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Yielding reinforcement elements in rock bolting technology

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ABSTRACT: Rock reinforcement is a key issue in underground design and construction. However, for certain applications where both adequately high supporting forces and the ability to overcome large displacements are required, it is often difficult to find a proper reinforcement unit. This paper describes historical approaches and examples for yielding support elements and recent developments focusing on a newly-developed friction stabilizer reinforcement unit. This reinforcement unit has been an object of several investigation and field testing projects. These testing approaches have shown that this rock bolt with the trade name “AT - Power Set” is well suited to overcome large displacements while maintaining its load-bearing capacity. In particular, the focus will be set on results of tests conducted at the Edgar Experimental Mine of the Colorado School of Mines in the years 2003-2004.

1. INTRODUCTION

According to the principles of NATM (New Austrian Tunnelling Method), the rock support is adjusted to the time-dependent deformations of the rock mass. When tunnelling through poor ground under high primary stresses, in many cases excavation leads to a considerable deformation of the tunnel. In such “squeezing“ conditions, the displacement values are often higher than the deformability of the support elements. The relatively low deformability of steel, concrete, or shotcrete supports under such conditions, results in spectacular buckling or shearing of the linings. Attempts to use stiff supports in most cases lead to an even more serious damage of the support, resulting in a severe hazard for the tunnelling crews.

Therefore the overall support system should also provide enough support for large displacements in order to maintain the shear strength of the rock mass as much as possible. An important issue when dealing with relatively heterogeneous ground is the short-term prediction of the rock mass quality ahead of the face and the displacements to be expected.

If the deformations caused by the excavation exceed the deformability of conventional support systems, adaptations with yielding support elements are an economical approach to handle these problems. Examples are yielding steel elements installed in longitudinal gaps in the shotcrete lining (see Fig. 1) [1].

Fig. 1. Galgenbergtunnel Austria; modified support system with integrated yielding steel elements.

This effective system is mostly combined with a rather dense rock bolt pattern to increase the shear strength of the rock mass and to prevent major unsymmetrical deformations. As a matter of course, the rock bolt's bearing capacity should be qualified for the expected deformations too.

Conventional rock bolts as e.g. fully cement or resin grouted rebars often fail due to excessively large displacements. Variations of the bonding medium and bolt-resin interface properties often do not provide satisfactory and constant results [2].

Historical approaches of different rock bolt designs for very large deformations will be presented. A new type of friction reinforcement element is specified in terms of laboratory and field testing data evaluation. After that, the new yielding rock bolt system, which is immediately acting and providing a substantial resistive force right after installation, will be discussed and compared to conventional ones.

2. BACKGROUND

The following rough classification provides an overview of the different types of rock bolts being used in underground mining and tunneling:

- Mechanically anchored
  Expansion shell or slot-and-wedge anchors
- Grouted rock bolts
  Cement or resin grouted bolts
- Frictional rock bolts
  Direct frictional bond between rock mass and bolt

The load transfer mechanism of the rock bolt is directly connected to the rock mass displacements. This may lead to strains that exceed the ultimate strain of the bolt material and/or the shear strength of the bond material. Because pre-tensioned bolts are exposed to a certain amount of strain already, the relative strain to the ultimate limit is even lower. High stresses in rock bolts often result in uncontrolled load discharges when failure occurs. This represents a major problem during construction; firstly the working safety cannot be ensured, and secondly the rock bolts need to be replaced through expensive re-bolting. In those cases, rock bolt systems need to be modified or re-designed to allow additional strains. For these purposes, there are different approaches such as:

- Implementation of an additional free bolt length for a large-scale elastic elongation
- Reduction of tensile stresses by a yielding or sliding element at the bolt's head
- Omission of the bolt plate or modify its deformations characteristics
- Application of a yielding bolt nut
- Modification of the shape of a grouted rebar, e.g. in form of a cone bolt [2], or modifications on the rib geometry of the rock bolt [3]
- Usage of a friction anchored rock bolt which slides in a controlled mode, where the bond strength is independent from displacements

In the past, several trials in design and construction were accomplished to develop yielding rock bolt systems. In the following, four examples from historical cases where rock reinforcement elements had to be developed to both withstand large deformations and retain their load-bearing characteristics will be presented.

2.1. Clamp connection nut

The mode of operation of this system is based on the interactions of the load-bearing behaviour of granules. As illustrated by Powondra [4], the system is based on a yielding nut with a compressible body. This compressible body consists of globes which are arranged inside the bolt's head (Fig. 2). This construction is special due to the constant load-deformation characteristics while ensuring a high degree of steel utilization.

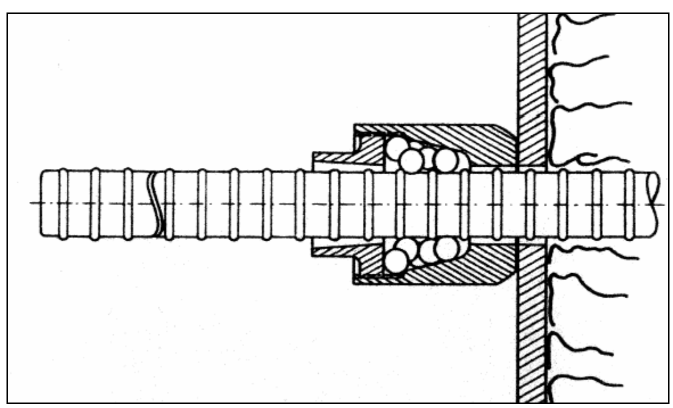

Fig. 2. Yielding rock bolt head [4].

The sliding mechanism can simply be described as follows: globes slip along the rock bolt and the bolt head, thus plastically deforming the rib steel. Fig. 3 shows a load-deformation plot of a test with a Ø 24 mm rib steel and Ø 8 mm globes. The y-axis shows the stress in the steel bar [kN/cm²] and the pull load [kN], respectively. The x-axis represents the displacement [cm]. Beside the efficient working mechanism, this construction has also disadvantages. Firstly, its large dimensions may be a handicap for tunnelling applications and secondly, it is also linked to a given bolt geometry (rib geometry) and cannot easily be adapted to a different rock bolt.

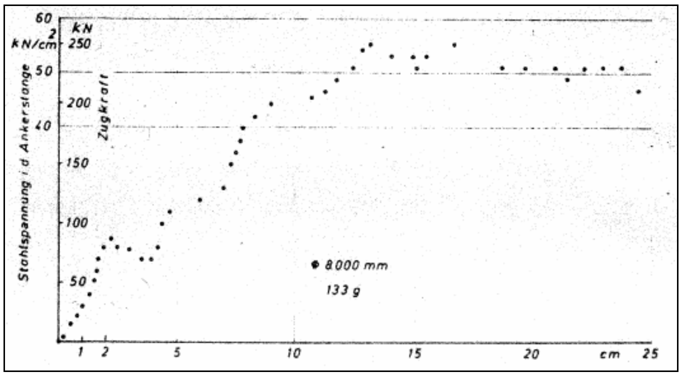

Fig. 3. Load-displacement plot [4].

2.2. Bolt head with a buckling tube

Another design for a yielding element is shown in Fig. 4, which was used at the Karawankentunnel in Austria. The load limitation in this element is adjusted with an inner buckling tube, which allowed in this case 20 cm relative displacement between the bolt head and plate. This system can be used with various bolt types and the element is not salient, because the yielding device is installed in the shotcrete lining.

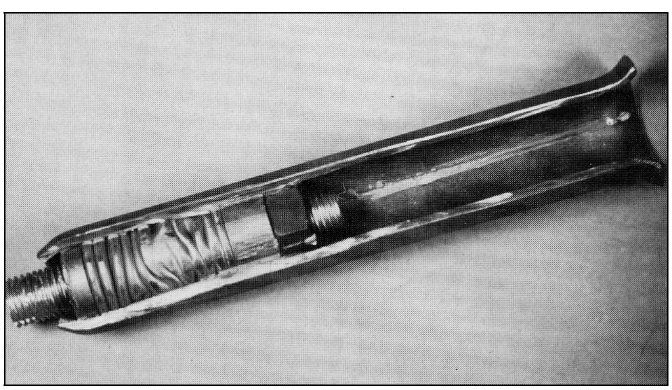

Fig. 4. Cross-sectional profile of a bolt head with buckling tube from Ingenieure Mayreder, Kraus Co. [5].

Although the displacement at the bolt head is warranted, failure of the bolt is possible. But this type of failure is not so bad, because the workers will not be endangered by the plate failure.

2.3. Deformable bolt plates

In order to increase the deformability at the bolt head in the range of some centimeters, a quite simple solution is shown in Fig. 5 and 6. In this case the bolt plate is not seated solidly on the shotcrete lining. Two bridge bearings made of steel pipes guarantee a higher deformability. Thus the punch through failure of bolt plates (Fig. 7) is protracted and due to the larger visible deformations predictable.

Fig. 5. Lining Stress Controllers in combination with deformable bolt plates at the Strenger Tunnel in Austria [6].

Fig. 6. Deformations on the bolt plate and pipe bridge bearing.

Fig. 7. Bolt plate before installation (left) and failed punched through bolt plate.

2.4. *Friction stabilizer bolts*

Friction stabilizer bolts generate their reinforcement action by a radial force against the borehole wall over the whole bolt length. They can overcome large displacements without failure. There are two main types of friction anchored rock bolts; first the "Split-Set" bolt introduced by Ingersoll-Rand and secondly the "Swellex" rock bolt invented by Altas-Copco. The Split-Set was invented by James J. Scott in 1973 and introduced to mining industry in 1977 by the Split-Set Division of Ingersoll-Rand. The working principle of Split-Set bolts is to install a thin-walled steel tube into a slightly undersized borehole. The Swellex bolt consists of a folded, thin-walled steel tube. The bolt is inserted into a borehole and expanded (unfolded) by high-pressure water.

Both systems provide immediate reinforcement action after installation and are able to sustain large rock mass displacements. With limitations, they can be used in various rock mass conditions including water-bearing rock. A major disadvantage of Split-Sets is their sensitivity to the borehole diameter. If the borehole is too large or not uniform (straight), installation may be difficult and the reinforcement forces lower as designated. The load-bearing capacity of friction stabilizer bolts is generally limited by the material strength of the thin-walled bolt tube. An important fact is that corrosion can only partially be inhibited (e.g. by protective coatings).

In the next chapter, an approach to achieve the mechanism of a yielding reinforcement element is presented in form of a new type of friction stabilizer unit. This unit is different to common friction stabilizer bolts by the kind of installation, material characteristics and its versatility in use.

3. SELFDRILLING FRICTION BOLT

3.1. *Introduction*

The Selfdrilling Friction bolt AT - Power Set is a friction stabilizer type reinforcement unit distributed by ALWAG, Austria. It was introduced to the market in 2003. The design of the Power Set is similar to a conventional friction stabilizer bolt.

The term "self-drilling" refers to the fact that the Power Set is installed continuously while drilling the borehole. The bolt is installed exactly in the same direction as the borehole is drilled. The outcome of this is a precise installation of a high-capacity reinforcement element (no bolts are broken or buckled during installation). Also, no laborers need to enter unsecured areas because the bolt provides immediately support action after being installed. An optional expansion element can amplify the application area as below-mentioned. The bolt consists of a Ø 50 mm steel tube with a longitudinal slot along its length; the steel material thickness is either 3.75 or 5.0 mm. Bolts have standard lengths from 1.0-4.0 m, the steel material is warm-welded fine-grained quality steel.

3.2. *Installation*

As mentioned before, the bolt is installed self-drilling with a single-use drill bit which remains inside the borehole. The drill bit is put on a hexagonal drill rod that is inserted within the bolt. Further on, this drill rod is linked to an adapter coupling which is connected to the shank adapter. An impact ring is placed between the Power Set and the adapter coupling to install the bolt simultaneously while drilling. Fig. 8 shows the components of the Power Set rock bolt system; Fig. 9 illustrates the self-drilling installation procedure.

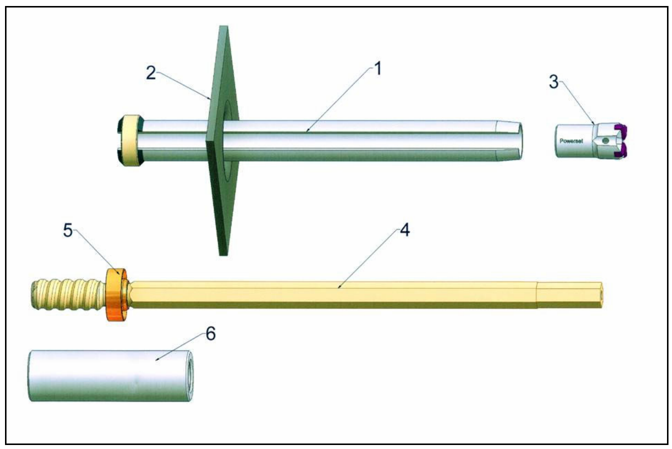

Fig. 8. Components of the Power Set rock bolt system (caption: 1 -Power Set bolt; 2 - anchor plate; 3 - drill bit; 4 - drill rod; 5 - impact ring; 6 - adapter coupling).

For applications where higher supporting forces are required, an optional expansion element can be added to the Power Set rock bolt system to increase the load-bearing capacity. This element simply consists of a metal sleeve and a conical pin, which extends the sleeve when it is inserted into it. It is installed into the Power Set bolt using the drill rod and fixed inside by hammer forces.

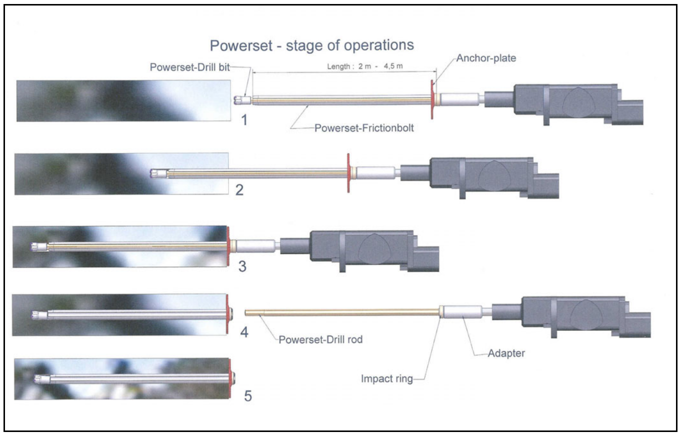

Fig. 9. Self-drilling installation procedure (five stages).

4. METHODOLOGY

To evaluate the characteristics of the AT - Power Set rock bolt system and underline its yielding ability, the following testing procedures have been accomplished:

- Material testing
- Laboratory tests in model rock
- In-situ pull tests

4.1. Material testing

Material testing was accomplished in 2004 at the MPA NRW (Materialprüfungsamt Nordrhein-Westfalen), Dortmund, Germany. Power Set bolts with a length of 1950 mm were tested in a servo-hydraulic combined compression-tensile test assembly; the free clamping length was 1350 mm [7].

4.2. Laboratory tests in model rock

Shear and tensile tests according to DIN 21521 were implemented at the laboratory of the DMT (Deutsche Montan Technologie GmbH) in Essen, Germany. The goal of these tests was to acquire additional information regarding the tension and shear capacity of the Power Set rock bolt [8]. Laboratory tests were conducted under standard conditions in a model rock mass. However, to check the true in-situ behavior of rock reinforcement, tests on site are essential.

4.3. In-situ pull tests

To obtain results for the load-displacement characteristics in different rock mass conditions, a data set of various pull testing results was used. Thereby, data from the following two mining sites was analyzed:

- Edgar Experimental Mine, Colorado School of Mines, CO, U.S.A.
- Esmeralda Mine, Division El Teniente, CODELCO Chile

The pull tests at the Edgar Mine were conducted in cooperation with the Colorado School of Mines in the course of a field testing evaluation program lasting from Nov. 2003 - Feb. 2004 and were documented in a diploma thesis [9]. In addition, several pull tests were conducted at the Esmeralda Mine during a product presentation in Sept. 2005. The Power Sets used for evaluation had a bolt length of 2.0 m.

The rock mass at the Edgar Experimental mine can be classified as metamorphic pegmatite, biotite gneiss and sillmenite gneiss. The RQD-values (Deere 1967) were determined to be in between 40 and 60; the RMR-values (Rock Mass Rating, Bienawski 1989) were in the range below 60 (corresponds to fair rock mass quality).

Granitic rock masses are predominant at the part of Esmeralda mine where the tests were conducted. The RQD-values are significantly higher, namely 85-100%. The RMR is in the range of 66-75, which indicates an overall good rock mass quality.

All pull tests were performed in general accordance with the DIN 21521 [10] and the ISRM Suggested Methods for Rockbolt Testing [11]. During testing, the load was applied by a hydraulic cylinder and recorded either from a load cell (+/- 0.5 kN) or a calibrated manometer (+/- 2.5 kN). The displacement was recorded by a digital micrometer with a resolution of 0.01 mm. The maximum testing load was (for safety reasons) set to approximately 300 kN. Fig. 10 shows the composition of the pull test assembly.

Fig. 10. Pull test assembly.

5. RESULTS

5.1. Material testing

The tensile tests were performed in two different ways. First, they were conducted by clamping the bolt on both ends. In the second testing procedure, the bolt was clamped on one side and the pull force was applied over a washer onto the collar. The results of the first testing series were an average tensile force of 349 kN for 3.75 mm thick and 309 kN for 5.0 mm thick bolts (note different steel material: $R_{m,3.75}$ = 740 N/mm², $R_{m,5.0}$ = 490 N/mm²). In addition, the average tensile forces for the second testing procedure were slightly higher: 350 kN for 3.75 mm and 317 kN for 5.0 mm thick bolts. It is assumed that the loading mechanism of the second type of tensile testing gives more realistic reference values.

5.2. Laboratory tests

The bolts tested had a length of 2.2 m (tensile tests) and 1.8 m (shear tests), respectively. The bonding length was 0.6 m for both types of testing. The rock bolt was located in a model rock consisting of cement inside a Ø 160 mm solid steel tube. During theses tests, the bolts with a larger steel material thickness showed better results. Fig. 11 illustrates the plot of a tensile pull test. The displacement (x-axis [mm]) is drawn versus the pull force (y-axis [kN]). The average maximum tensile force recorded during the tensile tests was 300 kN, the maximum displacement until the test was stopped was 180 mm.

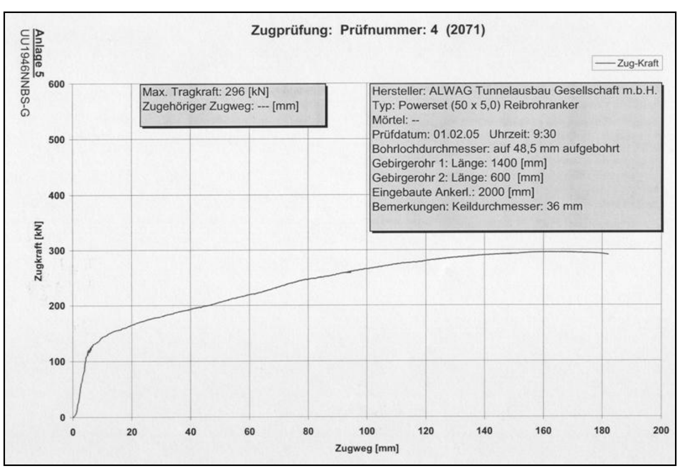

Fig. 11. Laboratory test – tensile pull test.

The combined tensile-shear tests were conducted under shearing angles of 50 and 90 degrees; the length of the shear blocks was 0.45 m. For these tests, the Power Set rock bolts were installed into pre-bored Ø 50 mm boreholes. Under a shearing angle of 90°, the average maximum shear force was in the range of 400 kN. The average shear displacement was 70 mm. In addition, for a shear angle of 50°, the average shear force was about 380 kN and the shear displacements were in the range of 40 mm. Contrary to the tensile tests, bolts with 3.75 mm steel tube thickness showed better results. Fig. 12 shows a plot of a combined tensile-shear test under a shear angle of 90°; Fig. 13 a test under a shear angle of 50°. The upper curve represents the shear force, the lower one the tensile force. The labeling of the axes of both graphs is similar to the first laboratory testing graph.

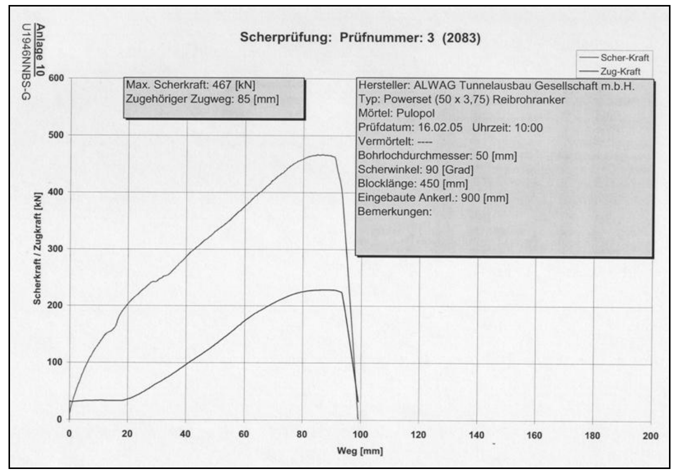

Fig. 12. Laboratory test – combined tensile-shear test 90°.

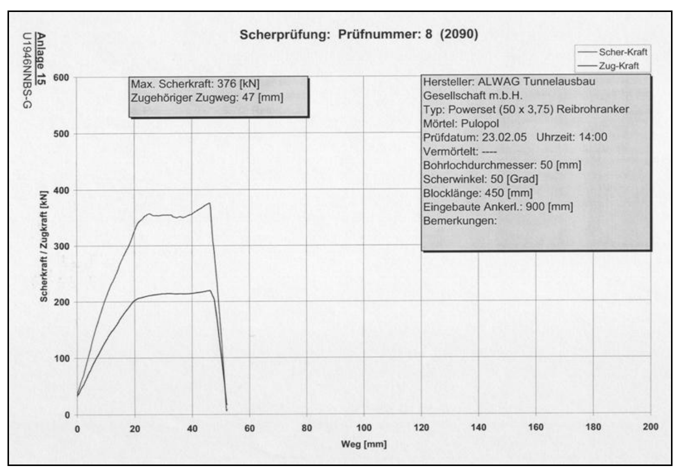

Fig. 13. Laboratory test – combined tensile-shear test 50°.

5.3. In-situ pull tests

The results of the in-situ pull tests are summarized in terms of load-displacement plots. All plots show loading-unloading cycles (see comments). At first, the results of Power Set rock bolts installed as common friction stabilizers (without expansion element) are presented. Fig. 14 and 15 show the pull test result graphs of the testing attempts at the Edgar Experimental and Esmeralda Mine. The Power Set rock bolts at the Esmeralda Mine have been re-tested; therefore a second loading-unloading-loading cycle is recognizable on Fig. 15.

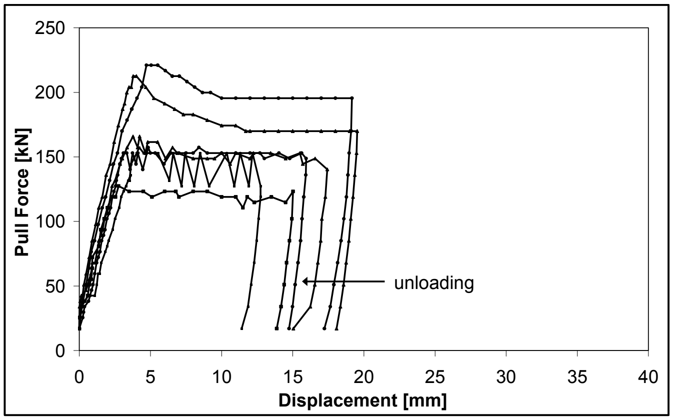

Fig. 14. In-situ pull tests – Edgar Experimental Mine 1.

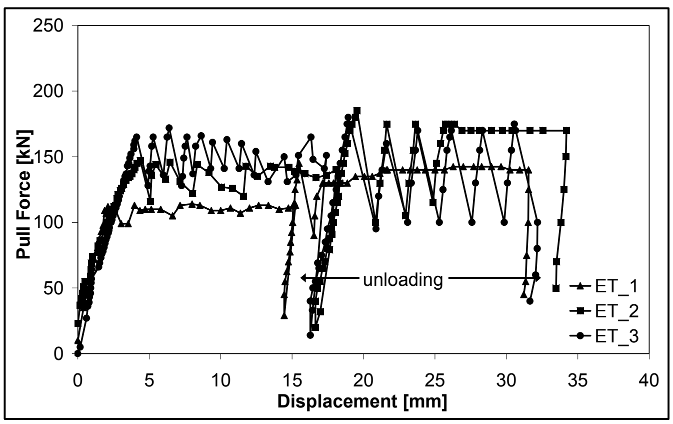

Fig. 15. In-situ pull tests – Esmeralda Mine.

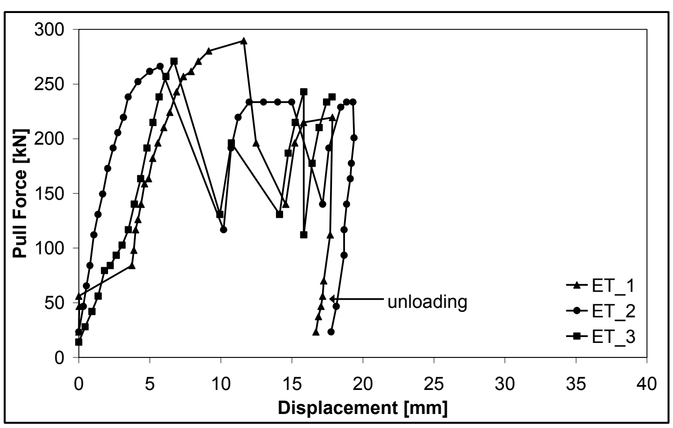

Fig.16. Consecutive pull tests – Esmeralda Mine.

These load-displacement graphs clearly show that Power Set rock bolts having a length of 2.0 m are able to take up a load in the range of 125 kN while undergoing large deformations. However, the trend that the bolts can undergo more deformations as shown in-situ was shown by laboratory tests where the proper equipment to do tests up to pull lengths of 180 mm was available.

Consecutive pull tests which where conducted 6 months after the initial tests (Fig. 15) on the same bolts indicate constant load-deformation behaviour and even an increase in the load bearing capacity (Fig. 16). The stick-slip type of curves shows the controlled yielding of the bolt (changeover of static and sliding friction). As noted before, in cases where higher supporting loads are required, an additional expansion element can easily be installed inside the bolt, thus increasing the load-bearing capacity. Fig. 17 shows the load-displacement graphs of consecutive pull tests (again loading and re-loading) on Power Sets installed with an additional expansion element. Similar to the Power Sets installed as common friction stabilizer units, the support loads stay at a constant level while the system keeps its yielding ability.

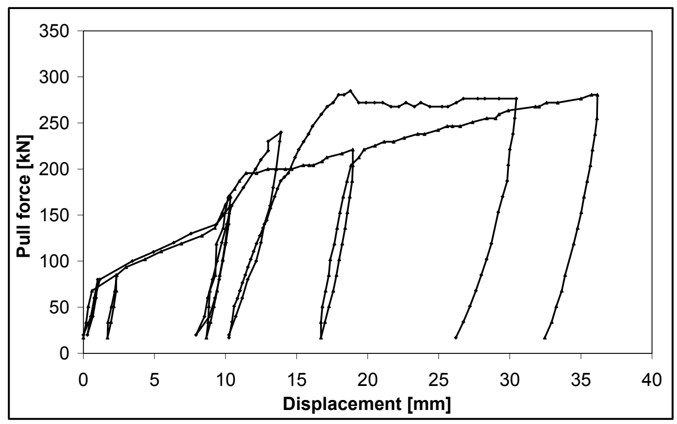

Fig. 17. In-situ pull tests – Edgar Experimental Mine 2.

If necessary, the load-bearing capacity can be increased at any stage by installing the expansion element. A combined Power Set rock bolt system behaves as shown in Fig. 18 and Fig. 19.

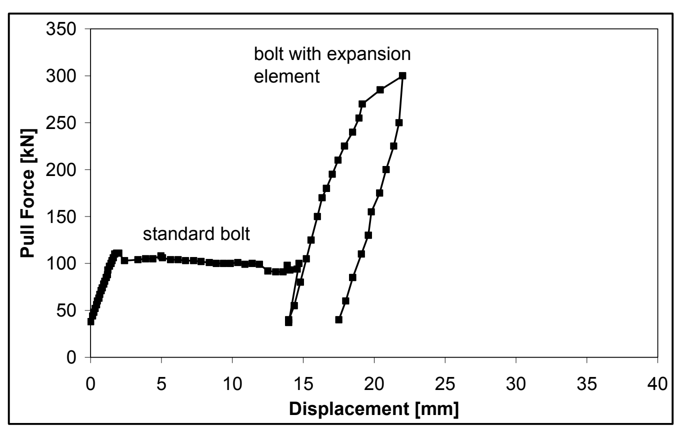

Fig. 18. In-situ pull tests –Esmeralda Mine.

After an initial pull test on a Power Set rock bolt the expansion element was installed and the bolt was re-tested again. At the beginning, very large deformations can be overcome sustaining a pull load of about 125 kN; after the installation of the expansion element the pull loads can be increased to over 300 kN.

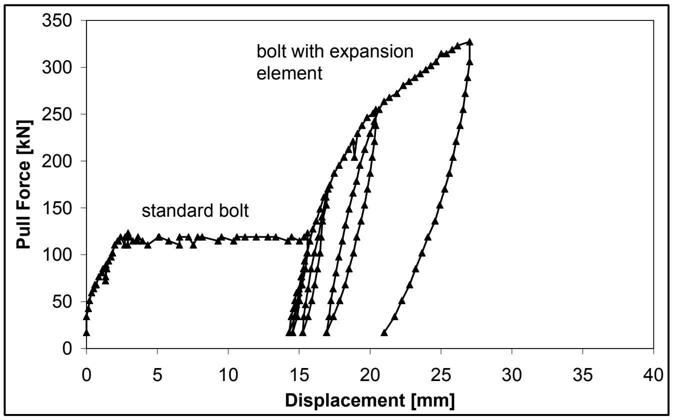

Fig. 19. In-situ pull tests –Edgar Mine.

6. DISCUSSION

In general, rock support should be compliant enough to accommodate the dilation generated by the failure process, but strong enough to support the dead weight of the broken rock [12].

In practice, a breakage of a rock bolt often occurs at the bolt head due to the excessive forces at this location. In addition to the aspects already mentioned; yielding rock bolts which are able to slide under high loads can absorb more energy than conventional rock bolts which makes them an interesting option for rock burst conditions [2].

Historical approaches to design yielding rock bolts with deformable bolt head elements or plates did bring successful results. Using an inherently yielding support unit brings several benefits such as fast installation and guaranteed supporting forces.

7. CONCLUSIONS

The AT – Power Set is a yielding reinforcement unit that utilizes the material strength without breaking while undergoing large deformations. The bolt's characteristics have been reviewed by a series of material, laboratory, and in-situ tests. The working safety is increased by avoiding sudden bolt and plate bursts. In combination with an additional expansion element, the Power Set rock bolt is a versatile reinforcement unit. This rock bolt system is an inherently yieldable reinforcement element where no additional yielding assemblies are necessary.

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