \tag{3}$$

where τ_S = shear strength of shotcrete (kPa)
F_S = force (kN) due to self-weight of shotcrete layer
A_S = cross sectional area (m^2) of the shear plane

For calculation purposes, the cross sectional area is given by

$$A_S = L_S \sqrt{2}\, t_S \tag{4}$$

where L_S is the average length of the shear surface

In general, the equation for the force due to gravity is

$$F_S = V_S\ \gamma_S \tag{5}$$

where V_S = volume of shotcrete (m^3)

Therefore, Equation (3) may be rewritten and the shear strength calculated from:

$$\tau_S = \frac{V_S\ \gamma_S}{L_S\ \sqrt{2}\ t_S} \tag{6}$$

The volume of shotcrete (V_S) supporting a 1 m^3 block of rock is given approximately by:

$$V_S = 1 \text{ x } 1 \text{ x } t_S \tag{7}$$

Substituting Equation (7) into Equation (6)

$$\tau_S = \frac{1^2 \, t_S \, \gamma_S}{L_S \sqrt{2} \, t_S} \tag{8}$$

By eliminating "t_s" from Equation (8), the required shear strength of shotcrete is given by:

$$\tau_S = \frac{\gamma_S}{L_S \sqrt{2}} \tag{9}$$

For a 1m square face, L_S = 4m. Therefore, the minimum required shear strength is:

$$\tau_S = \frac{23}{4\sqrt{2}} = 4\text{kPa} \tag{10}$$

That is, the minimum shear strength required for shotcrete to support its own weight is typically about 4kPa.

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 achieved.

5.2 Required shotcrete shear strength for self-weight and block support

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 the excavation. The volume of loose rock that may become unstable is naturally minimised during blasting by waves that vibrate the excavation surfaces and by subsequent hydro-scaling procedures that clean the excavation surfaces.

The specific arrangement of excavation span, stress and structural geology associated with each excavation will be different and the specification of a single or standard unstable volume of rock is not possible. However, example calculations may be used to show that within a few hours of spraying, shotcrete is quite capable of supporting a significant volume of unstable rock and that this volume or mass of rock may be calculated as a function of layer thickness and time after spraying.

Two scenarios will be considered: Firstly, the one cubic metre block shown in Figure 9 and secondly, the equilateral tetrahedral block of rock with 1 metre side lengths as shown in Figure 11. If the latter block existed in the roof of an underground excavation, its face triangle (i.e. the expression of its shape visible in the roof when viewed from beneath) would be an equilateral triangle with side lengths 1 metre.

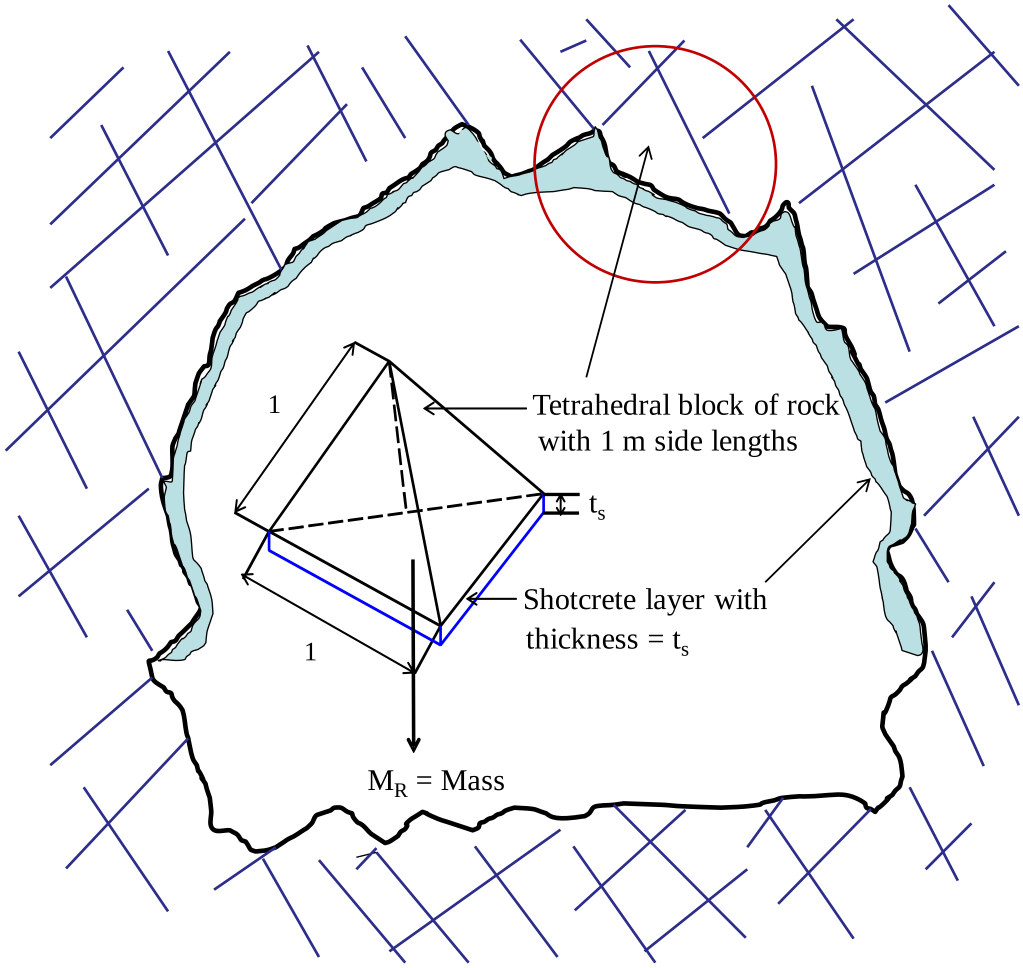


Figure 11. An equilateral tetrahedral block of rock with shotcrete layer with thickness (t_s).

The minimum shear strength required for shotcrete to support these two blocks with 1 metre side lengths can be calculated from:

$$\tau_S = \frac{F_T}{L_S \sqrt{2}\, t_S} \tag{11}$$

where F_T = total force to be resisted by the shotcrete in shear = $F_S + F_R$ (12)

and $F_R = M_R\, g$ (MR is mass of rock and g = gravitational acceleration assumed to be 9.81 m/s^2)
L_S = 4m (for 1 metre cube block)
L_S = 3m (for equilateral tetrahedral block of rock with 1 metre side lengths)

The minimum shear strength required for shotcrete with different thickness to support the two different shaped blocks are shown in Figure 12.

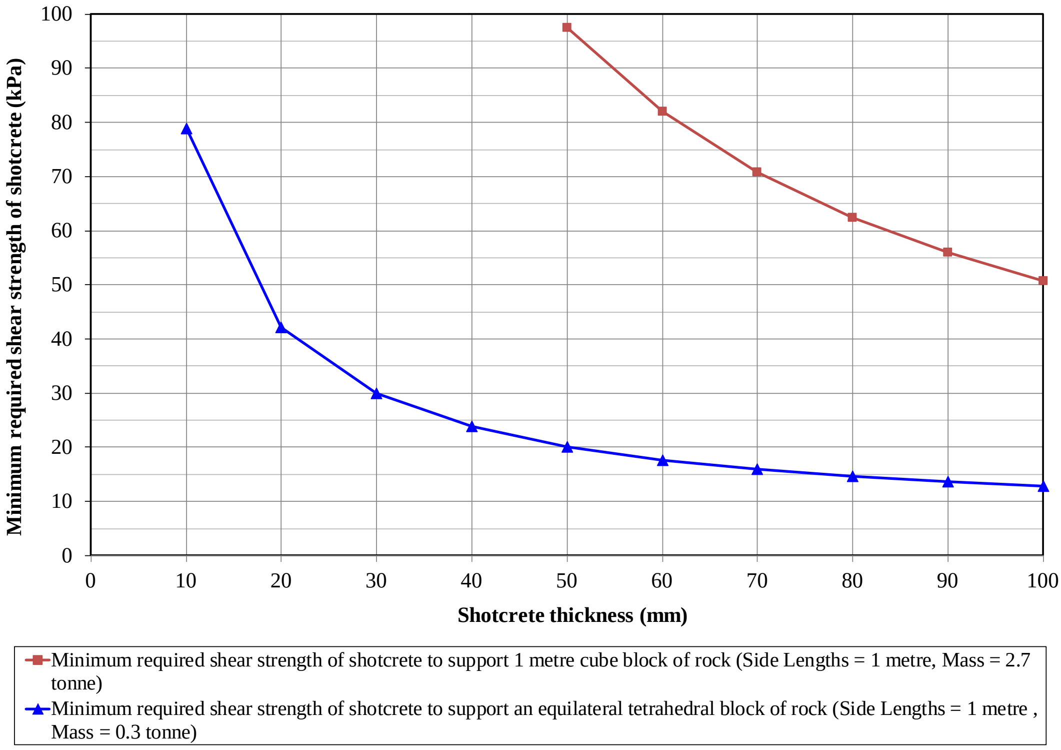


Figure 12. Minimum shear strength required for shotcrete with different thickness to support a 1 metre cube block of rock and an equilateral tetrahedral block of rock with 1 metre side lengths.

6. SAFE RE-ENTRY TIME

The safe re-entry time for ICS in underground mine excavations for a given shotcrete thickness can be calculated from a correlation between a minimum shear strength required to develop in freshly sprayed shotcrete in order to support itself and a 1 metre cube block of rock or an equilateral tetrahedral block of rock with 1 metre side lengths as described earlier together with the development of shear strength of shotcrete paste with curing time as described in section 4.

Figure 13 shows the shear strength required to be developed for different thickness layers of shotcrete to support the layer and a one metre cube block of rock. It was computed for a rock with an average unit weight of 27kN/m^3 (this is a common assumption for most rock types) and results in a total mass of the block of 2700kg. The graphs show that an average shotcrete layer of about 50mm thickness needs to develop a shear strength of about 97kPa. This level of shear strength will develop at about 3 hours and 50 minutes after spraying, for a shotcrete mix with accelerator, synthetic fibres and aggregates.

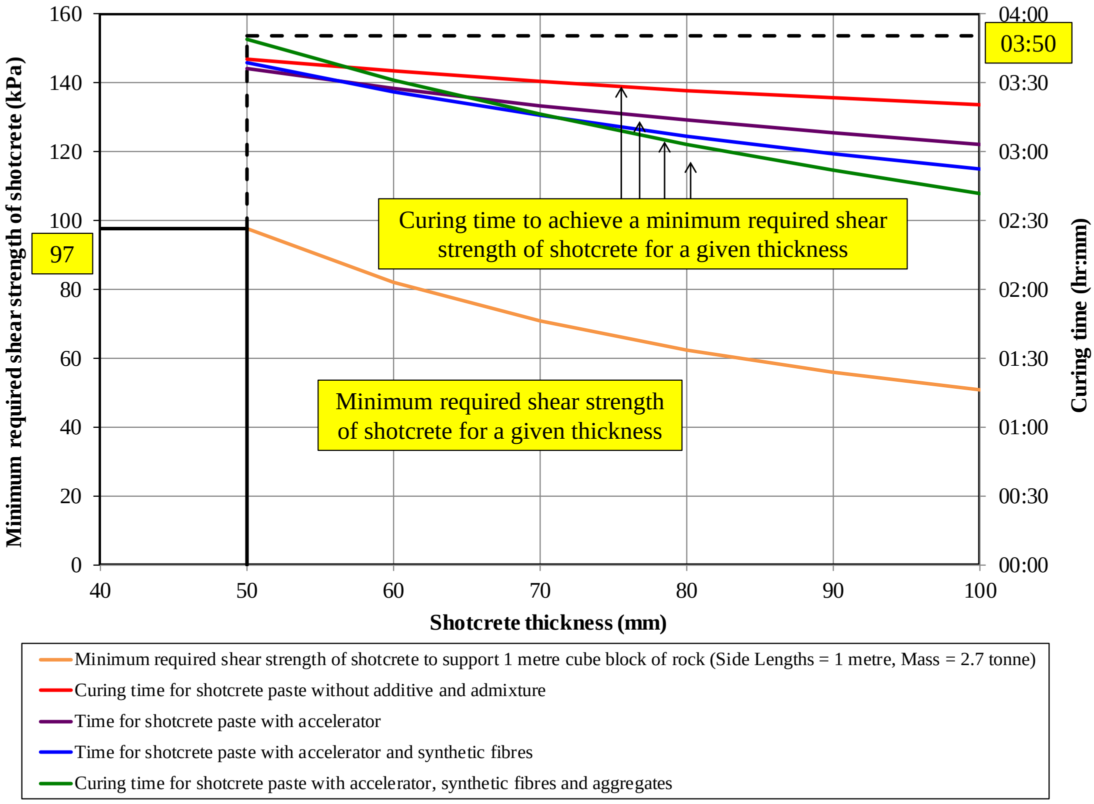


Figure 13. A graph of minimum shear strength required to develop in a shotcrete layer in order to support itself and a one cubic metre block of rock.

Figure 14 shows the shear strength required to be developed for different thickness layers of shotcrete to support an equilateral tetrahedral block of rock with 1 metre side lengths in addition to supporting its own mass. In this example it is computed for a rock with an average unit weight 27kN/m^3 which results in a total mass of the block of 300kg. The graph shows that an average shotcrete layer of about 50 mm thickness needs to develop a shear strength of about 20kPa. This level of shear strength will develop at about one hour after spraying, for a shotcrete mix with accelerator, synthetic fibres and aggregates. It is clear that additional curing time will be required for thinner layers of shotcrete prior to safe re-entry.

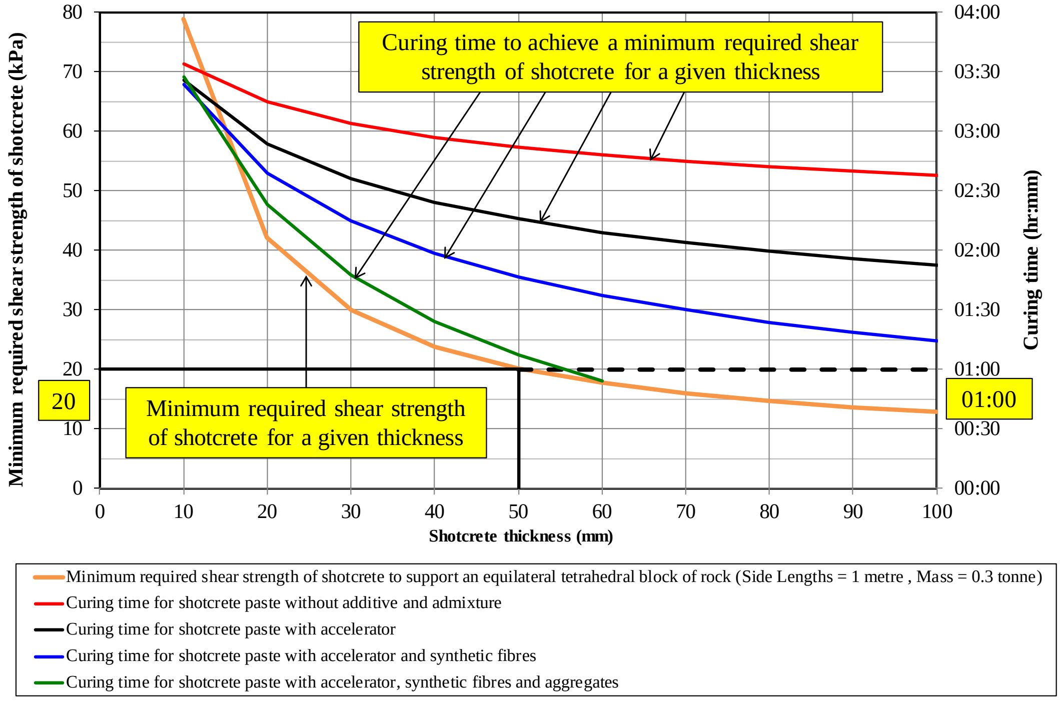


Figure 14. A graph of minimum shear strength required to develop in a shotcrete layer in order to support itself and an equilateral tetrahedral block of rock with 1 metre side lengths.

7. CONCLUSIONS

Currently, re-entry times range from 2 to 4 hours based on the time when the Uniaxial Compressive Strength of shotcrete determined by a penetration test reaches 1MPa. The implication of a UCS value of 1MPa as a benchmark for re-entry time is somewhat confusing since the resistance of shotcrete to rock failure is provided mainly by its shear strength and possibly its adhesive strength to the rock substrate. There are two structural requirements of the 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 super incumbent mass of an estimated unstable volume of rock. The minimum shear strength required for shotcrete to support its own weight is typically about 4 kPa. It was found that an average shotcrete layer of about 50 mm thickness needs to develop a shear strength of about 97kPa to support a 1 cubic metre of rock (2.7 tonne) in addition to supporting its own mass. That level of shear strength will develop at about 3 hours and 50 minutes after spraying for a shotcrete mix with accelerator, synthetic fibres and aggregates. It was also found that an average shotcrete layer of about 50mm thickness needs to develop a shear strength of about 20kPa to support an equilateral tetrahedral block of rock with 1 metre side lengths (0.3 tonne) in addition to supporting its own mass. That level of shear strength will develop at about one hour after spraying for a shotcrete mix with accelerator, synthetic fibres and aggregates.

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