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In-situ Dynamic Testing of Ground Support Using Simulated Rockbursts

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Abstract

The Australian Centre for Geomechanics (ACG) is conducting a number of simulated rockburst experiments in Western Australian underground mines as part of its Mine Seismicity and Rockburst Risk Management research project. By simulating rockburst damage using blasting, it is possible to gauge the performance of complete ground support systems (incorporating rockbolts or cables, surface support and the connections between them) in-situ when subjected to strong ground motion, as would be generated by a large seismic event nearby. This paper describes the testing method used and presents the results of simulated rockburst tests at a number of Western Australian mines on various ground support systems. A dynamic support classification is shown which compares the dynamic capacity of the ground support systems tested. The test results are compared to ground support performance observed in actual rockburst case studies.

1 Introduction

In practice, ground support behaves as a system when subjected to dynamic loading during a rockburst. It is the capacity of and interaction between the individual ground support elements (the rockbolts, surface support, plates, connections, etc) which determine what damage will be sustained to the ground support during a rockburst. For this reason, it is essential to consider the behaviour of the "ground support system" when dealing with rockburst prone conditions. Whilst theoretical design calculations provide a starting point, the complicated interaction of the individual support elements with an inhomogeneous and structurally complex rock mass subjected to dynamic loading can not reasonably be represented using a single equation.

As part of its mine seismicity research, the ACG has built up a large database of rockburst damage case studies over the last decade (Heal, 2007). The database consists of 83 well documented seismic events which caused damage and contains 254 individual instances of rockburst damage. Forty-nine different ground support systems are represented in the catalogue, with the most common shown below in Figure 1.

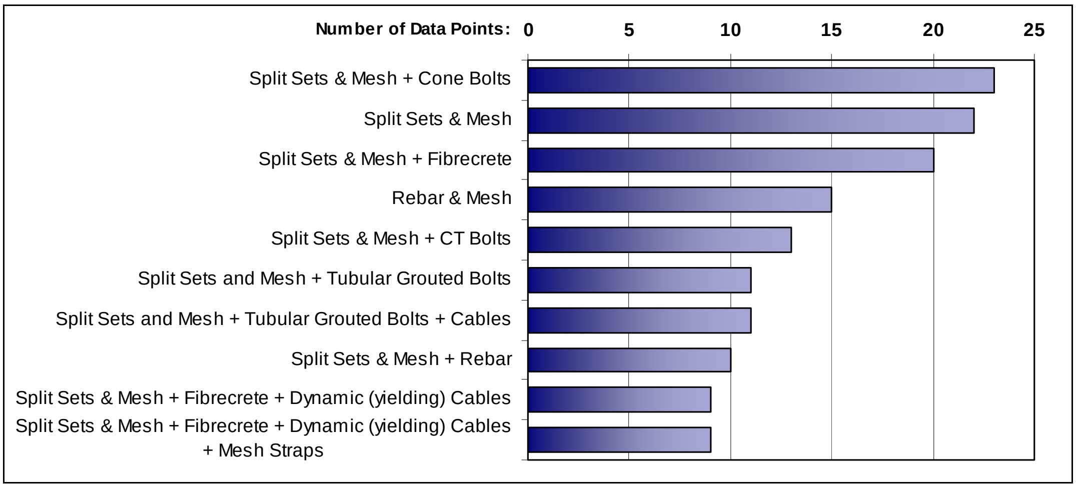

Figure 1 The most common ground support systems in the ACG rockburst catalogue (Heal, 2007)

Immediately apparent from the rockburst catalogue data was the fact that most ground support failures occurred not because of the failure of reinforcement elements (rockbolts or cables), but due to surface support or fixture failure. The failure mode for ground support in the catalogue is shown in Figure 2. The data shows that there was rockbolt or cable failure in only 30% of cases. It also provides an indication of the reason for the failures and what could have been done to prevent them, for example:

- Surface fixture failures – use bigger or thicker plates or avoid installation damage.
- Split Set ring failures – install at the correct angle or avoid installation damage.
- Surface support failures only – stronger surface support or improve the connection between rockbolts and surface support, particularly by improving strength at mesh overlaps.
- Rockbolt or cable failure – use more appropriate (e.g. yielding) support.
- Failure beyond embedment depth – use longer rockbolts or cables.

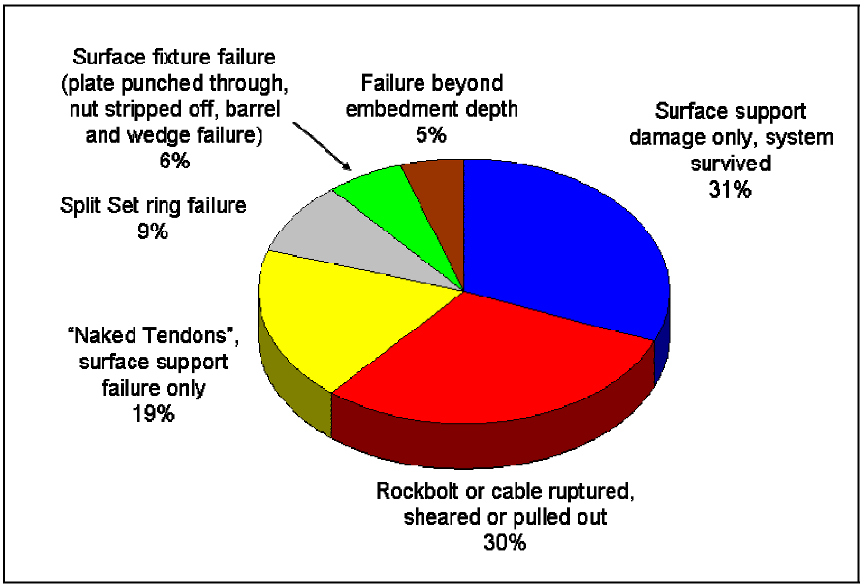

Figure 2 Ground support system failure modes in the ACG rockburst catalogue (Heal, 2007)

To address these uncertainties in the design and selection of ground support for rockbursting conditions, the ACG is conducting a number of simulated rockburst experiments in Western Australian underground mines as part of the Mine Seismicity and Rockburst Risk Management research project. By simulating rockburst damage using blasting, it is possible to gauge the performance of complete ground support systems (incorporating rockbolts or cables, surface support and the connections between them) in-situ when subjected to strong ground motion. Testing ground support systems in-situ also allows investigation of the influence of rock mass discontinuities, pre-existing rock mass damage and stress on rockburst damage as well as the influence of support and reinforcement systems to reduce displacement and damage due to strong dynamic loading. Ultimately it is hoped that the results will assist in the development of more robust ground support design and selection methodologies and a means for assessing the anticipated performance of installed support systems, for use in seismically active mines. Ground support systems tested were those commonly in use in Western Australian mines, as well as several systems employed specifically for their apparent suitability under dynamic loading. Two thin spray-on liner (TSL) surface support products were also tested, to determine their appropriateness for use in rockburst prone conditions.

In the past, simulated rockbursts using blasting have been carried out to assess the relative performance of bonded surface support systems (Espley et al. 2002, Archibald et al. 2003), study the response of rockbolts or shotcrete to dynamic loading (Haile and Le Bron, 2001; Tannant et al., 1994a, 1994b and 1995; Tannant and McDowell, 1995) and for broad ground motion studies (Hagan et al., 2001). In the ACG experiments, series of simulated rockbursts have been undertaken at a number of mine sites to allow testing of a range of ground support systems under varied rock mass conditions.

2 Testing layout

Simulated rockburst experiments are conducted by blasting adjacent to the walls of disused excavations. Typically three blastholes are drilled parallel to the test wall at each site, as shown in Figure 3.

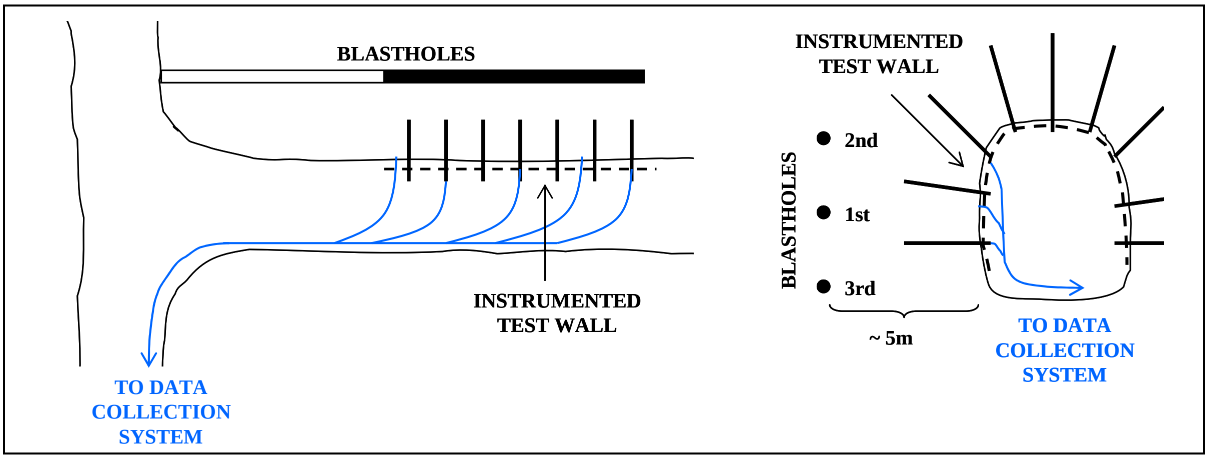

Figure 3 Conceptual plan and cross-sectional views of a simulated rockburst test site layout

Each blast hole is separately charged and detonated to allow successively larger dynamic loading upon the test wall. The blasts are designed to reproduce an actual seismic event as closely as possible. This can be achieved by maximising the release of shock wave energy and minimising the effects of rapidly expanding gases. As such, packaged emulsion products are used for the experiments (60 mm cartridges in a 76 mm hole or 80 mm cartridges in an 89 mm hole). Typically, the first blast is designed to achieve a peak particle velocity (PPV) of around 0.5 m/s on the test wall, the second 1.5 m/s and the third 3 m/s. The blast design procedure is outlined in Heal et al. (2005). Additional blastholes are drilled at each test site to allow for damage to the second or third blasthole due to the preceding blasts (an example is shown in Figure 8). Quantities of packaged emulsion ranging from 6 kg to 60 kg have been used in single blasts.

Ground motion monitoring at each test site is conducted using heavily overdamped 14 Hz SM6 geophones mounted on the test wall and connected to a 16 channel Impulse seismic monitoring system. The Impulse system allows a maximum sampling rate of 10 kHz per channel, which is adequate to prevent aliasing of waveforms, considering the maximum frequency of ground motion expected to be generated by the blasting is not more than 1 kHz.

A number of 46 mm observation holes are drilled perpendicular to the test wall for borehole camera observations. These measurements allow investigation of the degree and nature of rock mass fracturing before and after each blast and, specifically, the thickness of failed rock acting upon the ground support for use in energy demand calculations.

Extensive mapping of each test site before and after each blast is carried out using Sirovision, a three-dimensional photogrammetry system developed by the CSIRO and designed primarily for structural mapping of underground or open cut rock faces. Sirovision allows the generation of fully digitised three-dimensional images from stereo pairs of photographs, when accurate survey support is available. As well as mapping, images generated before and after successive blasts are used to identify areas of rock bulking or ejection, accurately measure deformation of surface support and measure the displacement of rockbolt plates and ends. These measurements contribute to the qualitative and quantitative assessment of ground support system performance. In addition, the Sirojoint module allows the user to accurately measure the parameters defining discontinuities in a rock mass and analyse the structure of a rock mass by using three-dimensional images (CSIRO 2003). An example of a three-dimensional image generated from a high resolution digital image is shown in Figures 4, 5 and 6. The Sirovision software uses two digital images of known camera separation to generate a ranged three-dimensional image. Accurately surveyed points visible on the images can then be used to translate the ranged image into a true three-dimensional image, relative to the mine’s co-ordinate system. Four numbered points in Figure 4 were used to orient the three-dimensional image in Figure 6 in the mine specific co-ordinate system.

Figure 4 One of two high resolution digital images used by the Sirovision software to generate the three-dimensional point cloud in Figure 5 and the three-dimensional image in Figure 6

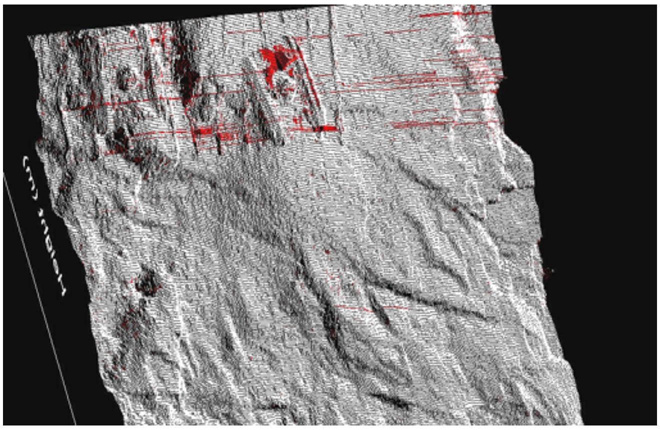

Figure 5 A three-dimensional point cloud generated using the digital image in Figure 4

Figure 6 A three-dimensional image generated from the point cloud in Figure 4 and digital image in Figure 5

All simulated rockbursts are recorded using a Canon MV750i digital video camera, set up at sufficient distance from the test wall to avoid damage due to ground shaking or ejected rock or support fragments. The camera is used to maintain a permanent record of each simulated rockburst, as well as assessment of the nature and velocity of ejected rock and support fragments during the experiments. In some blasts, rock mass damage due to the simulated rockburst can be observed before dust obscures the video record. In tests conducted to date, the camera has also provided good before and after shots of each test, as shown in Section 3.

A typical test site layout is shown in Figure 7, from the Mt Charlotte 1155 Access test site. This particular test site was located in a stope access. Blastholes were drilled from an adjoining excavation oriented at right angles to the test site, to allow drilling of blastholes parallel to the test wall. The blasthole drilling instructions from the Mt Charlotte test site are shown in Figure 8. An additional blasthole was provided for the third blast to allow for the possibility of blasthole damage due to preceding blasts.

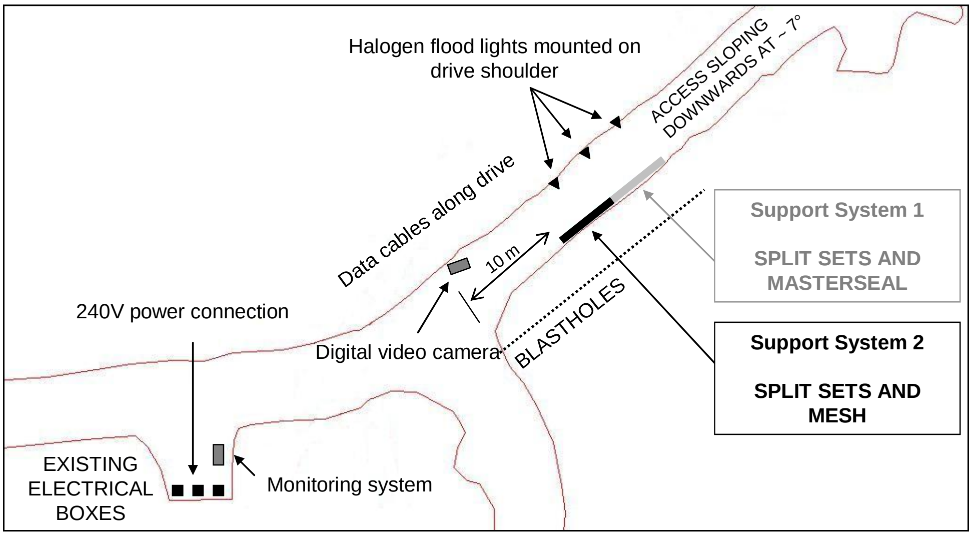

Figure 7 Test site layout from the Mt Charlotte test site (April 2005)

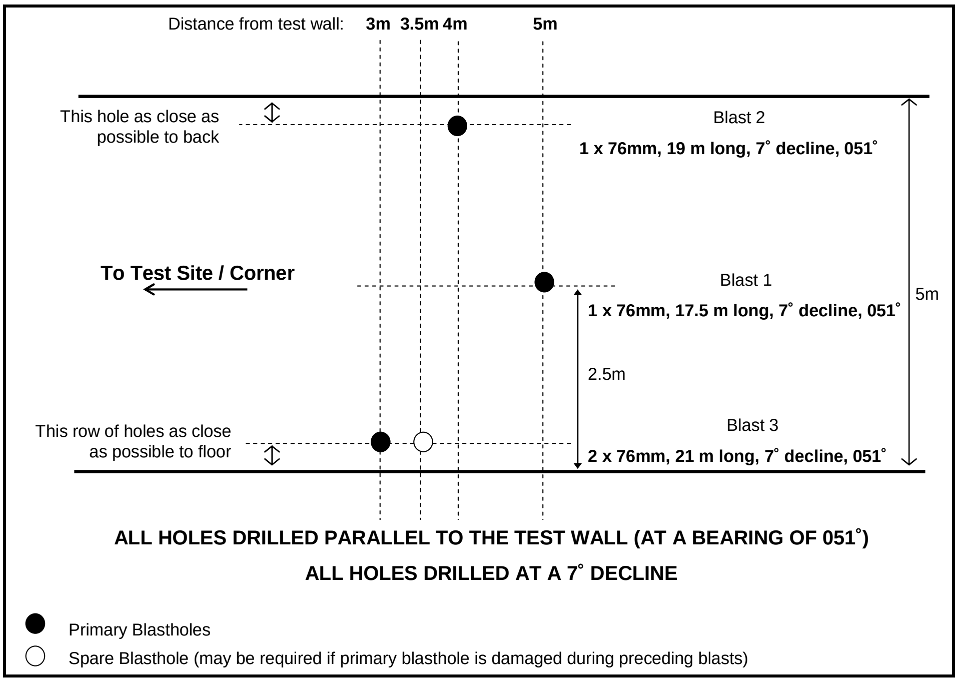

Figure 8 Blast hole drilling instructions from the Mt Charlotte test site. Blastholes were oriented parallel to the test wall, as shown in Figure 7

A photograph of the completed test wall setup is shown in Figure 9, taken prior to the first blast. The photograph shows the two ground support systems tested side by side (in this case Split Sets and Masterseal on the left and Split Sets and Mesh on the right). The numbered Sirovision control points can be seen spread out across the test wall, the locations of which were surveyed before and after each blast. Also visible are the surface mounted geophones connected with coaxial cable. The cables are protected by conveyor belt where they run along the drive floor, to protect them from falling or ejected material during blasting.

Figure 9 Completed test wall setup from Mt Charlotte, shown prior to the first blast. The numbered circles are Sirovision control points. Surface mounted geophones connected by coaxial cable are attached to the test wall surface at various locations

3 Test results

Simulated rockbursts have been conducted at 5 test sites, with a total of 12 blasts. Test sites and ground support systems tested are summarised in Table 1 on the following page. The range of PPV's measured by surface mounted geophones on the test wall for each blast is also shown. A large variation in PPV was often observed across the test wall at each site, not only due to the blasthole geometry but also, presumably, due to variations in rock mass composition and structure between the blasthole and the test wall. A principal aim of the testing was to design each blast to generate a wide range of damage across the test wall to maximise the amount of data. This was generally achieved, except at the first test site (Long Shaft 13/2 Access) where severe damage was not generated on the two ground support systems tested as a conservative blast design was adopted. This was not the case in the later tests, where all support systems were tested to complete failure. The damage generated by the simulated rockbursts is considered to be similar to actual rockburst incidents, with damage observed such as rock mass bulking and bagging of mesh, Split Set rings stripped off, solid bar bolts (R27 Securabolts) snapped clean, punching failure of plates, plates cutting mesh and sections of shotcrete or thin spray-on liner ejected between individual rockbolt units, leaving undamaged rockbolts protruding. Photographs of damage observed at various sites are shown in Figures 10 to 14.

The issue of incremental damage to ground support is an important consideration for actual rockbursts. In the simulated rockbursts, for the most part, the early blasts generated limited damage to the ground support systems (or little enough damage to cause any noticeable effect on the support system capacity), except in the case of Fibrecrete or TSL surface support where there were instances of cracking and ejection of sections of liner in the early blasts. As is demonstrated in the next section, ejection of sections of liner is considered to correspond to the maximum damage level hence this has no effect on the calculated capacity on each system (which is at a lower damage level corresponding to the loss of support system functionality). In situations where cracking of liners occurred, the following blast typically generated much higher energy demands which caused ejection of sections which were previously undamaged, as well as those which were cracked, and this was not considered to effect the final calculated capacity.

The rock mass, however, often suffered significant damage due to the earlier blasts. This had the effect of increasing the thickness of failed rock which acted on the ground support system in the later blasts, resulting in higher energy demands for each successive blast. This increased failure thickness was consistently observed in borehole camera surveys before and after each blast.

Table 1 Ground support systems tested

Ground Support System	Test Site(s) (Date Tested)	Range of PPV's Generated (m/s)	Description
Split Sets and Mesh	Longshaft Rhondo North Access (June 2004)	1st blast: 0.3 – 1.3 2nd blast: 0.1 -1.0 3rd blast: 2.0 – 3.5	2.4 m SS47 Split Sets (1.2–1.5m spacing) and Weld Mesh (2.4 x 3.0m sheets, 100 x 100mm, 5.6 mm galvanised steel).
	Mt Charlotte 1155 Access (April 2005)	1st blast: 0.1 – 0.6 2nd blast: 0.2 – 0.8 3rd blast: 1.1 – 1.6	
Split Sets and Mesh with Cone Bolts and Fibrecrete	Longshaft 13/2 Access (April 2004)	1st blast: 0.4 – 0.8 2nd blast: 0.4 – 0.7 3rd blast: 0.5 – 2.4	2.4 m Grouted Cone Bolts (1.0 – 1.5 m spacing), 75 mm Fibrecrete (Dramix steel fibres), 2.4 m SS47 Split Sets (1.2–1.5m spacing) and Weld Mesh (2.4 x 3.0m sheets, 100 x 100mm, 5.6 mm galvanised steel).
High Density Split Sets and Mesh with Fibrecrete	Longshaft 13/2 Access (April 2004)	1st blast: 0.3 – 0.6 2nd blast: 0.3 – 0.5 3rd blast: 0.6 – 2.0	2.4 m SS47 Split Sets (0.6–0.75m spacing), 75 mm Fibrecrete (Dramix steel fibres) and Weld Mesh (2.4 x 3.0m sheets, 100 x 100mm, 5.6 mm galvanised steel).
Widely Spaced Split Sets and Mesh	Longshaft Rhondo North Access (June 2004)	1st blast: 0.3 – 1.1 2nd blast: 0.1 – 1.0 3rd blast: 2.1 – 3.5	2.4 m SS47 Split Sets (1.5m – 2.4m spacing) and Weld Mesh (2.4 x 3.0 m sheets, 100 x 100mm, 5.6 mm galvanised steel).
Split Sets and Masterseal	Mt Charlotte 1155 Access (April 2005)	1st blast: 0.1 – 0.5 2nd blast: 0.3 – 0.7 3rd blast: 1.3 – 1.7	2.4 m SS47 Split Sets (1.2 – 1.5m spacing) and Masterseal 845A Thin Spray-On Liner (4 mm thickness).
Split Sets and Fibrecrete	Darlot Walters 1240 Access (August 2006)	1st blast: 0.7 – 1.7	2.4 m SS47 Split Sets (1.2–1.5m spacing) and 50 mm Fibrecrete (Synmix synthetic Fibres).
Securabolts and Fibrecrete	Darlot Walters 1240 Access (August 2006)	1st blast: 0.6 – 1.9	2.4 m R27 Securabolts (1.2–1.5m spacing) and 50 mm Fibrecrete (Synmix synthetic Fibres).
Split Sets and Mesh with Fibrecrete	Darlot Walters 1240 Access (August 2006)	1st blast: 0.7 – 1.8	2.4 m SS47 Split Sets (1.2–1.5m spacing), Weld Mesh (2.4 x 3.0 m sheets, 100 x 100mm, 5.6mm galvanised steel) and 50 mm Fibrecrete (Synmix synthetic Fibres).
Securabolts and Mesh with Fibrecrete	Darlot Walters 1240 Access (August 2006)	1st blast: 0.6 – 1.9	2.4 m R27 Securabolts (1.2–1.5 m spacing), Weld Mesh (2.4 x 3.0 m sheets, 100 x 100mm, 5.6 mm galvanised steel) and 50 mm Fibrecrete (Synmix synthetic Fibres).
Split Sets and Tunnelguard with Cone Bolts	St George 8 Level Stockpile (January 2007)	1st blast: 0.4 – 3.1 2nd blast: 2.7 – 3.2	2.4 m SS47 Split Sets (1.25 m x 1.1 m spacing), 3 m grouted Cone Bolts (1.25 m x 1.1 m spacing) and 10 mm thick Tunnelguard thin spray-on liner.
Split Sets and Mesh with Cone Bolts	St George 8 Level Stockpile (January 2007)	1st blast: 0.7 – 2.7 2nd blast: 2.4 – 3.1	2.4 m SS47 Split Sets (1.25 m x 1.1 m spacing), Weld Mesh (4.0 m x 2.4 m sheets, 100 x 100mm, 5.6 mm galvanised steel) and 3 m grouted Cone Bolts (1.25 m x 1.1 m spacing)

Figure 10 Before and after shots from the digital video camera at the Longshaft Rhondo North Access site. Ground support systems tested were "Split Sets and Mesh" and "Widely Spaced Split Sets and Mesh"

Figure 11 From Mt Charlotte 1155 Access – ejection of rock supported with Masterseal 845A TSL around Split Set plates. A rockbolt mounted geophone is visible

Figure 12 Ejection of Fibrecrete and Split Sets left protruding at the Darlot Walters 1240 Access test site. Note the section of mesh reinforced Fibrecrete higher in the photo suffered far less damage

Figure 13 Moderate damage to the Split Sets and Mesh with Cone Bolts test section at the St George 8 Level Stockpile site. Severe bulking of mesh was observed and the small Cone Bolt plate has cut the mesh

Figure 14 After the 2nd blast at the St George site. The system in the foreground (Split Sets and Mesh with Cone Bolts) mostly survived however the other system (Split Sets and Tunnelguard TSL with Cone Bolts) was completely destroyed

The video footage recovered from several of the simulated rockbursts shows an initial shock wave generated by the blast which causes fracturing, bulking and ejection of a section of the test wall. This is followed by a rush of finer fragments and dust which overtakes the larger fragments first ejected. It is believed this second phase is due to the effects of rapidly expanding gases generated by the blast. Ground motion recordings of each simulated rockburst also show a distinct initial pulse, followed by further vibrations at a much lower ground velocity. The important point is that the initial shock caused the damage to the test wall and ground support systems and not the gaseous phase. Hence it is considered that a rockburst was successfully simulated. Selected frames from the video recording of the Darlot simulated rockburst are shown in Table 2. The video was recorded at 25 frames per second (due to limited lighting).

Table 2 Individual frames of 1st blast footage from the Darlot Walters 1240 Access test site

	*Before the simulated rockburst* *t = 0s*
	*Shock phase* *t ~ 40ms* This frame shows the arrival of the shock wave from the blast. The propagation of the shock wave generates fracturing across the test wall, particularly in the central region supported by Split Sets and Fibrecrete or Securabolts and Fibrecrete
	*Bulking and ejection* *t ~ 80ms* Fracturing of the rock mass has caused it to expand (bulk). The energy transferred to the bulking rock imparts a velocity on the fragments, ejecting them.
	*Ejection* *t ~ 120ms* The broken material is ejected away from the test wall.

	*Ejection* *t ~ 160ms*
	*Ejection with gas phase now visible in ejected material* *t ~ 200ms* This is the first evidence of a gas phase. Fine matter is ejected behind the fragments ejected first. The expanding gasses would have begun acting on the test wall itself well before they are evident in the video.
	*Gas phase* *t ~ 240ms* The fine matter is overtaking the larger fragments. Since these particles weigh less, they have a higher velocity than the large fragments.
	*Gas phase* *t ~ 280ms* The fine matter continues to overtake the larger fragments.

4 Analysis

Throughout the simulated rockburst testing, the Support Damage Scale (SDS, Kaiser et al. 1992) has been used to assess damage to each ground support system (see Table 3). The SDS allows comparison of damage between the support systems tested, to which measured PPV's or energy demands can be matched. A damage assessment for each simulated rockburst is carried out by separating the test wall into grid squares. Each grid square represents a data point, for which there exists a PPV taken from contour plots of test wall PPV, a SDS rating and a failure thickness, as measured using the borehole camera. Measurement of failure thickness allows calculation of the energy demand (kJ/m^2) over the test wall, which accounts for not only the PPV generated during each simulated rockburst but also the mass of failed rock acting on the ground support system.

Energy demand is calculated using the methods described by Kaiser et al. (1995), which are considered by the authors to be the most widely adopted approach to dynamic support design or selection.

$$\text{Energy demand per square metre} = \frac{1}{2} t\rho v^2 \tag{1}$$

where:

v = the PPV measured by surface mounted geophones (m/s).

t = thickness of failed rock as observed using the borehole camera (m).

ρ = rock density (kg/m^3).

Note that a gravity component is not included in this case since rock ejection is from the wall of the excavation. Were ejection to occur from the backs, the equation would become:

$$\text{Energy demand per square metre} = \frac{1}{2} t\rho v^2 + t\rho g d \tag{2}$$

where:

g = acceleration due to gravity (9.8m/s^2).

d = downward displacement (m) up to the support system displacement capacity.

The use of only 3 variables and well defined damage categories limits the subjectivity of the analysis. Also, by using energy demand to categorise support performance, many of the factors affecting the demand are considered, such as rock mass structure, composition and density as well as the inconsistencies in blasthole charging. These factors act to alter the density, PPV and failure thickness, all of which are captured in the analysis. The damage assessment procedure is shown graphically in Figure 15.

Table 3 The Support Damage Scale (SDS, Kaiser et al., 1992). Note that the shotcrete damage descriptions were also used when assessing damage to thin spray-on liners

Damage Level	General Description	Support Damage	Shotcrete Damage
S0	Conditions unchanged	No new damage or loading	No new damage or loading
S1	Support undamaged but **first signs of distress** detectable	No damage to any support component	Shotcrete shows new cracks, very fine or widely distributed
S2	**Slight damage** to support **Loading clearly evident but full functionality maintained**	Plates and wooden washers on some rockbolts are deformed, showing loading Individual strands in mesh broken Mesh bagged but retains material well	Shotcrete cracked, minor flakes dislodged Shotcrete is clearly taking load from broken rock mass (mostly drummy)
S3	**Moderate damage** to support Support shows **significant loading and local loss of functionality**; retaining function primarily lost (except in laced or shotcreted areas)	Plates, wooden washers, and wood blocking on rockbolts are heavily deformed, showing significant loading; bolt heads may be "sucked" into rock Mesh torn near bolt heads with some strands broken and mesh torn or opened at overlapping edges Moderate bagging of mesh and isolated failures of rockbolts Cable lacing performs well	Shotcrete fractured, often debonded from rock and/or reinforcement Major flakes possibly dislodged Holding elements mostly intact
S4	**Substantial damage** to support **More extensive loss of retaining and holding functions** (except for lacing systems)	Mesh is often torn and pulled over rockbolt plates; if it did not fail, it is substantially bagged (at capacity) Many rockbolts failed Rock ejected between support components Cable lacing is heavily loaded with bagged mesh	Shotcrete heavily fractured and broken, often separated from the rock mass with pieces lying on the ground or hanging from reinforcement (Connections to holding elements often failed or holding elements failed locally)
S5	**Severe damage** to support Support **retaining, holding, and reinforcing functions failed**	Most ground support components broken or damaged Most rockbolts fail and rock peels off cable bolts Shotcrete non-functional Mesh without cable lacing heavily torn and damaged Cable lacing systems heavily stressed and often failed	For damage level S5, shotcrete fails to be functional and the left-hand column applies

Notes: *1) The damage indicators listed in this table describe damage that is new and was caused by the rockburst. If the observer cannot ascertain that the damage was inflicted by the rockburst then the damage should be ignored for the purposes of damage classification.*

2) One or more damage scales may be observed in same section and should be recorded separately.

3) Rock and support damage levels need not correspond.

4) Because the function of shotcrete support is somewhat different and more complex than for other support systems, a separate column of indicators is provided over the range of S0 to S4. It is important to record where shotcrete is present and when it has been used to determine the support damage level.

5) Failure of rockbolt applies to failure of nut, plate, anchor or shank.

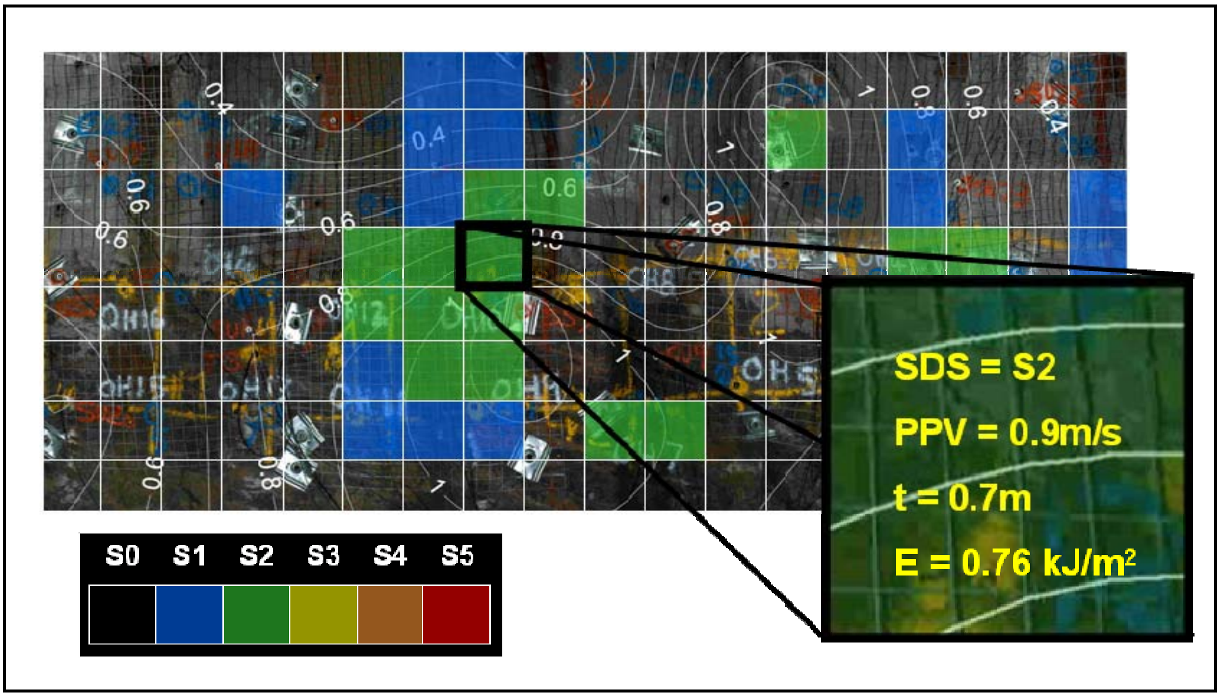

Figure 15 An example of the damage assessment procedure – each grid square is assigned a SDS rating, a PPV and a failure thickness to give a value for energy demand per square metre

Support performance charts, generated using the method illustrated in Figure 15 are shown for the 11 ground support systems tested to date (Figures 16 to 26). The left chart shows the energy demand (kJ/m^2) on the horizontal axis required to cause damage to the ground support system (by SDS rating) on the vertical axis. The right chart shows the PPV (m/s) required to cause each level of support damage (again by SDS rating). Minimum, maximum, average and median values are shown for both charts. The support performance charts show that energy demand is more closely related to support damage than to PPV. This is expected since energy considers the thickness of failed rock as well as the ground velocity acting on a ground support system, incorporating more of the variables which determine performance.

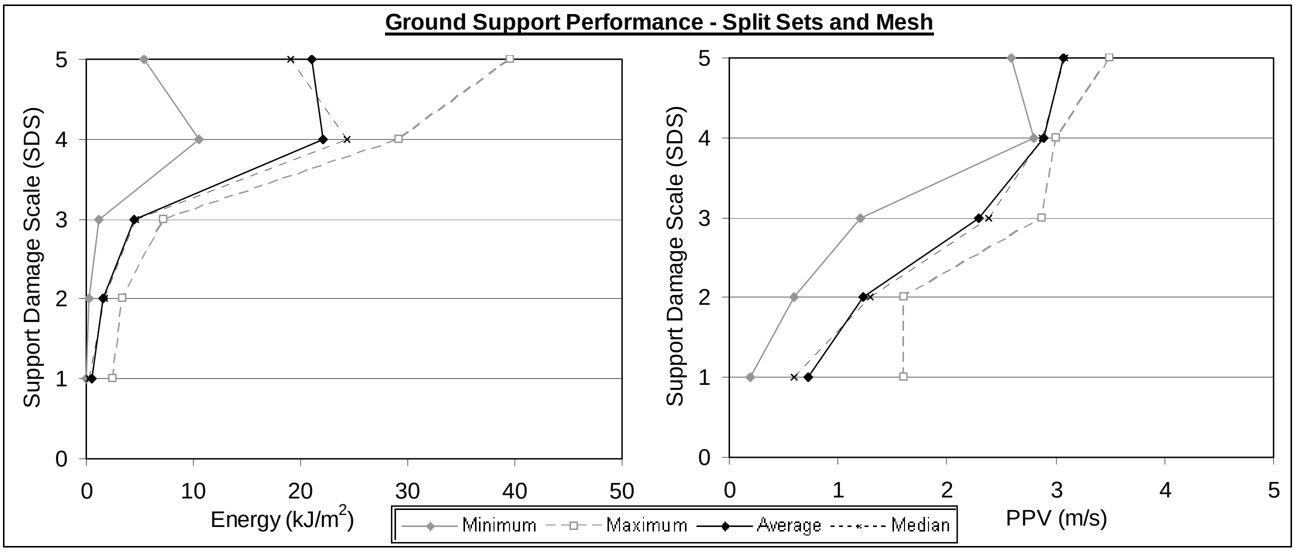

Figure 16 Ground support performance charts for "Split Sets and Mesh"

The charts shown in Figure 16 were created with data from two sets of simulated rockbursts, at two different mines.

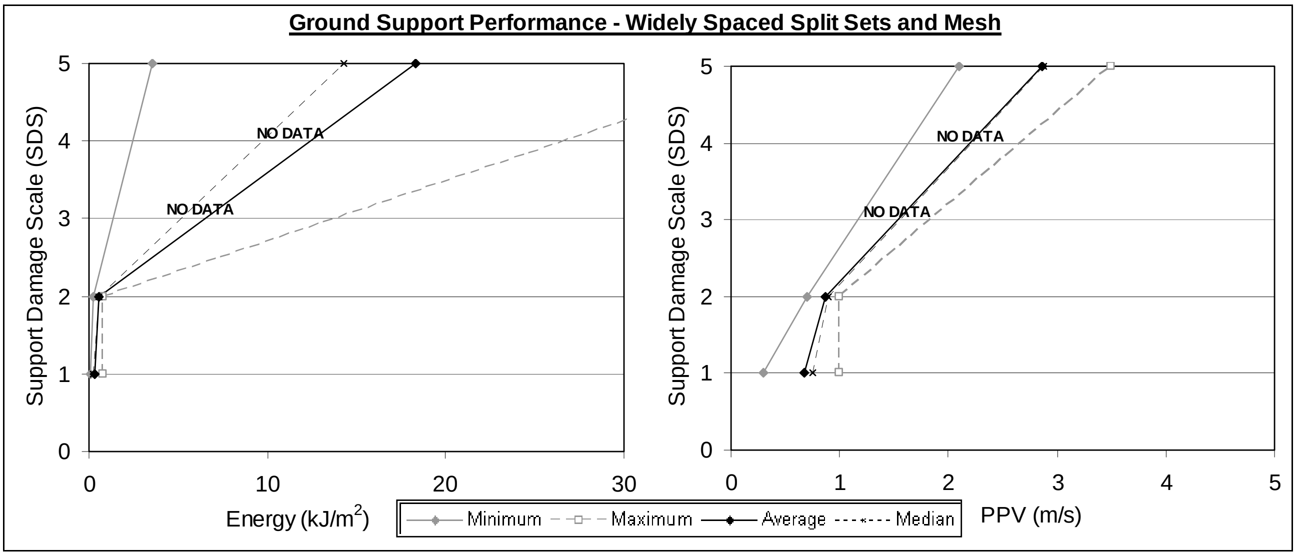

Figure 17 Ground support performance charts for "Widely Spaced Split Sets and Mesh"

There was no data available for SDS levels 3 and 4 for the "Widely Spaced Split Sets and Mesh" ground support system and care should be taken when reading the demands for these SDS levels from the charts. In this set of testing, the second blast generated less than anticipated PPV's, whilst the third blast resulted in severe damage to the test wall. The difference between these results and those for the "Split Sets and Mesh" system below SDS level 3 are likely to be due to the fact that damage to surface support occurred at lower energy demands for the "Widely Spaced Split Sets and Mesh". This is thought to be due to the increased bolt spacing, which resulted in the surface support being subjected to higher loads and less load transfer to individual rock bolt units.

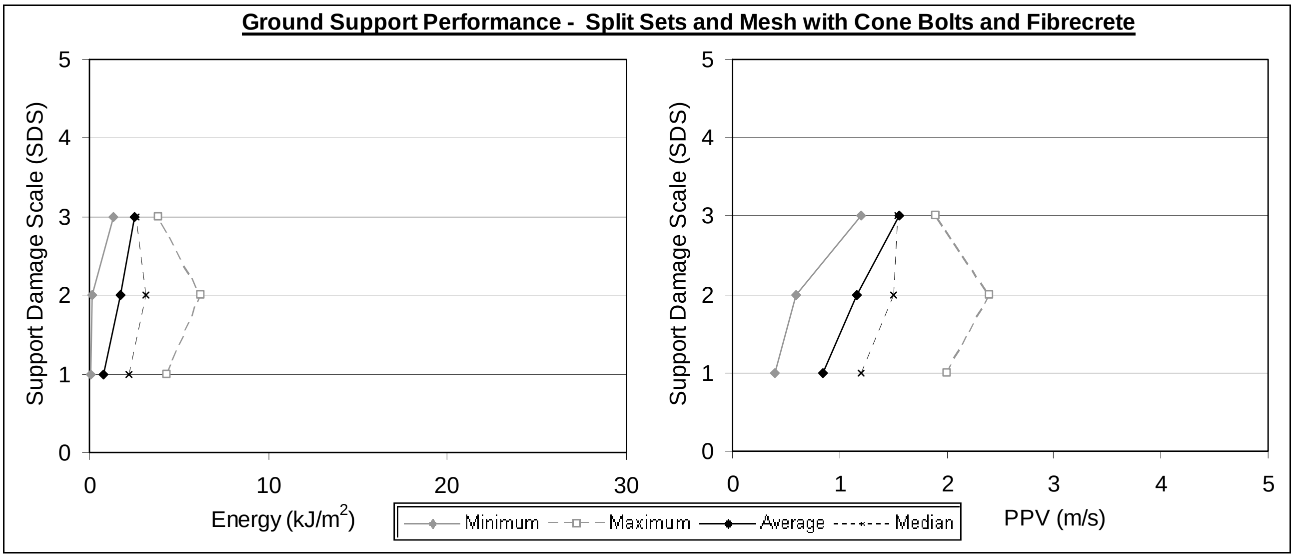

Figure 18 Ground support performance charts for "Split Sets and Mesh with Cone Bolts and Fibrecrete"

The site at which the "Split Sets and Mesh with Cone Bolts and Fibrecrete" ground support system was tested was the first in this series of simulated rockburst tests and a conservative approach was taken for the blast design. As such, heavy damage levels were not achieved for this ground support system. It is apparent though that higher energy demands than the two previous Split Set based systems are required to cause S1 and S2 damage to the "Split Sets and Mesh with Cone Bolts and Fibrecrete" system. The presence of Fibrecrete may also help to explain the difference.

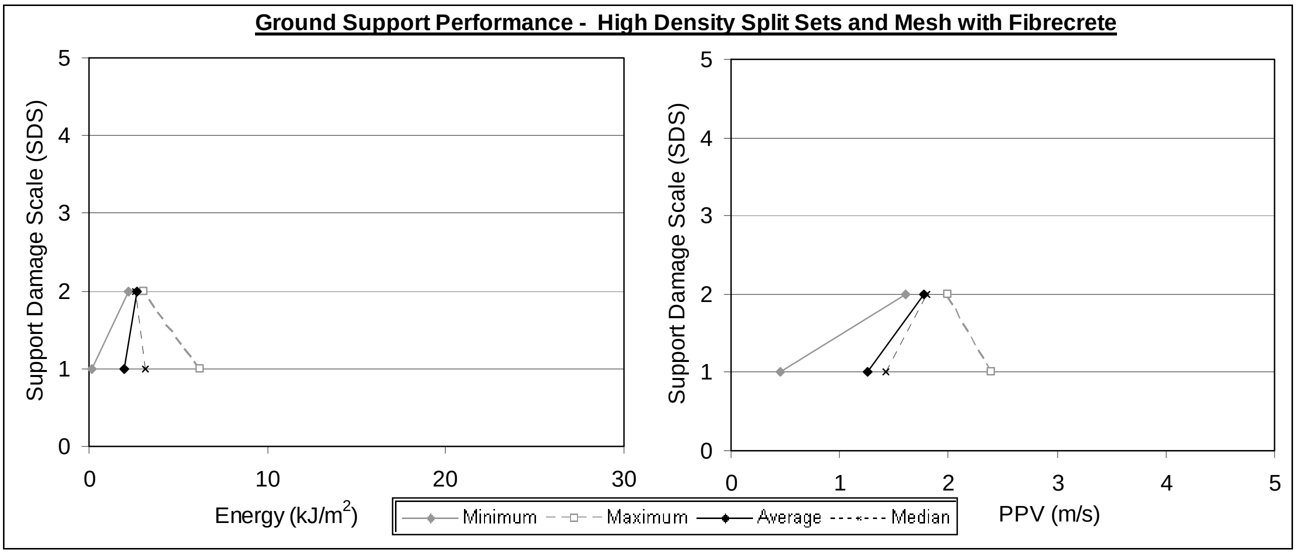

Figure 19 Ground support performance charts for "High Density Split Sets and Mesh with Fibrecrete"

Results from the "High Density Split Sets and Mesh with Fibrecrete" ground support system are also from the first test site and high damage levels were not achieved. The performance charts show similar PPV's and energy demands to those for "Split Sets and Mesh with Cone Bolts and Fibrecrete" but without S3 damage. It is likely that the very tight bolt spacing prevented the onset of S3 damage due to the fact that there was excellent load transfer from the surface support to the individual rockbolt units. This may suggest that performance at these low damage levels is more a function of bolt spacing than of the bolt type.

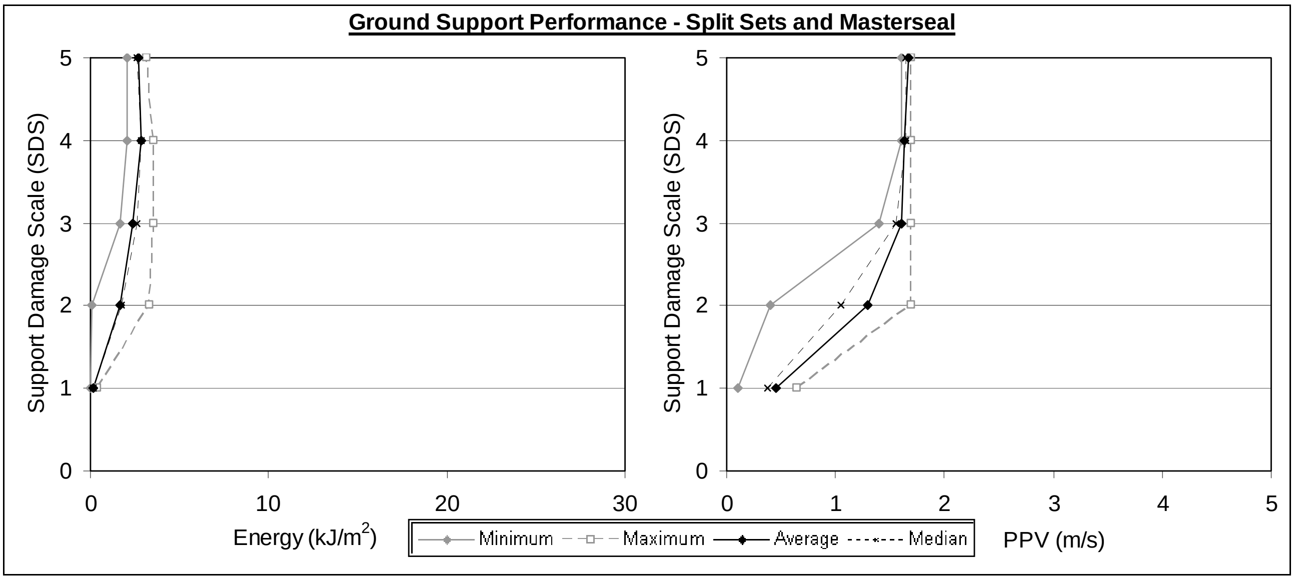

Figure 20 Ground support performance charts for "Split Sets and Masterseal"

Under low dynamic loads (less than around 2kJ/m^2) the "Split Sets and Masterseal" system provided good scat control and demonstrated a capacity comparable to the other systems. However it was found that high levels of damage occur soon after the onset of fracturing of the TSL. The tests on this system demonstrated that the 4 mm thick Masterseal 845A TSL is probably not adequate for conditions where moderate to severe rockbursting is expected.

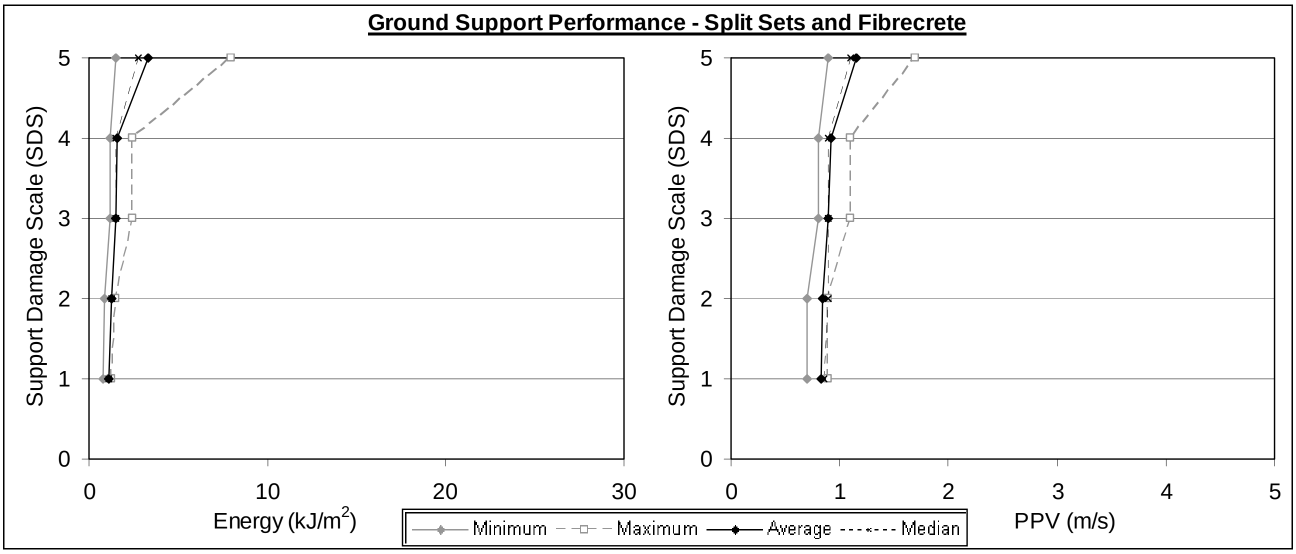

Figure 21 Ground support performance charts for "Split Sets and Fibrecrete"

For low PPV's and energy demands, the "Split Sets and Fibrecrete" ground support system had similar performance to the other support types. However SDS level 3 occurs at around 1.5 to 2 kJ/m^2, which is considerably lower than the systems with mesh. Once low levels of damage occur (cracking of Fibrecrete) the onset of more severe damage occurs with relatively little additional energy demand. Very little load transfer to individual rockbolts occurs once the Fibrecrete is fractured, allowing material to be ejected between bolts.

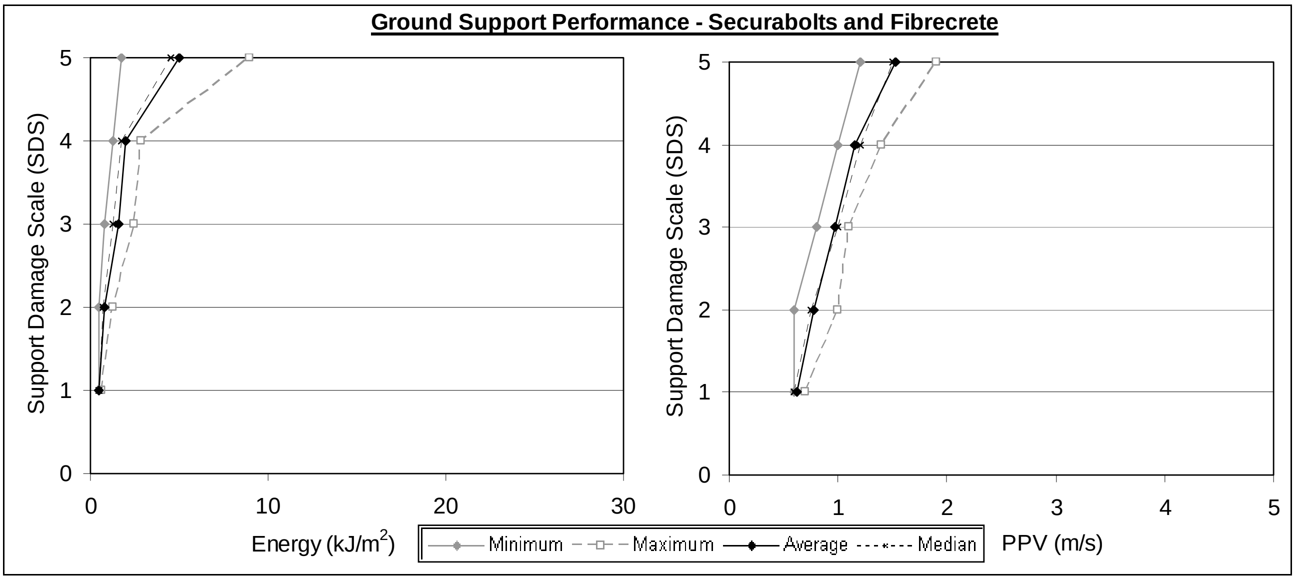

Figure 22 Ground support performance charts for "Securabolts and Fibrecrete"

The performance of "Securabolts and Fibrecrete" was similar to that of "Split Sets and Fibrecrete". The loss of functionality of the support system occurs at relatively low energy demands. Again, once the Fibrecrete cracks, there is little load transfer to the rockbolts.

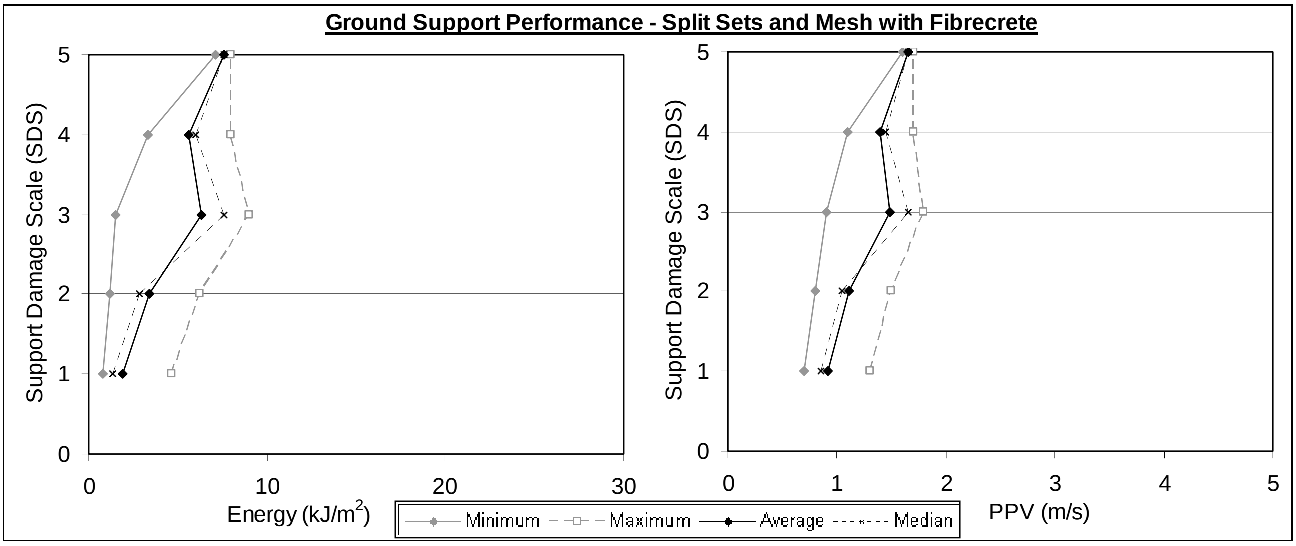

Figure 23 Ground support performance charts for "Split Sets and Mesh with Fibrecrete"

The performance of this ground support system was vastly better than the "Split Sets and Fibrecrete" system (without mesh). There is a considerably higher energy demand required to incur SDS level 3 damage, which presumably is the effect of the mesh. In this case the mesh provided much better load transfer to the individual rockbolts and largely prevented the ejection of material during the simulated rockburst. SDS level 4 is shown to occur at lower energy and PPV values than SDS 3 due to a lack of data for more severe damage.

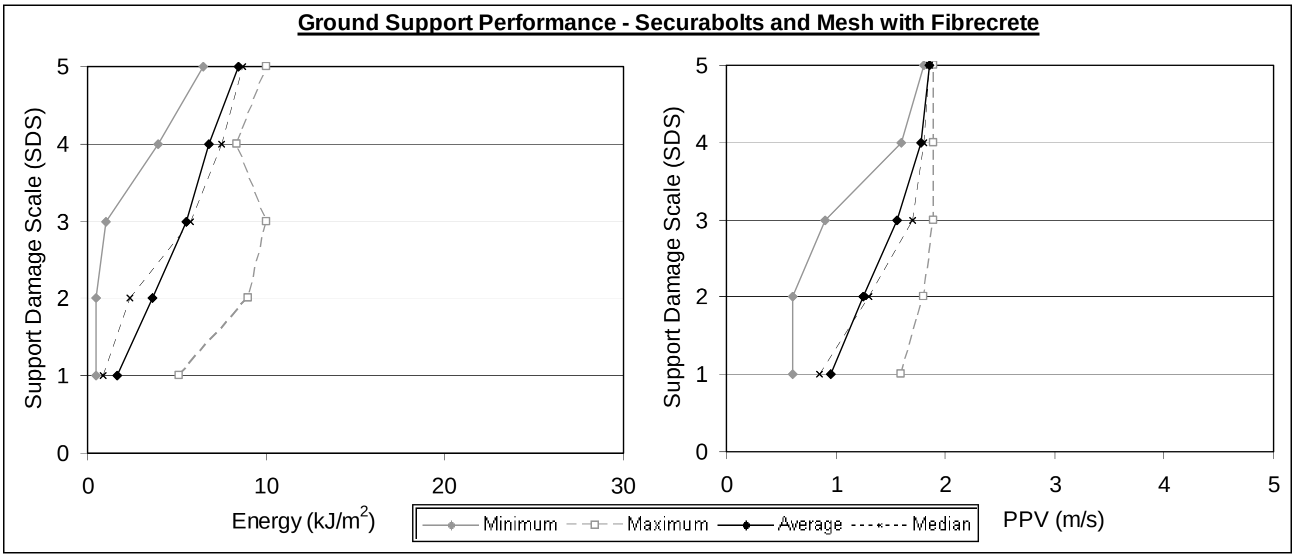

Figure 24 Ground support performance charts for "Securabolts and Mesh with Fibrecrete"

This ground support system shows slightly worse performance than the "Split Sets and Mesh with Fibrecrete" system, although much better than the "Securabolts and Fibrecrete" system. Again, the mesh has provided much improved load transfer and largely prevented the ejection of material into the drive.

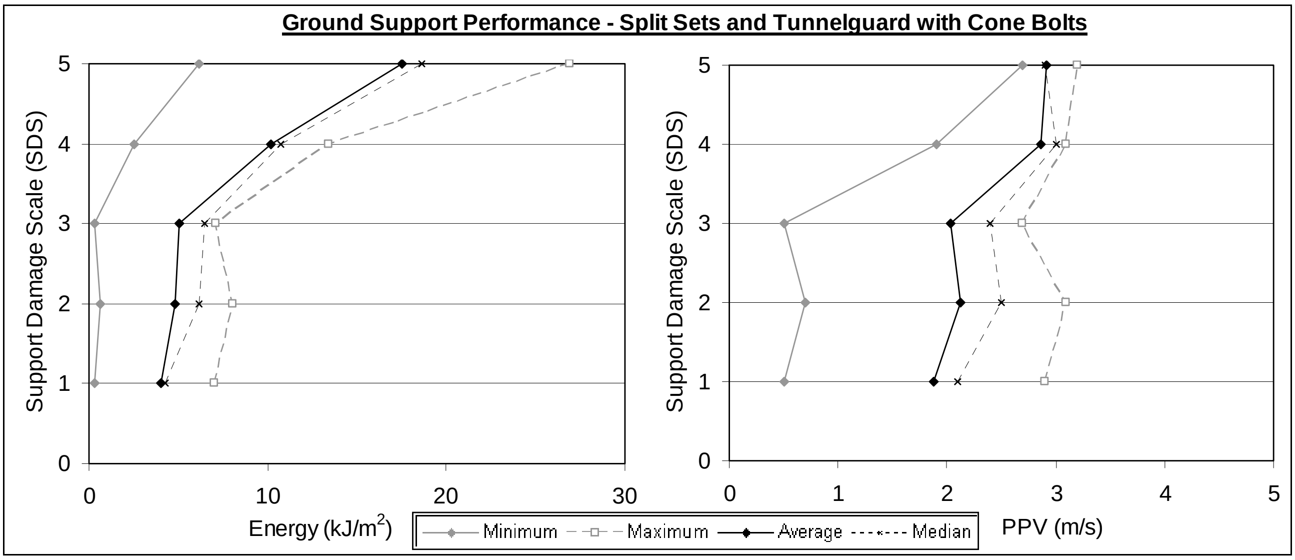

Figure 25 Ground support performance charts for "Split Sets and Tunnelguard with Cone Bolts"

Support Damage Scale level 3 damage occurred at an average of around 5 kJ/m^2 energy demand for the "Split Sets and Tunnelguard with Cone Bolts" system. The Tunnelguard appears to provide some degree of dynamic load transfer to the individual rockbolts for this system. The reason for this is probably the tight bolt spacing (minimum bolt spacing is around 0.6 m for this system). Other non-mesh ground support systems with a minimum bolt spacing of 1.2 m that have been tested show S3 damage at around 2 kJ/m^2 because the surface support fails completely before the rockbolts suffer any significant damage. In some sections of the test wall the Tunnelguard was found to fracture at relatively low energy demands however the tight bolt spacing appeared to prevent rock ejection. The "Split Sets and Tunnelguard with Cone Bolts" system was found to prevent low energy spitting and spalling. The system was found to withstand relatively high PPV's (around 2 m/s) when there was a very low failure thickness. Tunnelguard may be a useful product for spraying on development headings where low energy spitting of scats and spalling may be expected (i.e. fragments less than a few kilograms), but not where a higher failure thickness occurs. Tunnelguard seemed to perform better than the other thin spray-on liner tested using simulated rockbursts, Masterseal 845A.

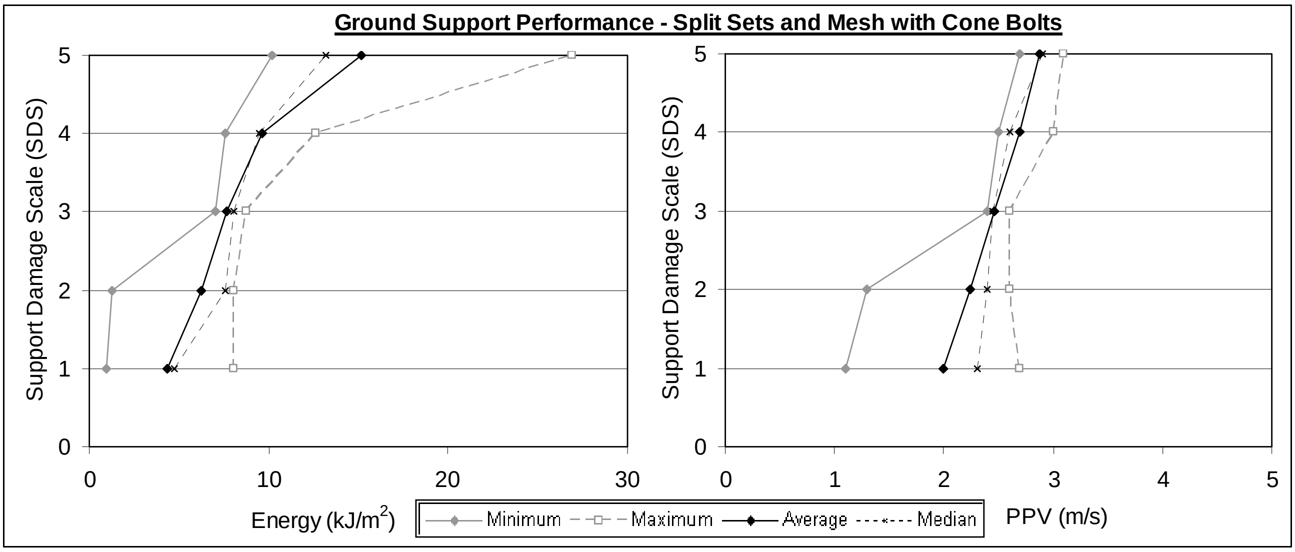

Figure 26 Ground support performance charts for "Split Sets and Mesh with Cone Bolts"

The performance of "Split Sets and Mesh with Cone Bolts" was better than that of the previous system. The mesh provides much better load transfer to the individual rockbolts. The "Split Sets and Mesh with Cone

Bolts" system only marginally outperformed the "Split Sets and Mesh" support systems tested at other mine sites. This is considered to be due to the fact that in many cases where there was bagging of mesh, the mesh was cut by the small Cone Bolt plates. If larger plates had been used it is likely that this ground support system would have performed better and some areas rated R4 or R5 damage would probably have instead sustained R2 or R3 damage.

5 Discussion

Figure 27 shows a comparison of ground support systems tested using simulated rockbursts from a number of mine sites, as well as some data from actual rockburst case studies from the ACG rockburst catalogue (Heal, 2007). The chart shows the average energy demand for S3 damage. This damage level is significant because it is the level at which the loss of support functionality occurs, significant rock ejection is possible and rehabilitation would be required. The PPV for the actual rockburst data from case studies was estimated using a far field scaling law (Kaiser et al., 1995). The support systems for which SDS level S3 and greater was not achieved are not included in Figure 27.

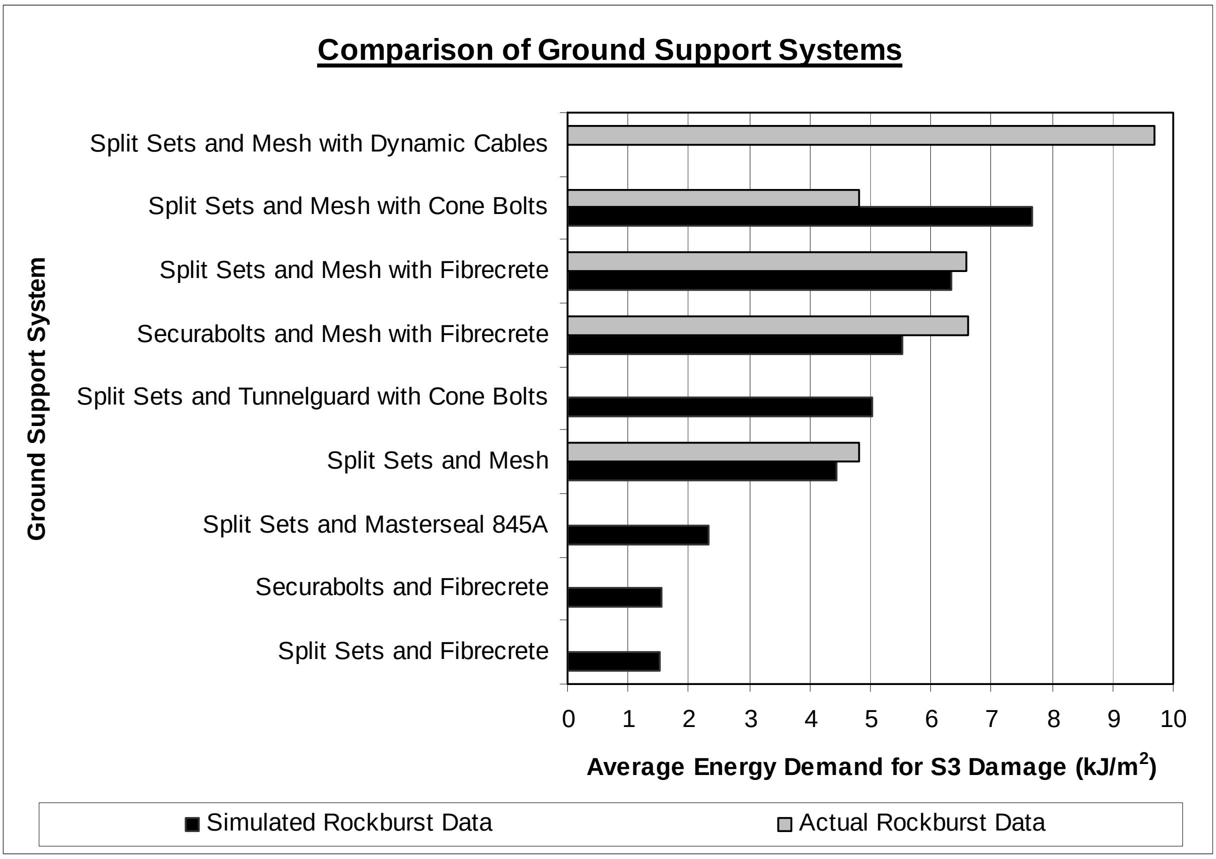

Figure 27 Average energy demand required to cause S3 damage for ground support systems

Figure 27 demonstrates the consistently better performance of support systems incorporating mesh over those which don't. The chart shows that ground support systems without mesh can be expected to fail at energy demands of around 1.5 to 2 kJ/m^2 while those with mesh can be expected to fail at energy demands of around 5 to 8 kJ/m^2. The 1.5 to 2 kJ/m^2 threshold may in fact represent the inherent energy capacity of the unsupported rock mass. This may explain the difference between the Split Sets and Masterseal 845A (Mt Charlotte) and Securabolts or Split Sets and Fibrecrete (Darlot) energy demand for S3 damage. The exception is the Split Sets and Tunnelguard with Cone Bolts system tested at St George. As mentioned previously, it is thought that the tighter bolt spacing meant there was better load transfer to the individual rockbolt units, which prevented some of the damage that would have otherwise occurred to the Tunnelguard.

The addition of Cone Bolts improved the dynamic capacity of the Split Sets and Mesh ground support system. It is likely that because the mesh has allowed some transfer of the dynamic load due to the simulated rockburst to individual rockbolts, the energy capacity of the rockbolts themselves has come into play. It is anticipated that even better performance can be achieved from ground support systems with stronger surface support, such as heavy gauge mesh straps or cable lacing. Dynamically capable support elements such as Cone Bolts and dynamic (or yielding) cables could perhaps have their full capacity engaged during a rockburst when strong surface support is used. Also, better load transfer from the bolts to the surface support would improve dynamic capacity, as was demonstrated by the fact that Cone Bolt plates were found to cut the mesh in several instances during testing. Larger plates or a small section of heavy gauge mesh behind each Cone Bolt plate may have greatly improved their performance.

Fibrecrete, shotcrete or thin spray-on liners alone are not considered to be a suitable surface support for use in conditions where strong dynamic loading due to mine seismicity and rockbursting may be expected. All were found to provide some degree of capacity against low energy spitting and spalling. The tests demonstrate the importance of surface support in a ground support system designed for use in rockbursting conditions. A ground support system with a strong surface support (for example mesh or mesh with cable lacing or heavy gauge mesh straps) can more readily transfer the dynamic load to the individual rockbolts, at which point the full dynamic capacity of the system is engaged. A ground support system with “yielding” rockbolts without effective and strong surface support is likely to be ineffective in rockbursting conditions because the surface support fails before the rockbolts provide any significant capacity, allowing rock to be ejected into the excavation between rockbolts.

6 Conclusion

The simulated rockburst testing of ground support has sought to provide hard data for dynamic support selection in rockburst prone mines. Having an understanding of the maximum expected peak particle velocity or maximum expected seismic event magnitude in a particular area of the mine, and being able to observe or estimate a worst case failure thickness which may occur during a rockburst, it is possible to use the results presented in this paper to estimate the likely level of damage to a ground support system already installed, or aid in the decision as to what ground support system is appropriate. The testing has demonstrated that, as in many other fields of engineering, a ground support system subjected to heavy dynamic loading is only as strong as its weakest component, which is often the surface support or connections between the surface support and rockbolts or cables. Practitioners can make sure that the ground support systems they select are more appropriate for the prevailing ground conditions in seismically active areas of a mine by ensuring strong surface support is used and there is adequate load transfer between the individual support elements.

The fact that the underground mining environment is constantly changing, and features beyond a supported wall or back may not be visible suggests that conservatism is vital in this approach. Despite years of research around the world, our understanding of the performance of ground support systems in-situ during dynamic loading is still limited. Testing programs like the simulated rockbursts presented in this paper and other laboratory testing programs currently underway are attempting to address the gaps in the existing knowledge of the subject. It is hoped that in the future, ground support systems incorporating yielding reinforcing elements with very strong surface support such as thicker gauge mesh or mesh straps and cable lacing will be tested using simulated rockbursts to prove that they may be capable of withstanding very heavy dynamic loading.

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