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PERFORMANCE OF SHOTCRETE SURFACE SUPPORT FOLLOWING DYNAMIC LOADING OF MINING EXCAVATIONS

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ABSTRACT

Shotcrete is commonly used as surface support for deep underground mining excavations in order to dissipate the energy of violent rock mass failures. Laboratory strength testing data and field observations indicate that the optimum arrangement of surface support is to reinforce shotcrete with fully encapsulated steel mesh. Integration of shotcrete and mesh in this manner increases the energy dissipation capacity of the surface support system, maximises load transfer to reinforcement and ensures that both components of the surface support system are simultaneously and equitably loaded. If ultimately loaded to failure, mesh reinforced shotcrete often fails in large blocks defined by the reinforcement pattern. This mode of failure is indicative of continuous surface support containment capacity between adjacent reinforcement elements.

INTRODUCTION

Shotcrete is a surface support product in which specially mixed concrete is sprayed at high speed onto rock excavation surfaces to achieve rock mass integrity and load carrying capacity. It is particularly useful where the rock mass is of poor quality and is now widely accepted throughout the global mining industry, particularly in deep mines which are prone to violent rock failure due to mining induced stress changes (Villaescusa, 2014). Shotcrete provides consolidation of the zone of loose rock around the excavation boundary, ideally penetrating small perimeter fractures to provide confinement to the rock mass between adjacent reinforcement elements (Thompson, et al., 2012). The batch design of shotcrete may include thin steel or plastic fibres within the concrete matrix. Such products are referred to as fibre-reinforced shotcrete.

The layers of shotcrete lining an excavation may deform plastically when subjected to dynamic loading (Saw, et al., 2012). Barrett & McCreath, 1995, identifed six possible shotcrete failure mechanisms. These include adhesion loss, flexural, direct shear, punching shear, compressive and tensile failure. These mechanisms are illustrated in Figure 1. The individual prevalence of each mechanism of shotcrete failure is heavily dependent upon the rock mass failure mechanism, which defines the characteristics of the loading mass and its associated displacements.

Adhesion loss and flexural failure are considered to be the most common forms of shotcrete failure (Holgrem, 1976, Fernandez-Delgado, et al., 1976). Adhesion failure may occur due to debonding of shotcrete from low friction rock surfaces. Flexural failure is generally associated with rock mass bulking and may occur following a wide variety of rock mass failure mechanisms. The direct shear failure mechanism requires that a differential load act on the shotcrete layer across a very narrow boundary. Displacements associated with shear rupture of geological discontinuities oriented sub perpendicular to the excavation surface could generate such loading conditions.

Punch shear failure of shotcrete is most often observed where the dynamic loading demand on the ground support scheme is high. This mechanism is more likely to occur in highly stressed rock masses where the shotcrete is retained by pattern reinforcement. Compressive failure is a common observation in high rock stress environments and may also be referred to as shotcrete spalling. This mode of failure may present in excavations where high stress concentrations are oriented tangential to the excavation surface, such as the roof of excavations subject to high horizontal stress or walls of excavations subject to high vertical stress. Tensile failure of shotcrete is rare in straight-line development. Most often it can be seen in the apex of intersection pillars where the rock mass is exposed in two directions. It may also be observed in wide span excavations.

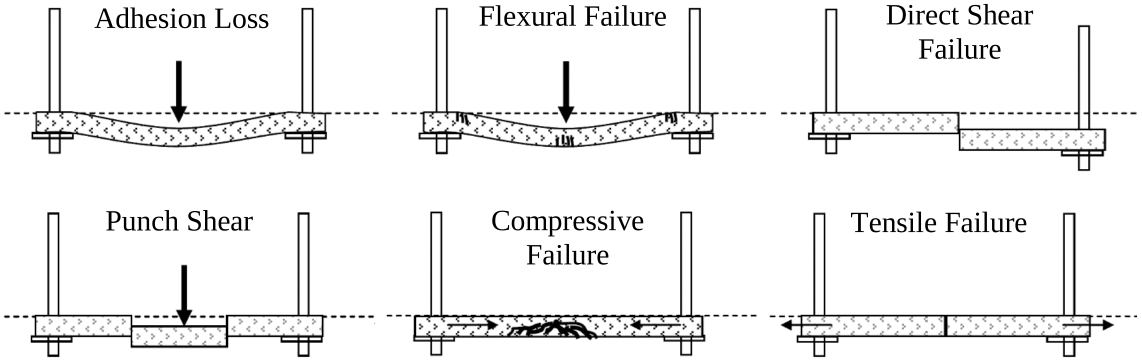


Figure 1 - Shotcrete failure mechanisms (Morton, et al., 2009, modified after Barrett & McCreath, 1995).

SHOTCRETE STRENGTH TESTING

Large shotcrete samples have been tested at the WA School of Mines under both static (Morton, et al., 2009) and dynamic (Villaescusa, et al., 2010) loading conditions. The static results shown in Figure 2 illustrate the force-displacement and cumulative energy dissipation of 1.3m x 1.3m fibre-reinforced shotcrete test samples of different thicknesses. A common thickness of sprayed shotcrete in underground mining is 100mm. The test of a 100mm thick sample indicates a static energy dissipation capacity of 2.4kJ/m^2 at 80mm displacement. A similar value could be expected for shotcrete layers in underground excavations. Dynamic test specifications and performance data are presented in Table 1. These tests indicate that a 102mm thick shotcrete sample is capable of dissipating 1.5kJ/m^2 of energy during a sudden loading event. Further detail on the test methodology and results may be found in Morton, et al., 2009 and Villaescusa, et al., 2010.

Collectively, these results indicate that fibre reinforced shotcrete layers of 100mm thickness or less are not appropriate as a sole method of surface support where sudden loading demands exceed 1.5kJ/m^2 or where static demands exceed 2.5kJ/m^2. Where the energy demand on the surface support exceeds this value, the addition of mesh is required either external to or encapsulated within the shotcrete, in order to provide increased energy dissipation capacity, load transfer redundancy and containment of failed shotcrete. Furthermore, shotcrete as the sole form of surface support is only appropriate where the rockmass block sizes exceed the spacing of the reinforcement pattern and expectations of stress induced fracturing around the excavation perimeter are minimal. Otherwise, shotcrete instability could be expected to develop between the reinforcement pattern.

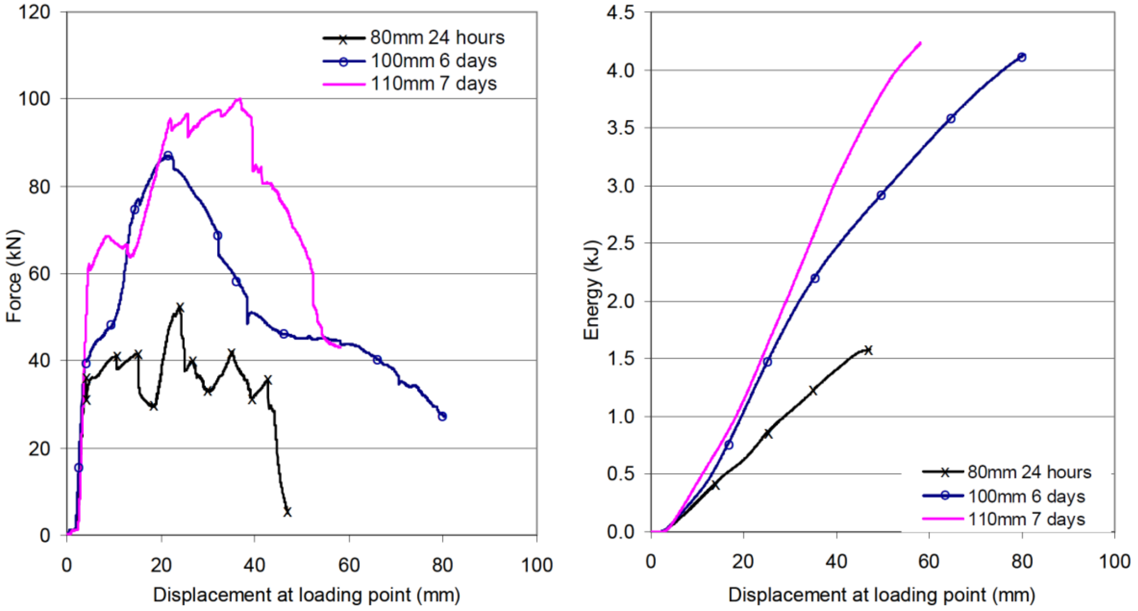


Figure 2 – Static force-displacement and cumulative energy dissipation curves for fibre reinforced shotcrete test samples of varying thickness and cure time (Morton, et al., 2009).

Table 1 - Shotcrete dynamic test specifications and performance summary (Villaescusa, et al., 2010)

Sample Number	*Sample Size (m)*	*Thickness (mm)*	*Loading Mass (kg)*	*Impact Velocity (m/s)*	*Input Energy (kJ)*	*Peak Force (kN)*	*Energy Dissipated (kJ)*
1	1.4 x 1.6	90	446	4.45	4.4	93	1.8
2	1.4 x 1.6	102	446	5.69	7.2	96	3.5

Figure 3 displays charts of static force-displacement for a) mesh reinforced and fibre reinforced shotcrete test panels of various thicknesses and cure time (Morton, et al., 2009) and b) weld and chain link mesh (Villaescusa, et al., 2012). Comparison of the loading response of these common surface support system components indicates the fact that for a surface support scheme consisting of shotcrete and external mesh, energy would be preferentially dissipated by the shotcrete layer over the initial 0-100mm range of displacement. On the basis of this test data it is suggested that such a surface support arrangement is not ideally integrated to simultaneously and equitably dissipate sudden energy demand while minimising overall damage to the ground support scheme. This conclusion is supported by underground observations of surface support failure presented later.

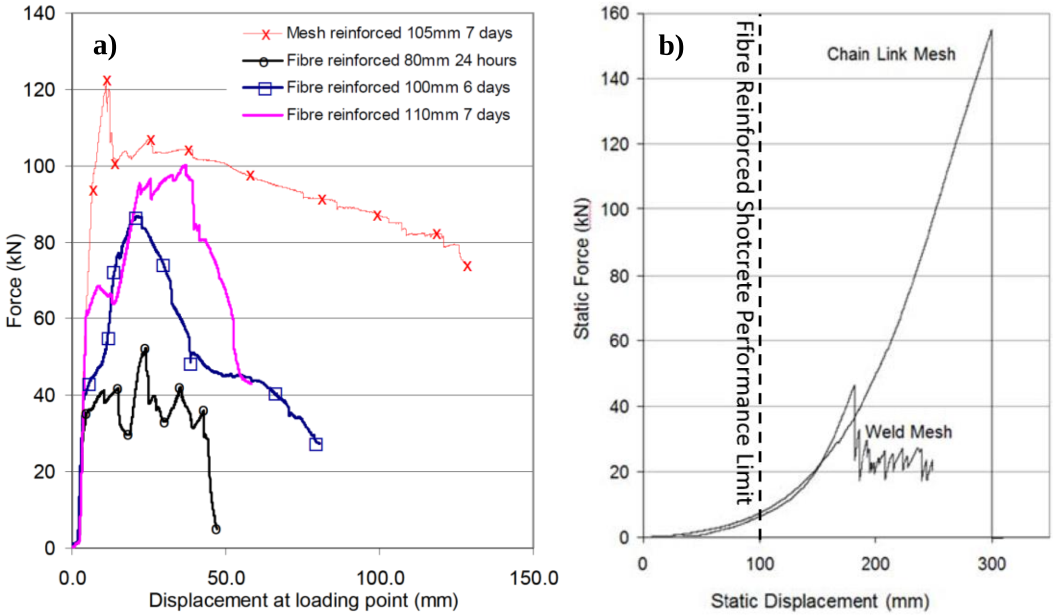


Figure 3 - Load-Displacement profiles for a) shotcrete (Morton, et al., 2009) and b) steel mesh (Villaescusa, et al., 2012).

Additional data from Morton, et al., 2009, shown below in Figure 4, indicates that a 105mm thick shotcrete layer internally reinforced with 5.6mm, 100mm aperture mild steel weld mesh (550MPa minimum tensile strength) is capable of achieving energy dissipation of 7.1 kJ/m^2. This represents a 60% increase in energy dissipation with respect to a surface support system where the mesh is installed externally. This test data supports a hypothesis of superior surface support performance when the shotcrete lining of underground excavations is internally reinforced with steel mesh.

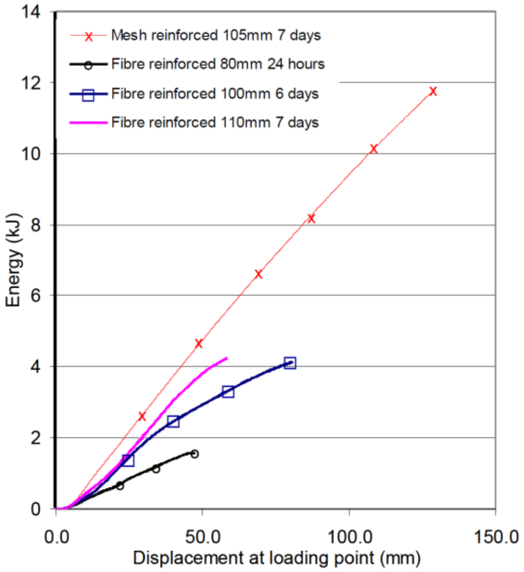


Figure 4 - Cumulative energy dissipation of shotcrete test panels (Morton, et al., 2009).

PERFORMANCE OBSERVATIONS

In underground mining there are three common surface support arrangements which include shotcrete. These include a single layer of shotcrete with no mesh, a single layer of shotcrete with external mesh and shotcrete with an encapsulated layer of mesh as internal reinforcement. This section presents observations of shotcrete performance for these three surface support arrangements. All arrangements are retained with pattern reinforcement.

1.1 Shotcrete

Several modes of failure are evident where shotcrete is installed as the sole component for surface support. Compressive failure coincides with areas of thick shotcrete application which are also subject to high stress concentrations tangential to the excavation surface. This failure mechanism may present as violent spalling (Figure 5). Compressive failure requires continuity of load bearing capacity across the shotcrete layer and therefore it usually occurs prior to the onset of other failure mechanisms which may generate fractures. Where the major principal stress concentrations are sub-horizontal, this mode of failure is most likely to occur in the roof and shoulders of the excavation. Walls are susceptible where significant loads are oriented sub-vertically. Compressive failure of shotcrete may be caused by low energy demand ($< 5\text{kJ/m}^2$) events.

Figure 5 - Compressive failure of shotcrete, also known as shotcrete spalling.

Spalling may also refer to adhesion failure between the shotcrete and rock substrate. Loss of adhesion may be expected where the excavation surface consists of rock with low friction properties or is covered by loose material such as a dust layer or small unstable rock fragments. Where adhesion may be affected by rock properties, it is advisable to also install pattern reinforcement to provide some retention to the shotcrete layer. In dynamic loading conditions, additional surface support such as mesh may not necessarily reduce the risk of adhesion failure, but it can provide containment to any broken rock or shotcrete that becomes dislodged. High pressure hydro scaling of the excavation surface prior to shotcrete application is a means of removing loose contaminents that may degrade final adhesion strength.

An important consideration in relation to any surface support system consisting solely of shotcrete is the process of load transfer to the reinforcement elements. Without mesh, load transfer between the shotcrete and reinforcement occurs via the reinforcement external fixtures (Figure 6) and, to a lesser extent, the short annulus of bonding agent or frictional coupling at the collar of the reinforcing element which is in contact with the shotcrete. Therefore, load transfer from the shotcrete to reinforcement is primarily concentrated at the reinforcement surface fixture. Load transfer to the reinforcement can be compromised where small blocks become unstable within the reinforcement pattern. Without mesh, no redundancy in surface support containment exists to contain blocks of shotcrete that fail around the plate, as shown in Figure 6 and Figure 7.

Figure 6 – Plates provide limited load transfer between shotcrete and reinforcement.

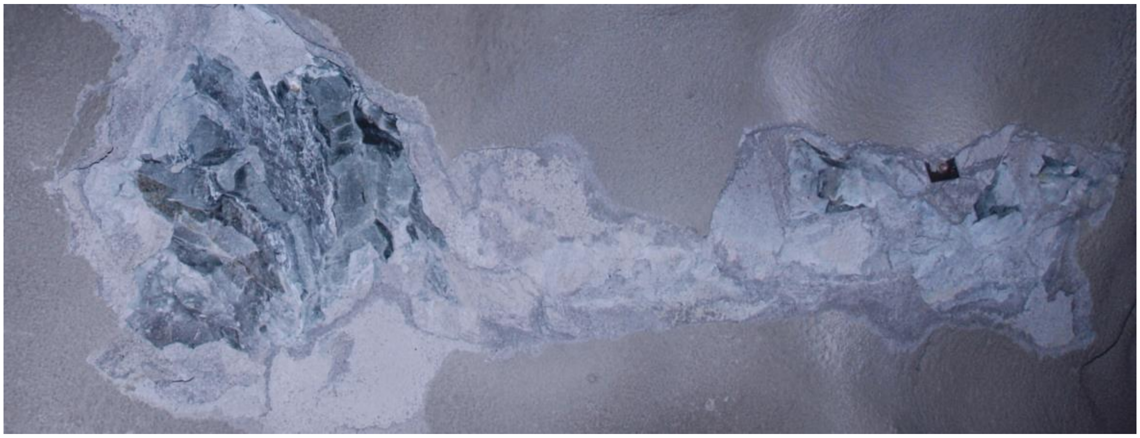


Figure 7 - Shallow spalling failure where shotcrete has no external or internal steel mesh.

If steel mesh is not included in the surface support system the addition of steel or plastic fibres within the shotcrete matrix improves the toughness of the shotcrete, increasing first-crack strength (Villaescusa, 2014). Common batch design specifications for fibre content are 5-7kg/m^3 for plastic fibres and 50-70kg/m^3 for steel fibres. Laboratory tests conducted by Morton, et al., 2009 have shown that fibres provide load transfer continuity across fractures only when displacements are less than half the length of the fibre. Field observations of fractures of various widths shown in Figure 8 support this conclusion. Only where the fracture width is less than half the fibre length, as in Figure 8a), is there continuity of some fibres spanning the fracture. The relatively low density of fibres in typical shotcrete mix designs means that their overall contribution to post-fracture displacement and energy dissipation capacity is limited.

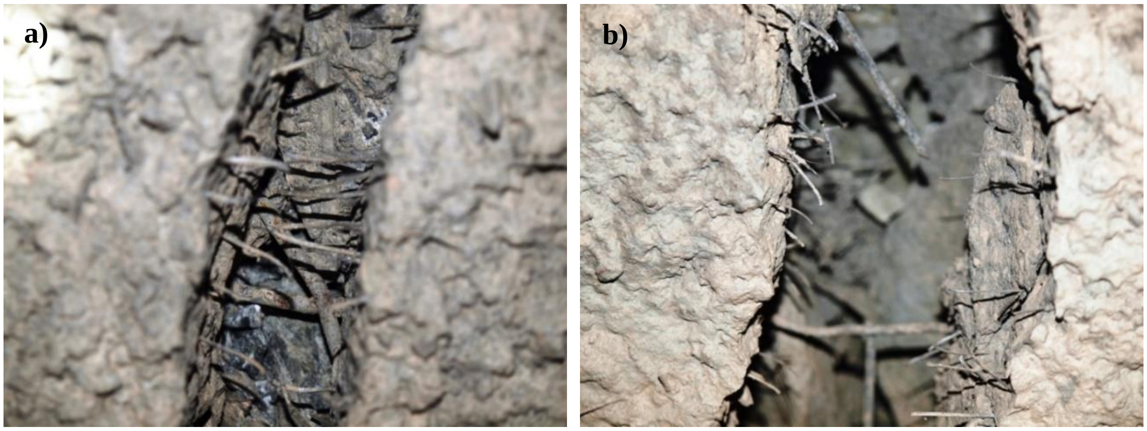
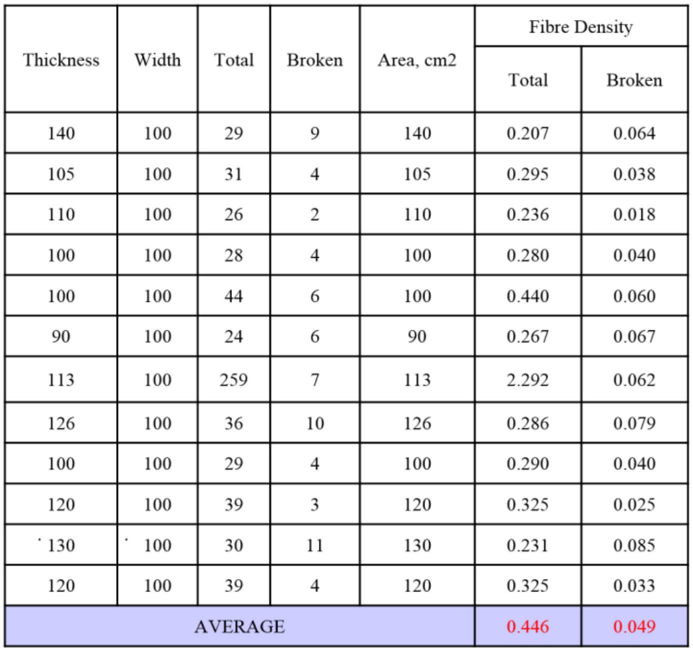


Figure 8 - Post-fracture effectiveness of shotcrete fibres is limited to displacements less than half the fibre length.

It is generally not practical to increase the strength of the fibre reinforcement of shotcrete by simply increasing the density of fibres in the mix beyond the typical values quoted earlier. This is due to the fact that installation issues arrise when the fibre dosage becomes too high. Such issues include sprayability of the mix and excessive rebound. Overdose of plastic fibres may also have secondary impacts, such as blocking the inlet of nearby dewatering equipment. The typical density of fibres associated with the mix specifications quoted earlier is in the order of 0.5 fibres per cubic centimetre of shotcrete. Furthermore, the mechanism of failure of the fibres is usually displacement through the shotcrete matrix, rathern than tensile rupture, as indicated by data from Villaescua, 2011 and shown below in Figure 9.



Thickness	Width	Total	Broken	Area, cm2	Fibre Density	
					Total	Broken
140	100	29	9	140	0.207	0.064
105	100	31	4	105	0.295	0.038
110	100	26	2	110	0.236	0.018
100	100	28	4	100	0.280	0.040
100	100	44	6	100	0.440	0.060
90	100	24	6	90	0.267	0.067
113	100	259	7	113	2.292	0.062
126	100	36	10	126	0.286	0.079
100	100	29	4	100	0.290	0.040
120	100	39	3	120	0.325	0.025
130	100	30	11	130	0.231	0.085
120	100	39	4	120	0.325	0.033
AVERAGE					0.446	0.049

Figure 9 - Observations of fibre density and failure across a fracture (Villaescua, 2011).

1.2 Shotcrete & External Mesh

Shotcrete primarily stabilises small loose blocks around the excavation perimeter and resists the relatively low loads that these blocks generate. For all but the lowest energy dynamic loading conditions it is generally necessary to combine shotcrete with some arrangement of mesh. The mesh may be either external to or embedded within the shotcrete in order to dissipate additional energy demand and minimise material ejection during sudden loading events. Repetitive dynamic loading has the potential to cause deterioration of shotcrete adhesion to the rock mass over time, as well as fracture generation. Without mesh this process could result in the development of unstable shotcrete blocks which may be ejected.

Consistent with laboratory observations (Holgrem, 1976, Barrett & McCreath, 1995, Morton, et al., 2009), underground field observations reveal the fact that flexural failure is a common mechanism of shotcrete damage. Flexural failure occurs following bulking of the rock mass surrounding the excavation and is frequently caused by sudden violent rock failures at great depth. Testing data presented earlier in Figure 3 indicates that mesh installed external to the shotcrete layer provides limited resistance to failure over the first 100mm of displacement. This is primarily due to the different stiffnesses of these two surface support components. This conclusion is supported by examples of common underground excavation damage illustrated in Figure 10.

These figures reveal the fact that when mesh is installed external to the shotcrete, the shotcrete and mesh are not integrated to simultaneously and equitably dissipate the dynamic energy demands imposed by the rock mass. However, external mesh does provide supplementary energy dissipation capacity and surface support redundancy by containing failed shotcrete which might otherwise be unstable and ejected. Fractured shotcrete blocks effectively become part of the unstable mass following failure, requiring the installation of mesh to provide redundancy in the surface support system. Considering the energy dissipation capacity of typical shotcrete layers, mesh should be included as surface support wherever shotcrete is installed and the energy demand is 1.5kJ/m^2 or more.

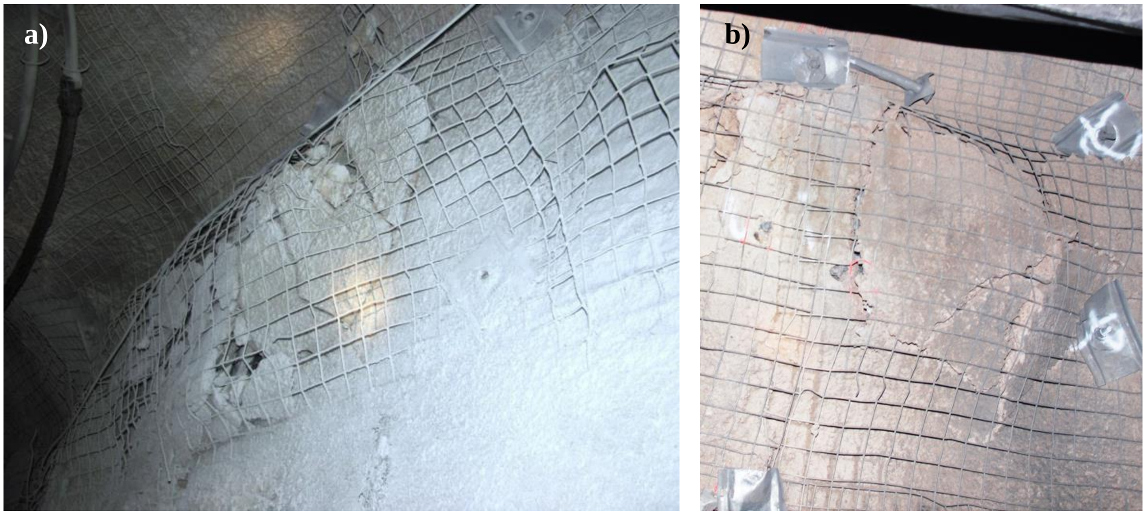


Figure 10 - Flexural failure of shotcrete with external mesh.

1.3 Shotcrete & Internal Mesh

Encapsulating mesh within shotcrete provides a significant improvement in the energy dissipation capacity of the surface support system. A portion of this increased capacity is activated for displacements preceding shotcrete fracture, given that the shotcrete and mesh are rigidly integrated. Post fracture displacement is also increased relative to fibre reinforced shotcrete. Mesh reinforced shotcrete typically fractures into blocks which are connected to adjacent blocks by mesh strands. Field observations of post fracture mesh-reinforced shotcrete suggest that surface support displacement capacity is increased when shotcrete is reinforced with high tensile woven mesh products which are able to articulate (Figure 11a). Mild steel weld mesh is not as robust as high tensile woven mesh. Hence, rupture of welded mesh occurs at lower displacements (Figure 11b).

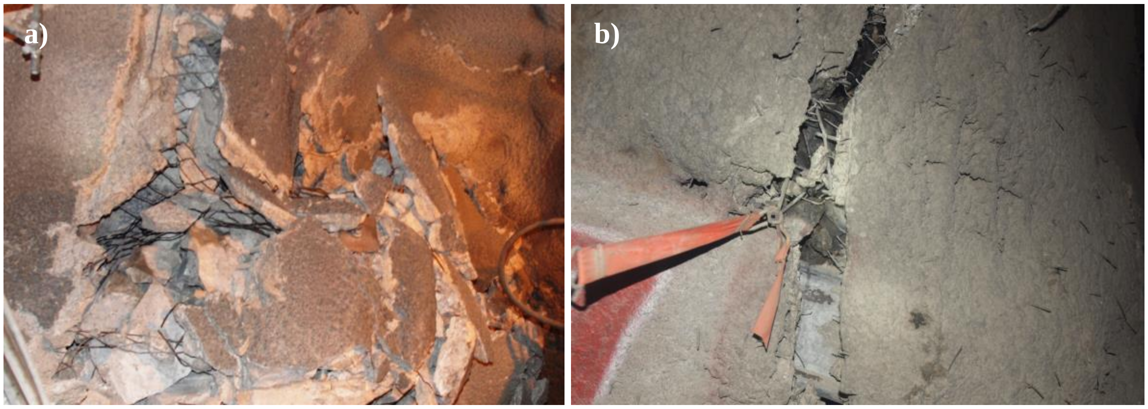


Figure 11 - Post fracture displacement capacity of a) high tensile articulating chain link mesh and b) mild steel weld mesh

As illustrated in laboratory data from Figure 3a, mesh reinforced shotcrete provides significantly increased energy dissipation and displacement capacity when compared to fibre reinforced shotcrete (Morton, et al., 2009). Importantly, although mesh reinforced shotcrete test samples displayed flexural damage, the samples remained intact and overall displacements were less than the 300mm threshold for very significant damage to surface support identified by Villaescusa, et al., 2014. Mesh reinforced shotcrete has superior toughness than shotcrete which is simply fibre reinforced, as the load-displacement chart in Figure 3 indicates.

The increased toughness of mesh reinforced shotcrete subjected to sudden loading is evident from underground observations shown in Figure 12. This image compares a surface support system consisting of external weld mesh and fibre reinforced shotcrete in (a) to an adjacent arrangement conisting of weld mesh reinforced shotcrete in (b). The stress conditions and rock properties controlling failure are considered to be consistent. However, the response reflects the differing stiffnesses of the arrangements. The main observation is that displacements are visibly less when mesh is encapsulated in shotcrete. Given the equivalent energy demand, this observation supports the notion that encapsulating the mesh in shotcrete stiffens the surface support system, as indicated by laboratory test data (Morton, et al., 2009). In this arrangement the shotcrete and mesh are rigidly interlinked and are therefore loaded simultaneously. Demand is equitably distributed to both surface support components and therefore the overall damage to the system is minimised. The mesh assists to reinforce the shotcrete layer, rather than provide external containment.

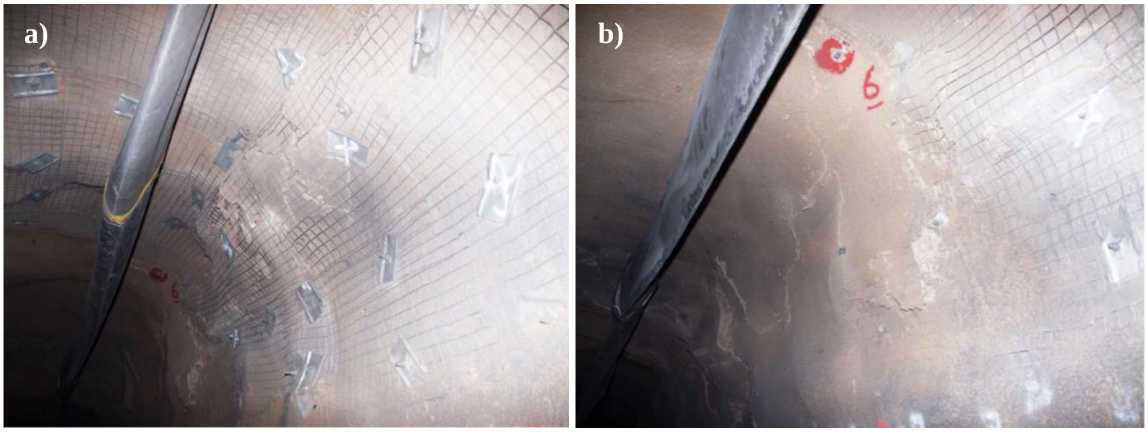


Figure 12 – a) Fibre reinforced versus b) mesh reinforced shotcrete displacement observations indicate superior surface support performance when mesh is embedded in shotcrete, rather than being installed externally.

Mesh encapsulated in shotcrete improves the performance of the surface support system by providing significantly greater energy dissipation and displacement capacity than fibres alone. In comparison to fibres, the steel strands of mesh allow greater displacements before complete dislocation occurs between loaded blocks of shotcrete (Figure 13). The energy dissipation capacity of encapsulated mesh reinforcement is significantly more than that provided by fibres. This is due to several reasons. Firstly, the random orientation of fibres within the shotcrete matrix means that, for any given loading condition, only a small portion of the fibres are loaded in the orientation of their greatest strength capacity (i.e. pure tension). The remainder are loaded in sub-optimal orientations such as shear, torsion, flexure or combinations. Hence, a significant portion of the energy dissipation capacity of the overall fibre content is not utilised.

Furthermore, observations of failed shotcrete in both laboratory investigations (Morton, et al., 2009) and underground damage shown here (Figure 14) indicate that where fibres are loaded in tension, it is most often the case that the fibres are drawn through the shotcrete matrix without causing rupture. This indicates that the energy dissipation capacity of fibre reinforcement is frequently defined by the strength of the frictional coupling between the fibre and shotcrete matrix, not the tensile strength of the fibre. In comparison to the energy dissipation capacity provided by encapsulated weld mesh or chain link mesh, the contribution from small fibres is relatively insignificant. Therefore, the strength benefits of including fibres in mesh-reinforced shotcrete is suggested to be minimal.

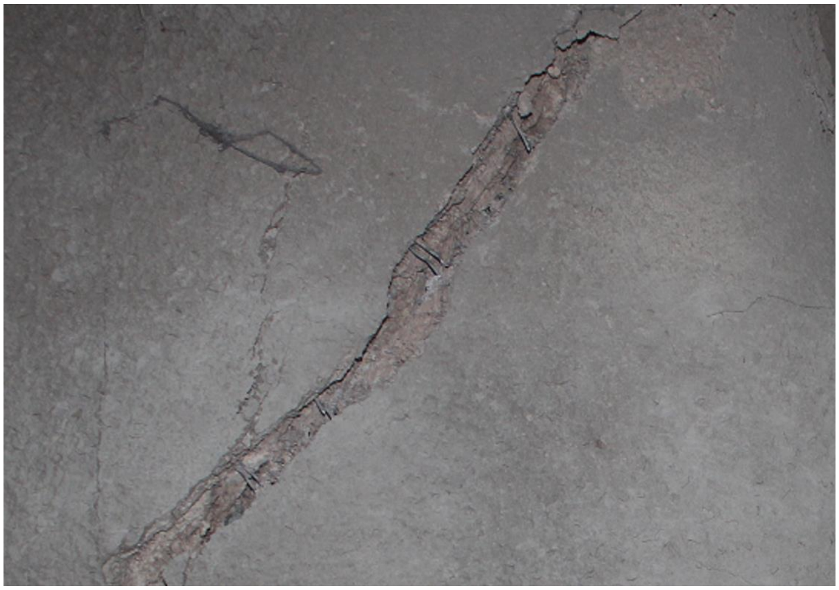


Figure 13 – Encapsulated mesh provides superior post-fracture energy dissipation capacity.

Figure 14 – Displacement capacity and failure mode of fibres and encapsulated mesh.

The integration of surface support components may be considered optimised for maximum energy dissipation when the system fails in large, rectangular blocks defined by the spacing of the reinforcement pattern, as illustrated in Figure 15 and Figure 16. Where demand exceeds capacity, failure in this manner indicates optimal load transfer to reinforcement and continuous containment of the loading mass of rock across the span of the reinforcement pattern. Discrete surface support failures in between the spacing of reinforcement are avoided, which indicates that the surface support is transferring the maximum possible load to the reinforcement. This mode of shotcrete failure has only been observed where shotcrete is internally reinforced with mesh.

Figure 15 – Mesh reinforced shotcrete response to sudden low energy demand. Fracture intersections correspond to the location of reinforcement elements.

Figure 16 – Mesh reinforced shotcrete failure in a rectangular block of a size defined by the reinforcement pattern following extreme energy demand (>50kJ/m^2).

Mesh reinforced shotcrete is often constructed by first applying one layer of shotcrete to the excavation surface before installing mesh and then a final shotcrete overspray layer. Although this is considered to be the optimal arrangement for maximum energy dissipation, there are vulnerabilities to this method of construction. The overspray layer is susceptible to adhesion and spalling failure, with ejection of small to medium size blocks occasionally observed. This form of failure may affect either the wall of the excavation (Figure 17) or the roof (Figure 18). This effect may be exacerbated by the presence of reinforcement surface fixtures embedded between layers which provide low adhesion.

Figure 17 - Loss of adhesion between primary and secondary shotcrete layers leading to formation of unstable blocks in the wall.

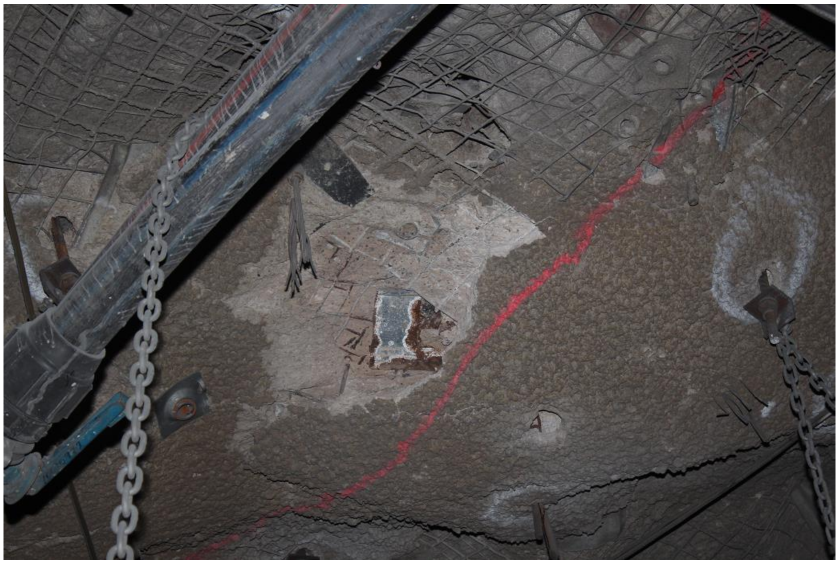


Figure 18 - Loss of adhesion leading to ejection of small blocks of shotcrete from the excavation roof, influenced by reinforcement surface fixtures.

Adhesion and spalling failures of the second layer of shotcrete may be minimised by hydro scaling the first shotcrete surface before second spraying. As well as removing any possible loose materials such as dust or small rock fragments which might negatively affect adhesion, wetting down the surface also provides additional hydration. This minimises moisture absorption from the wet shotcrete layer into the dry surface and formation of a low strength interface between the two shotcrete layers. Where thicker overspray shotcrete layers are installed, it may be beneficial to install an additional layer of mesh, external to the shotcrete, to contain any loose blocks that may form over time.

CONCLUSIONS

Shotcrete is an integral component of the surface support system of underground excavations constructed at great depth. Shotcrete alone is not considered appropriate as surface support in mining conditions where sudden violent rock mass failures regularly occur and the energy demand from these failures exceeds 1.5kJ/m^2. Repetitive fracturing leading to instability of the shotcrete layer may occur in these conditions. Where energy demands exceed 1.5kJ/m^2, shotcrete should be accompanied by steel mesh, which may be installed either externally or fully encapsulated within the shotcrete as internal reinforcement, depending on the energy dissipation requirements. External mesh provides minimal resistance to shotcrete failure over the first 100mm of displacement, and therefore acts predominantly as containment once the shotcrete becomes heavily fractured and unstable. Shotcrete with external steel mesh does not act as a fully integrated surface support system and this arrangement is not optimal for high energy demand mining conditions.

If the dynamic loading demands on excavations are expected to be high, the optimal surface support arrangement is to encapsulate steel mesh within the shotcrete layer. For maximum energy dissipation and ideal surface support system integration, the optimal arrangement is considered to be high tensile woven chain link mesh fully encapsulated in shotcrete. Mesh reinforced shotcrete can provide continuous containment of the loading rock mass across the span of the reinforcement pattern, even under very high dynamic loading demands with tightly spaced discontinuities and small rock block sizes. This arrangement ensures the maximum possible load is transferred from the surface support to the reinforcement system. A mesh layer installed external to the mesh reinforced shotcrete may also be required in order to contain any small fragments which loose adhesion or spall from the surface over time. In this context, small plastic or steel fibres provide comparatively little reinforcement benefit to shotcrete which is also reinforced with fully encapsulated mesh. This is largely due to the fact that the random orientation of fibres within the shotcrete matrix prevents them from being consistently loaded in the orientation of their greatest strength capacity.

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