doi:10.36487/ACG_repo/2435_G-07

The role of surface support in controlling rockbursting conditions

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ABSTRACT

Surface support is a crucial component of the ground support system, especially in rockbursting conditions. However, its role is often underestimated or neglected in the design and evaluation of ground support systems. Surface support is responsible for the toughness of the ground support system as provided means for interaction between the reinforcement elements such as bolts and cables. Combination of different types of surface support, such as Shotcrete, Fibre Reinforced Shotcrete (FRS), welded mesh, high tensile mesh and straps, can result in significant different response on the ground support system to dynamic loading. This paper summarizes the main findings from several large-scale drop tests and underground observations of ground support systems under rockbursting conditions. It also reviews the current methods of assessing the capacity of ground support systems and suggests some ways to improve them by incorporating the influence of surface support.

1 INTRODUCTION

Over time, it has become apparent that the weakest point in designing dynamic support systems is the surface support, also known as the retention system. In current procedures, its contribution to the ground support system is simply added to other single reinforcement elements. However, this assumption overlooks the fact that surface support is crucial in linking the areas affected by large deformations with the stable areas near the bursting location (boundary conditions). This paper presents a series of dynamic tests performed on ground support systems commonly used in seismic active mines in Australia and Chile. These tests were carried out at the large-scale drop test facility in Walenstadt, Switzerland. The nine selected test configurations included in this paper include shotcrete or Fibre Reinforced Shotcrete (FRS), complemented by surface reinforcement options like external mesh (with mesh overlaps), embedded mesh, and straps. The data from these tests were used to create load versus mid-span deflection curves similar to those used in reinforced concrete beam analysis. This paper summarizes the details of the test programs, including specimen properties, test setup and analysis procedures. The test results and significant observations are presented and discussed.

2 CURRENT PROCEDURES TO ASSESS SURFACE SUPPORT CONTRIBUTION

The current methods for calculating the dynamic capacity of ground support systems involve normalizing the capacity of each element and dividing the total energy of these elements by the installation pattern. In the case of surface support, the maximum bolting pattern spacing is used. The system's total energy capacity is then calculated by adding the contribution of each element of the ground support system in terms of kJ/m2 (Drover & Villaescusa, 2015; Kaiser & Moss, 2022). However, these procedure overlooks important factors, such as boundary conditions and changes in surface support stiffness, that can significantly affect how loads are distributed through the reinforcement elements (bolts and cable bolts). The stiffness of the surface support can be altered by changing the thickness of FRS, the position of the mesh, the use of simple or double mesh, and the addition of straps, among others. When using existing methodologies, the role of surface support is often minor compared to that of the reinforcement elements. Therefore, improving any ground support system using current methods can only be achieved by decreasing the spacing between reinforcement elements, two examples of current procedures are shown in Figure 1 and table 1.

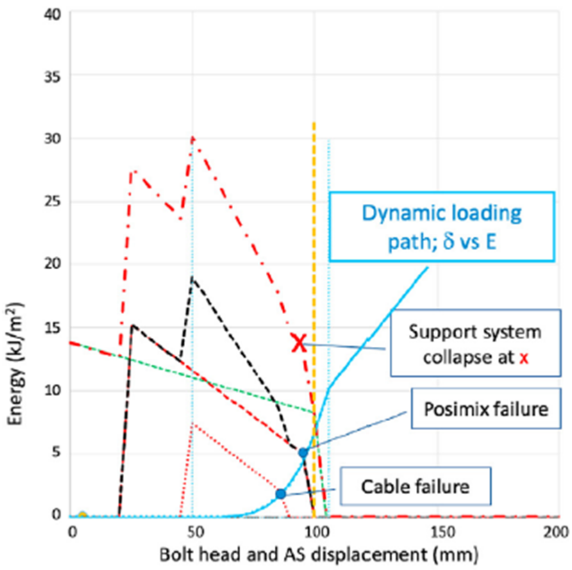

Figure 1 Normalized Energy versus Displacement Capacity of the Support System and Corresponding Energy Demand Loading Path.

According to Kaiser & Moss (2022) The interpretation of the graph shown in Figure 1 is that at the point of collapse, the theoretical remnant capacity is 13.6 kJ/m^2 (at red 'X') and the remnant capacity of the areal support of 8.6 kJ/m^2 is no longer available due to the loss of support when the bolts fail. The graph presented in Figure 1 suggests that the loading path of a seismic event can be independent of the ground support system's capacity path. This is problematic as it seems to violate Newton's third law. However, this type of error arises when energy is added while ignoring the load-displacement curves of the system. In the case of the example shown in Figure 1, it is assumed that the surface support does not contribute once the reinforcement elements fail. This assumption must be corrected as it arises from the wrong boundary conditions that ignore the surface support's contribution after failure of reinforcement elements. The boundary conditions for the surface support require connecting stable zones with heavily damaged areas where typically reinforcement elements fail. Examples of this boundary condition for the surface support can be seen in Figures 3 and 4.

Villaescusa et al (2016) updated his proposed qualitative definition of rock mass demand based on reaction pressure, surface displacement at failure, and energy demands per square meter. The demand can be classified into five categories: low, medium, high, very high, and extremely high. The classification is illustrated in Table 1 and the energy demand can be calculated using the graph shown in Figure 2. Hence when using this methodology, the practitioner must calculate the kJ/m^2 by adding the contribution of the surface support in terms of kJ/m^2, some examples of this can be found in Drover & Villaescusa (2016) and Celis & Parraguez (2023). The data presented in Table 1 indicates a linear correlation between displacement and energy. This observation suggests that all the tested systems in this table exhibit similar stiffness. However, it's important to note that varying the stiffness of the surface support will lead to comparable energy capacity but significantly different displacement thresholds.

Table 1 Typical rock mass demand for ground support design (from Villaescusa 2016)

Demand category	Reaction pressure (KPa)	Surface displacement (mm)	Energy (KJ/m^2)
Very Low	<100	<50	<5
Low	100-150	50-100	5-15
Medium	150-200	100-200	15-25
High	200-400	200-300	25-35
Very High	400-500	300-400	35-45
Extremely High	>500	>400	>45

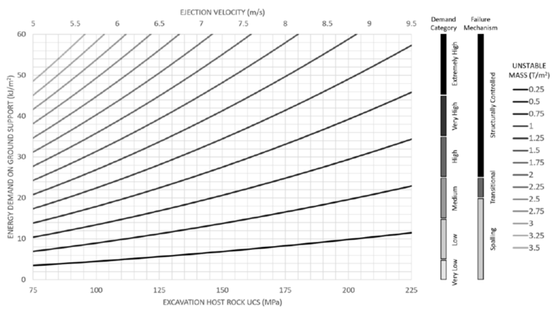

Figure 2 Range of energy demand for sudden and violent stress-driven failures (from Villaescusa et al., 2016).

3 GROUND SUPPORT SYSTEM BOUNDARY CONDITIONS DURING A STRAINBURST

When evaluating ground support systems, particularly the role of surface support, a critical challenge lies in defining boundary conditions that accurately reflect underground observations during rockbursts. Notably, many ground support system failures after a rockburst occurs due to the surface support's inability to transfer load from unstable volumes to stable regions within the rock mass. Some instances of this phenomenon are evident in Figure 3, where only FRS was used. Conversely, there are cases where surface support successfully bridges stable and unstable areas, as depicted in Figure 4. Furthermore, assessing the contribution of the surface support composite comprising FRS and mesh requires a more nuanced approach. Unlike a simple additive process of normalized capacities, the composite's response to loading now depends on its stiffness. To illustrate, consider designing reinforced concrete beams and slabs: merely adding constituents in kJ/m² does not yield the desired outcome; hence, a more thoughtful approach is necessary.

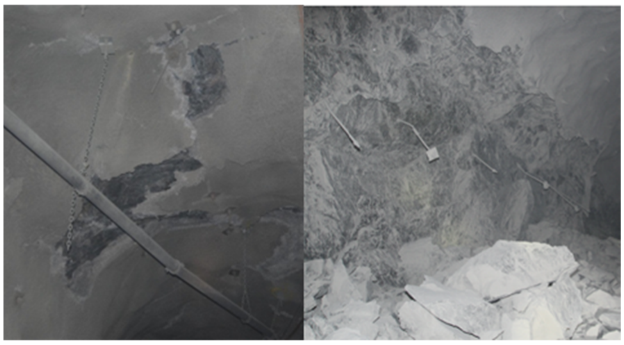

Figure 3 Illustrative cases of ground support breaches following Strainbursts in Block Caving Operations.

Figure 4 Instances of heavily damaged yet contained ground support following Strainbursts in Block Caving Operations.

4 EXPERIMENTAL INVESTIGATION

As highlighted in the preceding section, accurately assessing the contribution of surface support necessitates a proper representation of its boundary conditions and stiffness within the Ground Support System calculations. A potential method involves constructing and analyzing deflection versus load graphs for ground support systems, akin to the approach used in the design of reinforced concrete beams and slabs. However, the existing dynamic test setups impose limitations on the number of reinforcement elements allowed to fail. Despite these constraints, notable parallels exist between the boundary conditions of ground support systems observed in large-scale dynamic testing and those following a strain burst. These parallels are illustrated in Figures 3, 4, and 5.

Figure 5 Examples of Ground Support System Post-Drop Test: Heavy Damage and Breach (Left), Successful Retention of Falling Mass (Right).

4.1 Test arrangement and trailed ground support systems.

Figure 6 illustrates the test device with its essential features, designed to analyze the impact behavior of a trial ground support system when impacted by a free-falling mass. The device includes a two-level platform outfitted with the following components.

a) Upper level: This level contains the free-falling mass, consisting of concrete blocks weighing either 6,400 kg or 9,640 kg. In the tests conducted for this study, these blocks were dropped from heights between 0.48 meters and 2.5 meters, acquiring kinetic energy from 30 to 240 kJ upon impacting the ground support composite. Steel profiles guide the blocks, ensuring accurate alignment and impact trajectory.

b) Lower Level: This level features a surface support composite that directly absorbs the impact of the falling mass, transferring the load to the reinforcement elements. The study evaluated nine ground support systems, detailed in Table 2, showcasing a range of surface support composites, including shotcrete, FRS, and enhancements like external mesh overlaps, straps, or embedded mesh. Each system was standardized with a surface support composite measuring 3.6 meters by 3.6 meters.

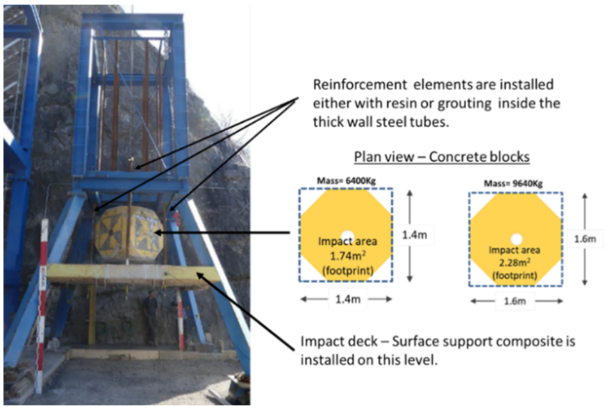

Figure 6 Configuration and Key Features of Large-Scale Drop Test Apparatus.

The test device, shown in Figure 6, is designed to analyze the impact behavior of a trial ground support system resulting from the impact of a free-falling mass. It comprises a two-level platform with the following components.

4.2 Key Characteristics of Examined Ground Support Systems

Nine ground support systems were selected for analysis based on previous testing campaigns, with their primary characteristics detailed in Table 2. To further investigate the role of surface support within each configuration, deflection-versus-load graphs were developed for these systems. The methodology used to construct these graphs is elaborated in the following section.

Table 2 Key Characteristics of Examined Ground Support Systems

Shotcrete thickness/UCS	FRS Thickness /UCS	Embeded Mesh/ Depth	Mesh Type	Mesh Overlap	Osro Strap	Central Reinforcement element / Type	Bolt Type / Pattern	Cable Type / Pattern	Mass	Dropping Height	Mass Restrained
(MPa)	(mm)/(MPa)	(mm)		(mm)			(m)	(m)	(kg)	(m)	
No	100/40	Yes/50	Welded Mesh	No	No	No	22mm A630-threadbar/1.4x1.4	No	6400	0.48	No
No	100/40	Yes/50	DCR MINAX 80/30	No	No	No	22mm A630-threadbar/1.4x1.4	No	6400	0.48	Yes
No	100/40	No	DCR MINAX 80/4.6	Yes (400 mm)	No	No	Posimix/1.4x1.4	No	6400	1.2	Yes
70/50	No	No	DCR MINAX 80/4.6	No	No	Yes/bolt	22mm A630-threadbar/1.0x1.0	No	9600	2.5	No
70/50	No	Yes/20	2xDCR MINAX 80/30	N/A	No	Yes/bolt	22mm A630-threadbar/1.0x1.0	No	9600	1.3	Yes
No	100/40	No	Welded Mesh	Yes (400 mm)	No	Yes/bolt	Posimix/1.0x1.0	No	6400	0.9	Yes
No	100/40	No	DCR MINAX 80/4.6	Yes (400 mm)	No	Yes/bolt	Posimix/1.0x1.0	No	6400	0.94	Yes
No	100/40	No	Welded Mesh	Yes (400 mm)	Yes	Yes/Cable	Posimix/1.4x1.4	Dice/1.4	9600	1.06	Yes
No	100/40	No	DCR MINAX 80/4.6	Yes (400 mm)	No	Yes/Cable	Posimix/1.4x1.4	Dice/1.4	9600	1.06	Yes

5 DEFLECTION VS. LOAD ANALYSIS METHODOLOGY

A systematic procedure was established to process the test data shown in Table 2, enabling the effective interpretation of these data through the creation of deflection versus load graphs for each ground support system. The primary steps of this procedure are summarized below.

Step 1: Calculate the system load by summing the loads recorded at each reinforcement element. Figure 7 illustrates the individual loads at each anchor, along with the system's total load, measured at various time intervals.

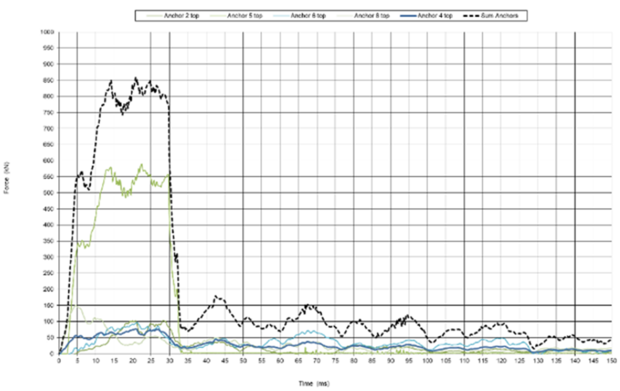

Figure 7 Time-Based Load Analysis of Total System and Reinforcement Elements

Step 2: Compare the loads measured by the reinforcement elements to the calculated load, which is derived from the acceleration-induced force on the falling block, as recorded by the accelerometer. Figure 8 presents an example of this comparison. This step ensures the alignment of the load dissipated by the ground support systems with the load exerted by the falling block, confirming that only minimal load is transferred to the external test structure, which is not part of the ground support system.

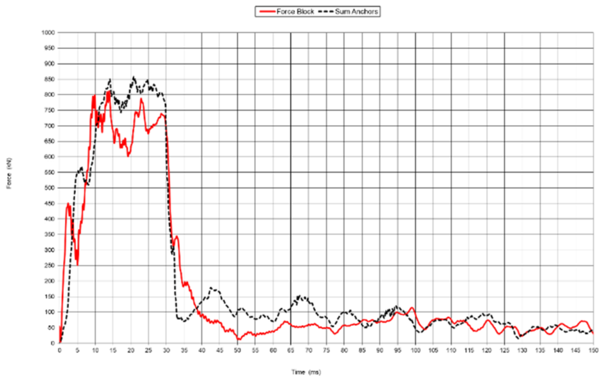

Figure 8 Comparison of load recorded by accelerometer in the falling mass versus total load recorded at anchor cells during drop test.

Step 3: Employ the vertical displacement of the block to quantify deflection, illustrated in Figure 9. In this figure's graph, negative time indicates the period before the collision, while negative values on the Y-axis represent the deflection.

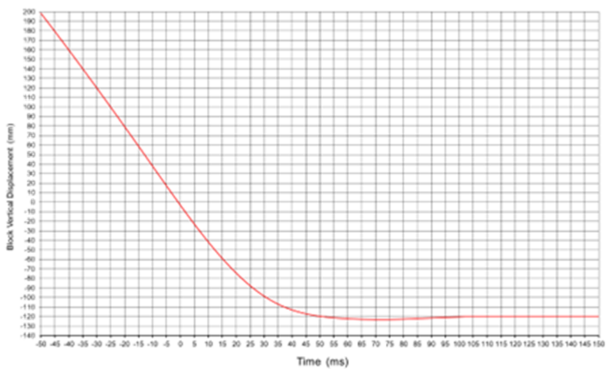

Figure 9 Time-Versus-Vertical Displacement Graph for the Falling Block During Impact Test.

Step 4: Generate deflection versus load graphs, assuming central deflection correlates with the vertical displacement of the falling block. This assumption is justified as the block's internal deformation is minimal and negligible for this analysis. Figure 10 displays an example graph for a twin-cable system.

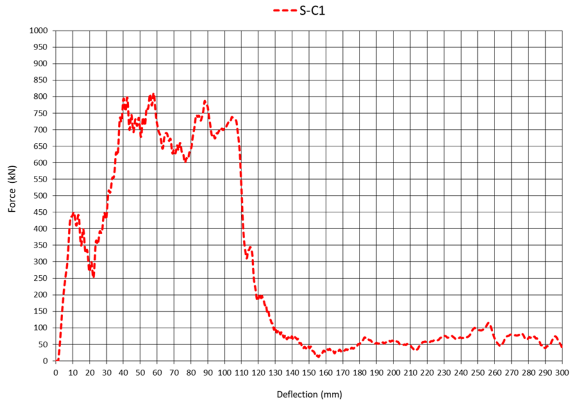

Figure 10 Deflection versus Load Analysis for Ground Support System S-C1.

6 OVERVIEW OF TEST RESULTS AND DEFLECTION ANALYSIS

To explore the impact of surface support composites on ground support systems, the configurations were categorized into three main groups. These groups were distinguished based on the falling mass's interaction with the reinforcement elements and the type of these elements—either primary (bolts) or secondary (cables). Figure 11 provides a visual representation of these groups.

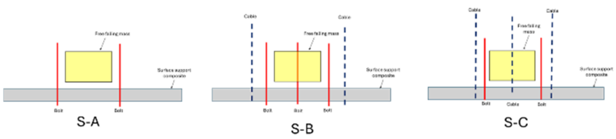

Figure 11 Categorization of Ground Support System Configurations by Reinforcement Type and Falling Mass Interaction.

Figure 11 delineates the key differences among ground support systems based on the interaction with a free-falling block, particularly focusing on surface support and reinforcement elements. The classification includes S-A, where the block directly impacts only the surface support without any central reinforcement; S-B, where the block impacts both the surface support and a central bolt; and S-C, where the impact is on both the surface support and a central cable.

6.1 Direct impact on Surface support without a central reinforcement element

Three system configurations, S-A1, S-A2, and S-A3, were evaluated to observe the effects of a free-falling block impacting the surface support without central reinforcement. The specifics of these systems are detailed in Table 2, with their respective test setups and outcomes illustrated in Figures 12, 14, and 16.

System S-A1

System S-A1 features a surface support layer of 100mm thick Fibre Reinforced Shotcrete (FRS) with an Unconfined Compressive Strength (UCS) of 40Mpa, complemented by an embedded welded mesh without overlaps. The reinforcement elements, consisting of rock bolts with a 22mm diameter, are arranged in a square pattern of 1.4m and located outside the impact zone. Figure 12 illustrates the arrangement and condition of the ground support system before and after the drop test. At the moment of impact, the kinetic energy is approximately 30 kJ.

Figure 12 Ground Support System S-A1: Pre and Post Impact Test Configuration.

The maximum load transfer, as illustrated in Figure 13, predominantly occurs within the initial 10mm of deflection, signifying the failure of the FRS. Following this, the welded mesh starts to engage around 20mm of deflection, bearing the load for an additional span of 20mm of deflection before it continues to stretch and eventually ruptures at approximately 170mm. Before the FRS failure, the system records a peak load of 370kN. This load then diminishes to a peak of 160kN at a total deflection of 40mm, beyond which the mesh undergoes deformation, transferring minimal load to the bolt until the system ultimately fails catastrophically.

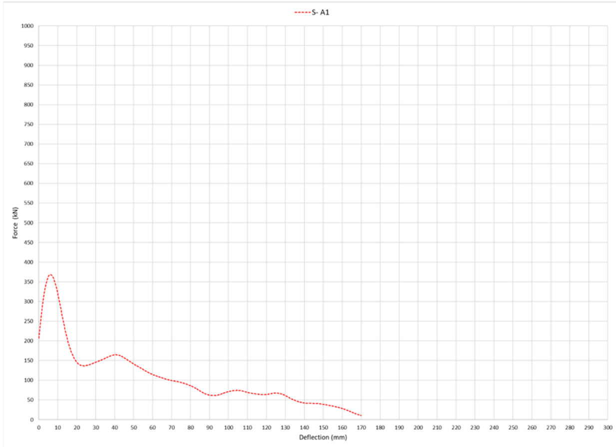

Figure 13 Load Transfer and Deformation Analysis of Ground Support System S-A1 During Deflection Stages.

System S-A2

System S-A2 shares the same features as System S-A1, except for the mesh type; it employs the high-tensile-capacity MINAX 80/4.6 mesh. Figure 14 shows the condition of System S-A2 before and after the impact test. At the moment of impact, the kinetic energy is approximately 30 kJ.

Figure 14 Ground Support System S-A2: Pre and Post Impact Test Configuration.

Inspection of the graphs shown in Figure 15 allows for the following observations: Similar to the S1-A system, most load transfer occurs within the initial 10mm of deflection, corresponding to the failure of the FRS. As the deflection increases to 20mm, the MINAX 80/4.6 mesh engages and sustains the load until the total deflection reaches 50mm. Beyond this point, the mesh continues to deform, ultimately arresting the falling mass at approximately 80mm of total central deflection before rebounding. Prior to FRS failure, the load recorded at the bolts ranged from 100KN to 165KN, contributing to a total system load of 450KN. Subsequently, the load dropped to

300KN, with the maximum load recorded by a bolt being 142KN. Finally, when the load decreased to 50KN, the system effectively halted the falling block.

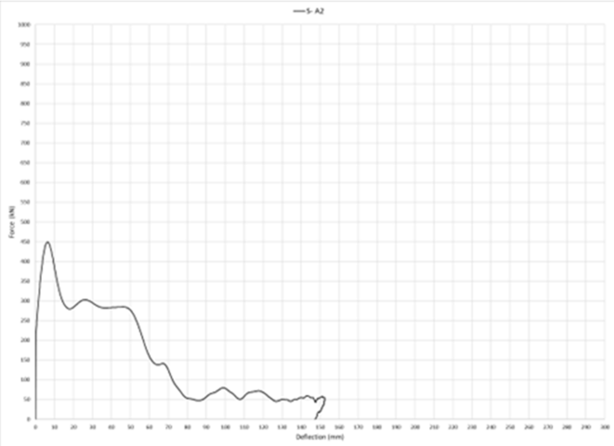

Figure 15 Load Transfer and Deformation Analysis of Ground Support System S-A2 During Deflection Stages.

System S-A3

System S-A3, tested subsequent to the centre bolt's failure in System S-B4, features a bolt spacing of 1.0 x 1.4 meters, demonstrated in Figure 16. This setup includes a 400mm mesh overlap with the high-tensile MINAX 80/4.6 mesh. Significant cracking and detachment observed in the Fibre Reinforced Shotcrete (FRS) indicate that, despite the FRS slabs being held in place by the mesh, there is a loss of connection from the impact zone to the stable zone. This suggests that the mesh primarily enhances the surface support system's performance by facilitating load transfer to the peripheral bolts in the stable area. At the moment of impact, the kinetic energy is approximately 75 kJ.

Figure 16 Ground Support System S-A2: Pre and Post Impact Test Configuration.

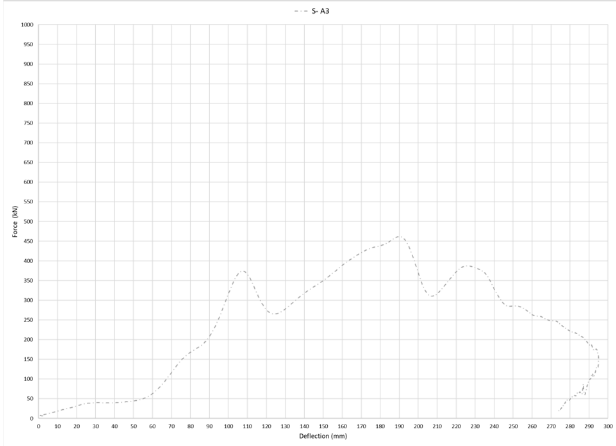

Figure 17 Load Transfer and Deformation Analysis of Ground Support System S-A3 During Deflection Stages.

Figure 17 reveals that the high-tensile mesh undergoes deformation without supporting any load until a deflection of 60mm is attained. Upon reaching a central deflection of 110mm, the mesh encounters its first peak load at 373kN. Further deformation leads to a second peak load of 461kN at 190mm of deflection, which is required to arrest the falling block at a total deflection of 290mm. After this deflection threshold, the block starts to rebound.

Figure 18 summarizes the performance of the three surface support systems, highlighting how their maximum energy values are significantly determined by the ability of the surface support to engage the reinforcement elements effectively. Furthermore, it is observed that the bolts located outside the impact zone distribute the load consistently within their elastic limits, without undergoing yielding.

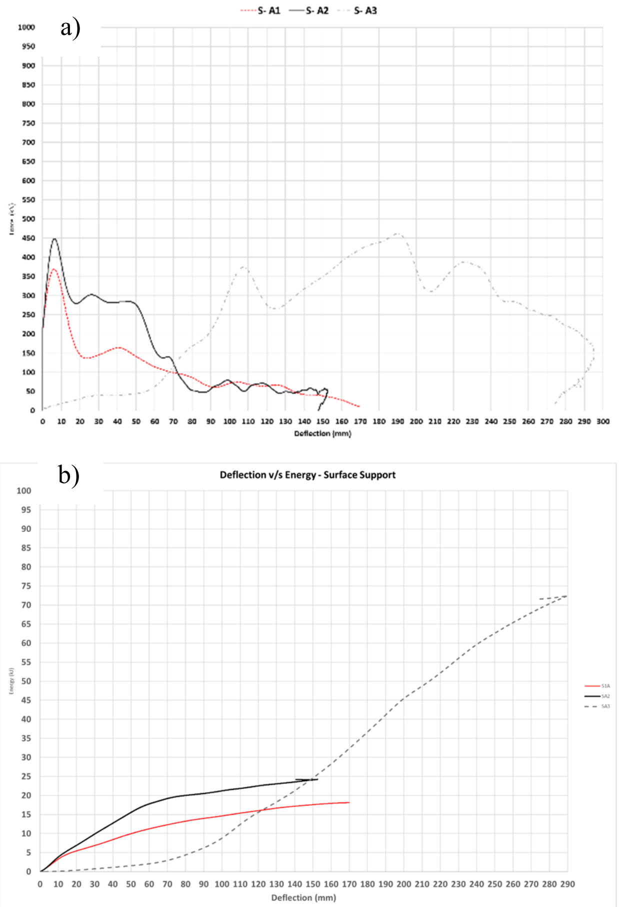

Figure 18 Comparative Analysis of Deflection versus Load (a) and Energy Dissipation versus Deflection (b).

6.2 Direct impact on surface support with a central bolt

Four ground support system configurations featuring a central bolt were evaluated—S-B1, S-B2, S-B3, and S-B4—as depicted in the central part of Figure 11. These systems underwent tests with a block impacting both the surface support and the central reinforcement element. Their main characteristics are detailed in Table 2.

System S-B1

The support system for the ground, S-B1, is composed of a 70mm layer of shotcrete with a UCS of 50 MPa. This layer also includes an external MINAX 80/4.6 mesh. For reinforcement, rock bolts (25mm in diameter, A630 Chilean Steel grade) are arranged in a 1.0 x 1.0 pattern both inside and outside the impact zone. Figure 19 illustrates conditions before and after the drop test. At the moment of impact, the kinetic energy is approximately 236kJ.

Figure 19 Ground Support System S-B1: Pre and Post Impact Test Configuration.

Figure 20 reveals that the initial peak deflection of 15mm corresponds to shotcrete failure and the onset of yielding in the central bolt within the impact zone. From 20mm to 60mm of deflection, the peripheral bolts outside the impact zone were engaged, with the maximum load reaching 525kN. After 60mm of central deflection, failure occurred near the plate in the central bolt, prompting mesh deformation. This continued until 100mm of total central deflection, when load transfer shifted back to the peripheral bolts. The system endured until reaching 230mm of total deflection and a maximum load of 390kN, culminating in the mesh's failure and the system's catastrophic breakdown. Notably, all bolts outside the impact zone were subjected to loads significantly below their yield points.

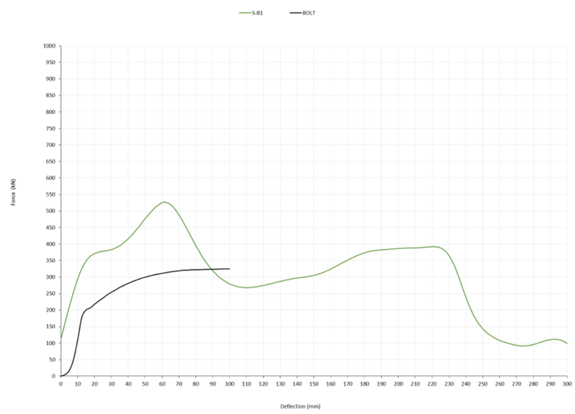

Figure 20 Analysis of Load Transfer and Deformation in Ground Support System S-B1 Across Deflection Stages with Theoretical Bolt Load-Deformation Curve (Black Line) Displayed.

System S-B2

The ground support system comprises two MINAX 80/4 meshes: one external mesh attached to the 70-meter shotcrete surface and another embedded mesh situated 20mm below the shotcrete layer. Rock bolts, 25mm in diameter and made of A630 Chilean Steel grade, are systematically arranged in a 1.0 x 1.0m grid pattern throughout both the impact zone and its periphery. Figure 21 depicts the system's configuration prior to and subsequent to the drop test. Except for the additional embedded mesh, this setup mirrors System S-B1. At the time of impact, the kinetic energy of the system is approximately 122kJ.

Figure 21 Ground Support System S-B2: Pre and Post Impact Test Configuration.

The data from the test is shown in graphs presented in Figure 22. The initial peak occurs at approximately 20mm of deflection, signifying the failure of the shotcrete and the onset of yielding for the central bolt within the impact zone. The system reaches its peak load at 40mm of central deflection. Following this, the load starts to decrease as both the mesh deforms. During this phase, the load is consistently maintained at 780kN and 725kN between 60mm and 87mm of total deflection. Subsequently, the deformation increases, accompanied by a drop in load from 728kN to 566kN. The system's load then rises again, reaching a new peak at 770kN with a total deflection of 144mm. After this peak, the load decreases until the falling block stops and begins to bounce back. Notably, all of the peripheral bolts in this test remained within the elastic range.

Figure 22 Analysis of Load Transfer and Deformation in Ground Support System S-B2 Across Deflection Stages with Theoretical Bolt Load-Deformation Curve (Black Line) Displayed.

System S-B3

This ground support system comprises a 100mm FRS with an external welded mesh (5.6 100/100). Additionally, there is a 400mm mesh overlap. Nine debonded Posimix bolts (25 mm diameter) in a 1.0x1.0 pattern were installed within the FRS panel. Figure 23 illustrates conditions before and after the drop test. At the moment of impact, the kinetic energy is approximately 56kJ.

Figure 23 Ground Support System S-B3: Pre and Post Impact Test Configuration.

The results from the test are depicted in Figure 24, which shows the load behavior of the system. Initially, a peak load of 471kN is observed at 10mm of central deflection, marking the failure of the FRS. Subsequently, the engagement of the two external meshes allows the system to maintain a load of 459kN during the yielding phase of the central bolt, up until a central deflection of 56mm. The tension in the mesh overlap then increases, driving the load to a maximum of 753kN at a central deflection of 95mm. The central bolt eventually fails near

130mm of central deflection, yet the system succeeds in halting the falling block. Throughout the test, all peripheral bolts remained within their elastic limits. A notable sharp decrease in loading capacity around 120mm of deflection suggests that the system was approaching its limit in load transfer capability to the surrounding bolts outside the impact zone.

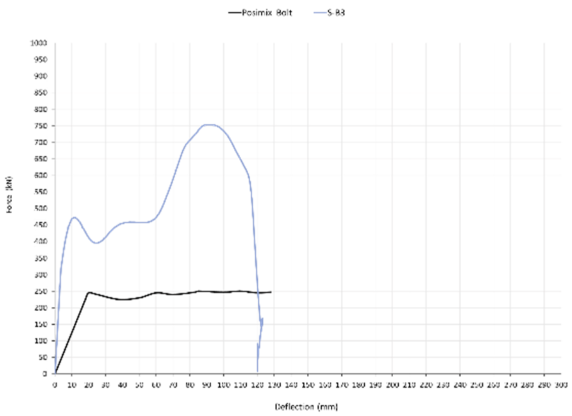

Figure 24 Analysis of Load Transfer and Deformation in Ground Support System S-B3 Across Deflection Stages with Theoretical Bolt Load-Deformation Curve (Black Line) Displayed.

System S-B4

This ground support system features a 100mm thick FRS layer, covered by an external MINAX 80/4 mesh, and includes a 400mm mesh overlap. It is reinforced with nine debonded Posimix bolts, each 25 mm in diameter, arranged in a 1.0x1.0m grid pattern within the FRS panel. Figure 25 displays the system's condition before and after the drop test. Except for the mesh type, this setup mirrors System S-B3. At the time of impact, the kinetic energy registered is approximately 59kJ.

Figure 25 Ground Support System S-B4: Pre and Post Impact Test Configuration.

The data from system S-B4, depicted in Figure 26, shows that at around 20 mm of deflection, a peak load of 450kN is reached, indicating the failure of the FRS. Concurrently, the central bolt within the impact zone starts to yield. A central deflection of only 44mm results in the central bolt detaching, attributed to thread stripping from installation errors. Following this point, a noticeable load reduction occurs, with the mesh undergoing progressive deformation. Load transfer to the peripheral bolts occurs at 65 mm of total central deflection, leading the system to its maximum load of 432kN at 97 mm of deflection. The load on all peripheral bolts remained significantly below their yield point. The block is eventually restrained at a total deflection of 170 mm, subsequently rebounding, contrasting with system S-B3 where the surface support's capacity was nearly exhausted.

Figure 26 Analysis of Load Transfer and Deformation in Ground Support System S-B4 Across Deflection Stages with Theoretical Bolt Load-Deformation Curve (Black Line) Displayed.

The data in Figure 27 encapsulates the performance of the four ground support systems, highlighting that systems employing a double mesh with high tensile strength consistently outperform others. All systems show a comparable load distribution pattern up to the pre-failure of Fibre Reinforced Shotcrete (FRS)/plain shotcrete and the pre-yielding phase of the central bolts, with system S-B4 being the exception (due to premature failure of the central bolt). Specifically, the graph in Figure 27 (left) demonstrates that combining FRS or plain shotcrete with high tensile mesh enables the systems to sustain load transfer significantly past the central bolt's failure, maintaining load transfer to the bolts outside the impact zone up to 220mm for SB-1 and 300mm for SB-4 of central deflection.

Moreover, the systems using either composite FRS and high tensile mesh or plain shotcrete and high tensile mesh initiate engagement with the peripheral bolts at less than 60mm of deflection. Initially, all systems exhibit similar energy absorption within the first 10 to 20mm of deflection. Subsequent energy dissipation rates are influenced by the external and embedded high tensile mesh layers, as Figure 27 (right) indicates, with deflection values ranging from 50mm to 112mm needed to dissipate 40kj, depending on whether single or double layers of high tensile mesh are utilized.

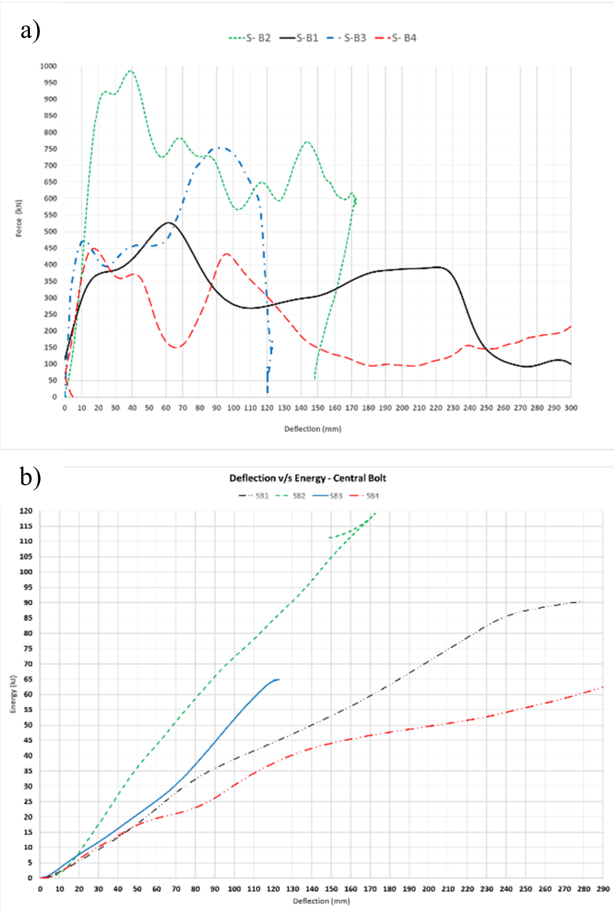

Figure 27 Comparative Analysis of Deflection versus Load (a) and Energy Dissipation versus Deflection (b).

6.3 Direct impact on surface support with a central cable-bolt

Two system configurations, S-C1 and S-C2, featuring twin cables installed in the impact zone, were examined. These setups are depicted in Figures 28 and 31 and involved testing with a block impacting both the surface support and a central twin cable reinforcement element. The primary characteristics and details of these systems are provided in Table 2.

System S-C1

The system includes a 100mm layer of FRS with an Unconfined Compressive Strength (UCS) of 40 MPa, reinforced by an external welded mesh (5.6 100/100). Additionally, there is a 400mm mesh overlap and Osro Straps positioned across three twin cables. The primary reinforcement consists of four Posimix bolts (25mm diameter), while the secondary reinforcement comprises five twin-strand cable bolts. The installation layout is depicted in Figure 28, with the post-test condition illustrated in Figure 29. At the impact moment, the system absorbed kinetic energy of approximately 100kJ.

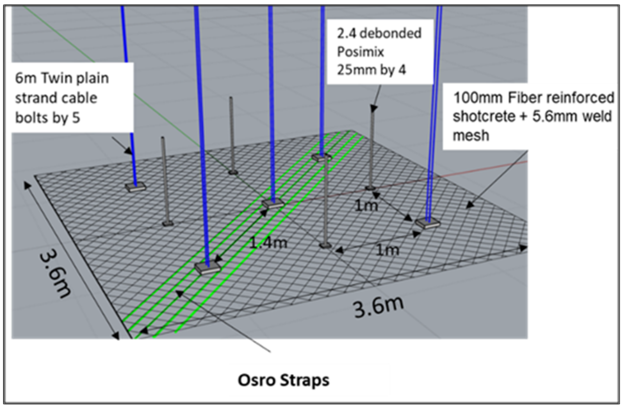

Figure 28 Installation Layout for System S-C1.

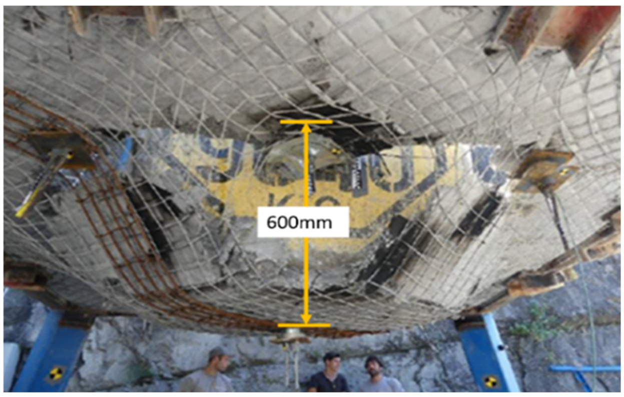

Figure 29 Post-Test Condition for system S-C1.

The data from system S-C1 is depicted in Figure 30, from which several critical observations can be drawn:

- The system exhibits a peak load of 450kN at about 10mm of deflection, leading to the failure of the FRS.
- As the central deflection reaches 30 mm, the central twin cable in the impact zone starts yielding under a peak load of 800kN. This load level is sustained as the central deflection extends to around 105 mm, after which the load decreases to 733kN.
- Subsequently, the load significantly decreases to 15kN when the central deflection widens to 155mm. At this juncture, the Osro strap activates, redistributing the load to the reinforcement elements located in the stable zone. The system continues to accommodate increasing central deflection, ultimately arresting the falling block at nearly 600mm with a rebound peak load of 130kN.

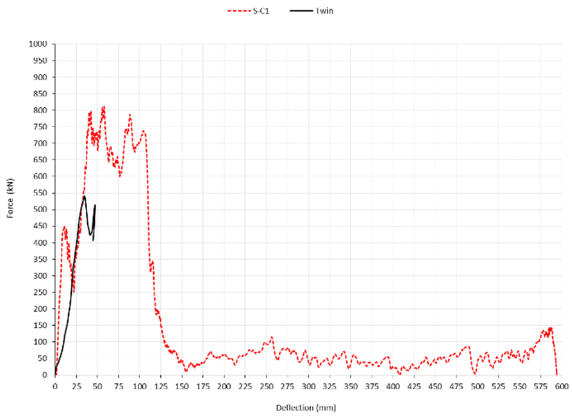

Figure 30 Analysis of Load Transfer and Deformation in Ground Support System S-C1 Across Deflection Stages with Theoretical Twin Cable Load-Deformation Curve (Black Line) Displayed.

System S-C2

The S-C2 ground support system comprises a 100mm layer of FRS with an UCS of 40 MPa. This layer is augmented with an external MINAX 80/4 mesh for additional support. The system's reinforcement is composed by four Posimix anchors, each 25mm in diameter, and five twin-strand cable bolts. The detailed arrangement of these components is depicted in Figure 31, while Figure 32 showcases the system's condition following the impact testing. During the impact, the system absorbed kinetic energy of approximately 100kJ.

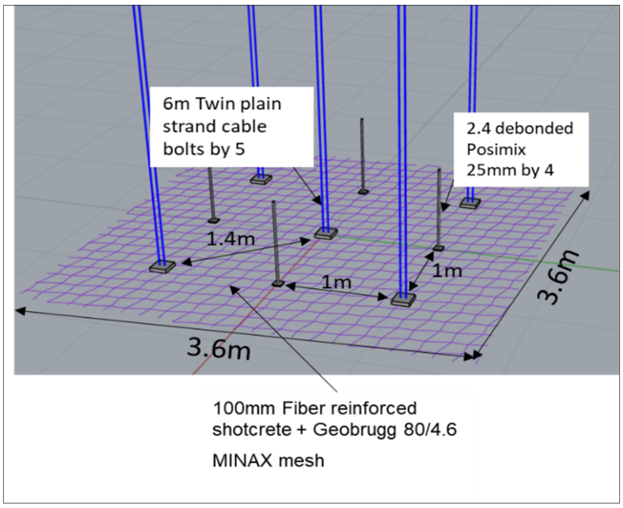

Figure 31 Installation Layout for System S-C2.

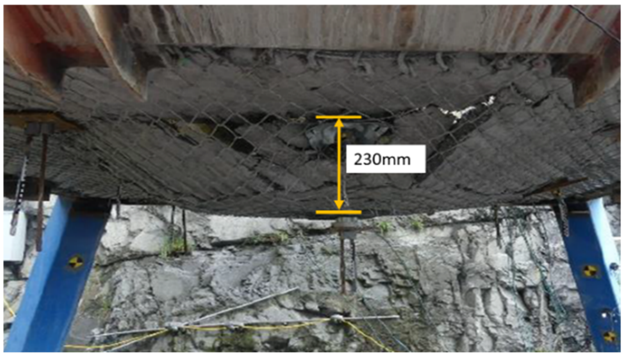

Figure 32 Post-Test Condition for system S-C2.

The performance of the S-C2 ground support system is illustrated in the graph presented in Figure 33, with the following significant findings:

- The system registers a peak load of 550kN at a deflection of approximately 15mm, leading to the failure of the FRS.
- Within the impact zone, the central twin cable starts to yield at a central deflection of 40mm, where it encounters a peak load of 800kN. The load continues to escalate until reaching 870kN at a central deflection of about 70mm.
- Following this, the load decreases to 118 kN when the central deflection extends to 150mm. At this point, the high tensile mesh becomes active once more, channelling the load to the stable zone's reinforcement elements. The system ultimately halts the

falling block at a central deflection nearing 200mm with a new peak load of 253kN. Beyond 250mm of central deflection, the block initiates a rebound.

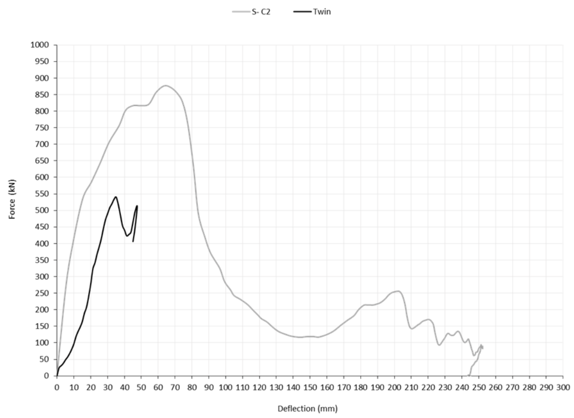

Figure 33 Analysis of Load Transfer and Deformation in Ground Support System S-C2 Across Deflection Stages with Theoretical Twin Cable Load-Deformation Curve (Black Line) Displayed.

The comparative analysis of the two ground support systems, both incorporating a central twin cable, is depicted in Figure 34. The data illustrates that using identical reinforcement elements twin cables and debonded Posimix anchors in the same layout, but with differing types of external surface support, can significantly alter deflection values and energy dissipation rates. As shown in Figure 34, both systems maintain comparable rates of energy dissipation until reaching a central deflection of 110mm, at which point the central twin cable fails. Subsequently, system SC-2 demonstrates a more efficient response, needing only 120mm of additional deformation to completely arrest the falling block. In contrast, system SC-1 requires nearly 490mm of further deformation to achieve the same outcome.

Moreover, although both systems effectively halted the block, System SC-1 is anticipated to be inadequate in preventing rockfall during a strain burst scenario. This is attributed to its limited containment ability, as the rock could dislodge and unravel through the gaps created by the mesh's failure, a situation depicted in Figure 29.

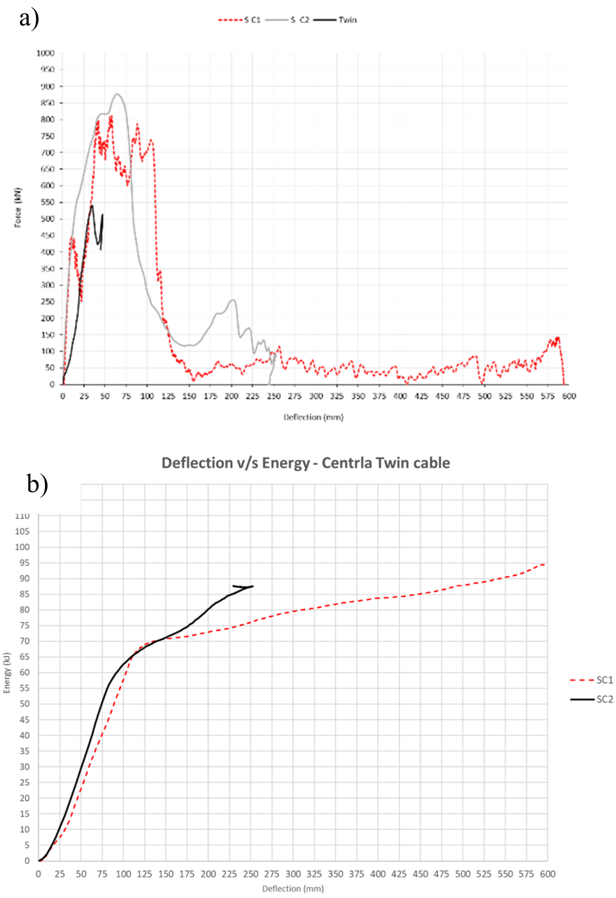

Figure 34 Comparative Analysis of Deflection versus Load (a) and Energy Dissipation versus Deflection (b).

7 CONCLUSIONS AND RECOMMENDATIONS

The study reveals that employing the same reinforcement elements in a consistent pattern, while varying the types of surface support (including shotcrete or FRS, welded mesh, high-tensile mesh, and straps), results in significant differences in deflection values and energy dissipation. This observation underscores the necessity for a thorough evaluation of the surface support composite, comprising FRS and various mesh types. The load response behavior of the ground support system, and therefore its capacity, is complex and cannot be understood simply by summing the final energy capacity of each of its individual elements. Instead, it is governed by the overall stiffness of the composite system. This stiffness is determined by the interplay between bolts in heavily damaged zones and those in stable regions, highlighting a critical aspect that current assessment methods for the dynamic capacity of ground support systems often overlook. Therefore, it's imperative to account for these interactions to accurately gauge the system's overall performance and reliability.

Changing the stiffness of the surface support results in similar energy absorption capabilities but different displacement limits. Overlooking the stiffness factor can result in flawed design approaches, causing excessive deformation even when the desired energy capacity could be achieved by optimizing the stiffness of the surface support composite.

In the nine scenarios analyzed, surface support engaged the bolts within their elastic range only in the stable zones.

Among the tested systems, the combination of double high tensile mesh with shotcrete exhibited the most effective performance in terms of loading capacity, deformation resistance, and energy dissipation. However, current evaluation methods make it difficult to fairly compare this system with others.

Given that the importance of surface support is often underrepresented in current evaluation methodologies, it is imperative to develop a new model that accurately represents the role of surface support in bridging stable and heavily damaged areas where reinforcement elements are prone to failure. The existing practice of adding normalized (kJ/m^2) capacities of individual components fails to account for these critical interactions.

The analysis presented in this paper provides a basis for a more comprehensive assessment of ground support systems, facilitating the comparison of systems with similar reinforcement elements but differing in surface support materials or configurations.

REFERENCES

Celis, M. S. & Parraguez, R. A. (2023). Estimate of ground support response under dynamic loads at El Teniente mine, Codelco, Chile. In J Wesseloo (ed.), Ground Support 2023: Proceedings of the 10th International Conference on Ground Support in Mining, Australian Centre for Geomechanics, Perth, pp. 101-114, https://doi.org/10.36487/ACG_repo/2325_06.

Drover, C. & Villaescusa, E. (2015). Estimation of dynamic load demand on a ground support scheme due to a large structurally controlled violent failure – a case study. *Mining Technology*. 125. 1-14. 10.1179/1743286315Y.0000000029.

Johansson, D., Ouchterlony, F. & Nyberg, U. (2007). Blasting against aggregate confinement, fragmentation and swelling in model scale. In P. Moser (Ed.), 4th EFEE World Conference on Explosives and Blasting (pp. 13-26). England: EFEE, European Federa-tion of Explosives Engineers

P. K. Kaiser & A. Moss (2022). Deformation-based support design for highly stressed ground with a focus on rockburst damage mitigation. *Journal of Rock Mechanics and Geotechnical Engineering, Journal of Rock Mechanics and Geotechnical Engineering* 14 50-66. https://doi.org/10.1016/j.jrmge.2021.05.007.

Villaescusa, E., Kusui, A. & Drover, C. (2016). Ground Support Design for Sudden and Violent Failures in Hard Rock Tunnels. In Proceedings of the 9th Asian Rock Mechanics Symposium (ARMS9), 18-20 October 2016, Bali, Indonesia.