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Investigation of New Energy Absorbing Mechanisms Used to Fix Rock Bolt Plates

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Abstract

In this study, different plate fixing designs were tested in order to improve rock bolting performances. Instead of commonly used steel nuts, different plate fixing designs were investigated by both laboratory and site studies. In addition, the usability of nuts and energy absorbers made of the polyamide type engineering polymer was investigated to assess whether they are advantageous for the aim of supplying high-energy absorbing features. In this experimental study, deformation-controlled load tests were carried out to evaluate the bearing and energy absorption capacities of totally eight different groups of specimens. According to the findings from this study, use of the polyamide material with steel nuts as an energy absorber material, rather than using instead of steel nuts supplies good results. As another outcome, it has been determined that use of proper washers between steel nuts and polyamide absorbers can significantly improve the energy absorption performances. It has been evaluated that the energy absorption capacity of the bolt plates can be economically increased up to 10 times by using suitable polyamide energy absorbers placed between the plate and steel nut parts. It was concluded that the polyamides can be used to remarkably improve the rock bolting performances especially in the rock masses where the high energy absorption capacity property is needed, like those with rock bursting, squeezing and swelling problems.

Keywords

rock bolts, rock bolt plates, energy absorbing plates, plate fixing mechanisms

1 Introduction

Rock bolts have been used to reinforce rock masses for more than 100 years. The widespread use of rock bolts has led to the understanding of contemporary support strategies in the 20th century. Rock bolts are usable to prevent both structural controlled and stress-controlled rock mass failures. Rock bolts can be classified in accordance with different parameters such as grout usage (grouted or friction bolts), grout type (cement, resin, etc.), shank body material (steel, polymeric composites, etc.), pre-tensioning properties (active, passive), energy absorption capacities (energy-absorbing bolts and others) and etc. [1–6].

Energy absorbing rock bolts were firstly developed to combat rock burst problems in deep mining works. Rock burst problems occur in hard and brittle rocks exposed to high-level stresses. As the underground mines become deeper, new mines with the rock burst problem are seen in different countries. Rock bursts which are violent events making the rock ejection from walls of excavations can be extremely hazardous and result in major collapses in deep rock engineering practices. Because impact loads occur in a consequence of the rock bursting, supports must have properly high energy absorption capacities for responding to the dynamic loads and for prevention of collapses [7–9].

To combat rock burst problems in deep mines, many challenges have been faced concerning the use of new rock bolts. The first rock bolt developed to use in the mines with the rock burst problem is the cone bolt having increased energy absorbing capacity resulting from the anchoring of the cone end of the shank. The cone bolts used since 1992 have a simple design with an expanded front end which can increase the anchoring performance in the grout material [10].

In the 2000s, various rock bolts like Garford bolt (Australia), Roofex bolt (Sweden), D-bolt (Norway) were developed to increase the energy absorbing capacity against the dynamic load resulting from the rock burst problem. The Garford and Roofex bolts have similar displacement limits, ductile support reactions and high load

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bearing capacity values making them effective to combat rock burst problems [11, 12]. The Garford and Roofex bolts consist of a solid steel bar sliding in polymeric materials, an anchor and a coarse-threaded sleeve at the far end of the bolt. D-bolts were invented in Norway and comprise a smooth steel shank and a number of integrated anchors. D-bolts are also advantageous in terms of supplying a notably improved energy absorption capacity by bolting in the burst prone rock masses [13, 14]. Besides of the bolt types dealt above, different rock bolts were also designed in the last two decades and various studies were carried out for the aim of improving rock bolts against the rock burst induced impact loads [15–18]. As the increase of mining depths make more miners to experience the rock burst problem, energy absorbing rock bolts seem to be used more widely in near future than being in todays. The main issue in the support design works for the burst prone rock masses is to provide high energy absorption capacity.

Energy absorbing rock bolts are also preferable in rock masses with the squeezing problem. The squeezing problem occurs in soft rocks exposed to high-level stresses. The squeezing rocks have high convergence values and need to use support systems that let significant displacements without failing and loss of the bearing capacity. The energy absorption value depends on both load bearing and deformability properties [19–22].

Support systems with high energy absorption capacities are also advantageous in the clayey rock masses with the swelling problem. Ideal support reactions for the swelling clay zones can be supplied by deformable support systems. The high load bearing capacity property is not enough alone to make stabilization of the clayey zones. Therefore, clay swelling events can be seen to cause damages of the stiff support systems despite high load bearing capacity values. To prevent the clay swelling, much more support pressure is needed in comparison with those of the deformable support systems used in the clayey zones. Using deformable support systems, relatively low support pressures can be sufficient to stabilize the clayey zones [23–25].

Anchorage capacity of the plate part is an important parameter for rock bolting performances. The plate fixing mechanisms vary reinforcement/support reactions of rock bolts. For improving the energy absorption capacity of the plate part, load bearing capacity and displacement limits should be improved together [26–28]. As the energy unit of Joule (J) is equal to N·m, the are under load (N) and displacement (m) graphs can be used to calculate the energy absorption capacity.

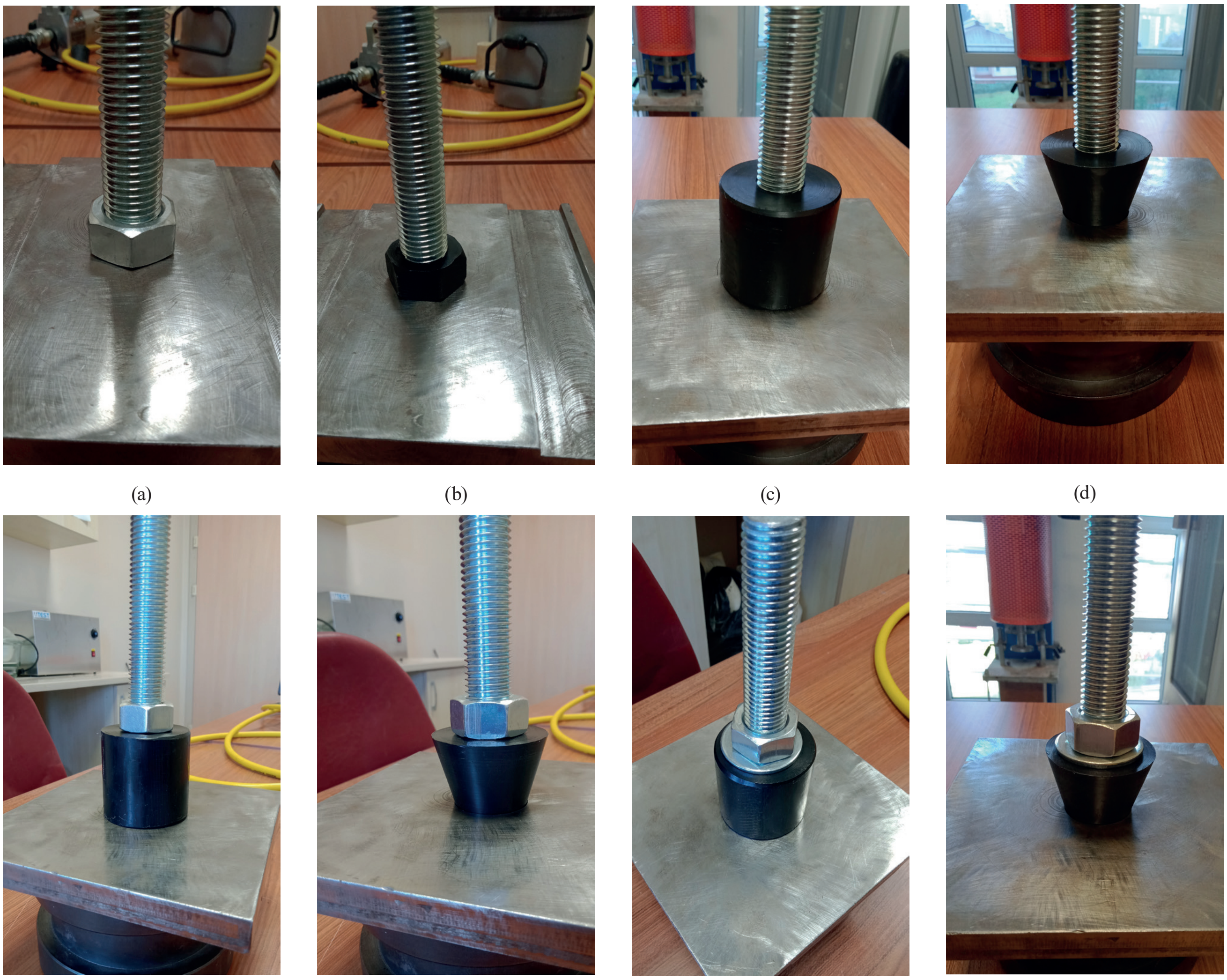
In this study, various plate fixing designs were investigated to assess whether new engineering polymers can be used instead of the steel nuts. Additionally, different support fixing mechanisms were developed within this study to investigate their effectiveness to improve the energy absorption capacity property of the rock bolt plates. It was aimed to design new plate parts with significantly higher energy absorption capacities than ordinary plate designs. Details of newly investigated plate fixing designs are given in the following section.

2 Materials and methodology

In the tests of different plate fixing designs, bolt specimens with a shank diameter of 20 mm were used. In the laboratory study, 24 specimens were used for eight different groups of plate fixing designs. Three specimens for each group were tested to evaluate their energy absorption capacities according to the load-displacement graphs. Fig. 1 shows different plate fixing mechanisms tested in this study. Loading was applied using a press equipment as seen in Fig. 2. In the loading test, plates were put on a drilled steel block which lets bolts to freely move in it (Fig. 3). As the press moves vertically, the plate and nuts were pushed towards each other. The displacement-controlled loading rate was selected as 3 mm/min for each of the specimens tested within this study. Load variations by time and load-displacement data were recorded by the testing equipment.

Ordinary six-sided metric 20 (M20) steel nuts with the nominal inside diameter of 20 mm were used as the plate fixing device of the first specimen type. In the second group, nuts made of the polyamide type engineering plastic were tested instead of the steel ones in the first group. The sizes and geometry of nuts of the first and second specimen groups were the same. The reason to test polyamide nuts is to investigate whether an increased displacement limit and energy absorption capacity can be supplied, or not. Polyamide type engineering polymers generally have tensile strength values varying from 75 MPa to 90 MPa and compressive strength values varying from 85 MPa to 100 MPa. Polyamide materials are used in different purposes needing for a good chemical resistivity, like drinking water carriage and storage applications. As a result of their mechanical properties, polyamides are also used as machine element materials and popular in the machine manufacture [29–31].

In the third group another polyamide nut type with the length of 50 mm was tested. Thread designs of all the nuts tested in this study were the same and usable with the standard metric 20 (M20) bolts with the diameter of 20 mm.



(a) (b) (c) (d)

(e) (f) (g) (h)

Fig. 1 Designs of different specimen types of group 1 (a), group 2 (b), group 3 (c), group 4 (d), group 5 (e), group 6 (f), group 7 (g), group 8 (h)

Fig. 2 A photograph from the loading test

(a) (b)

Fig. 3 The steel block (a) used under the steel plate (b)

In all the tested specimens, threaded bolts with the same design and physical properties were used. As a result of increasing nut length, load bearing capacity and energy absorption capacities of the third specimen group nuts were aimed to be improved in comparison with the second group nuts with the length of 15 mm.

Table 1 Results obtained from the experimental study
(F_{max}: Maximum load level, DF_{max}: Displacement at the maximum load level, EAC: Energy absorption capacity, SD: Standard deviation)

Specimen Group	Specimen number	F_{max} (kN)	SD for F_{max} (kN)	DF_{max} (mm)	SD for DF_{max} (mm)	EAC (Joule)	SD for EAC
1	3	133	4	2.45	0.17	361	14
2	3	14	2	4.08	0.29	224	17
3	3	38	3	5.91	0.34	823	51
4	3	35	2	17.32	0.25	906	49
5	3	131	4	52.11	0.28	2482	113
6	3	136	3	30.56	0.41	2157	108
7	3	132	5	51.39	0.26	3340	135
8	3	135	4	27.24	0.30	2384	116

In the fourth group, conic polyamide nuts were used for the purpose of supplying an additional increase of the displacement limits and energy absorption capacity due to the plate slide on the nut. The cone part cut angle is 15° for the conic polyamide nuts. A special plate design including a drill with the same cut angle of 15° was used with the conic polyamide nuts (Fig. 3). The hole drilled through the steel plate has diameter values varying from 26 mm to 34 mm. The conic nuts had outside diameters changing from 23 mm to 50 mm and the length of 50 mm which is the same as that of the third group specimens.

The fifth and sixth groups are steel nut used versions of the same polyamide nut designs of the third, fourth groups of specimens, respectively. The steel nut design used in the fifth and sixth groups is the same with that in the first group. Steel nuts were contacted to the polyamide nuts in the fifth and sixth groups. In the seventh and eighth specimen group designs, washers with the outer diameter of 39 mm, inner diameter of 23 mm and a thickness of 3 mm were used between the steel and polyamide nuts. The seventh group specimen design is the washer added version of the fifth group with non-conical polyamide nuts. In the eighth group, washers were used between the conical polyamide nuts and steel nuts. The conical nut design used in the fourth, sixth and eighth groups were totally the same. The eighth group specimen design is the washer added version of the sixth group specimens with conical polyamide nuts. Also, same steel nuts were used in sixth and eighth groups. It should be noted herein that only one type steel nuts were used in this experimental study.

Due to their ductile material properties, polyamide nuts continued to show displacements during gradual decreases in load values instead of a drop resulting from the sudden breakage. Therefore, in the tests of second, third and fourth group of specimens which have the case of using only polyamide nuts, loading was continued until the load value decreased to a low level of 2 kN. In the tests of other specimen groups which include the steel nuts, loading was continued until the steel thread breakage.

3 Results

According to the results obtained from this study, load bearing capacity of the polyamide nuts were found to be significantly lower than those of the steel nuts (Table 1). On the other hand, their displacement property was assessed to supply good energy absorption capacity values. In the tests of steel nuts, the load bearing capacity was lost as the threads of the nuts are deformed. On the other hand, load bearing capacity was not immediately dropped as the maximum load levels of polyamide nuts are achieved. After reaching the maximum load level, polyamide nuts started to slide on the bolts as seen in Fig. 4. It has been observed that the polyamide nuts can maintain a significant

Fig. 4 Polyamide nut slide on bolts

load bearing capacity while sliding on bolts. However, the load capacity values decreased as the sliding deformation increased. Load-displacement properties of different specimen groups can be seen in Fig. 5. The graphs are given as one for each specimen groups to show their energy absorption characteristics. The mean energy absorption capacity values calculated in accordance with the load-displacement data are given in Table 1. Loading of specimens with steel nuts was continued until the steel nut thread failure.

To obtain both high load and displacement capacity characteristics, steel and polyamide nuts can be used together according to the results. It was observed from the third and fourth group specimens that the steel nuts began to be embedded in the polyamide nuts as the load values increase above 40 kN (Fig. 6). As a result of the steel thread cracking, the tests were finalized. In the use of conic polyamide nut and steel nut together (sixth specimen group), load levels were found to continue increasing

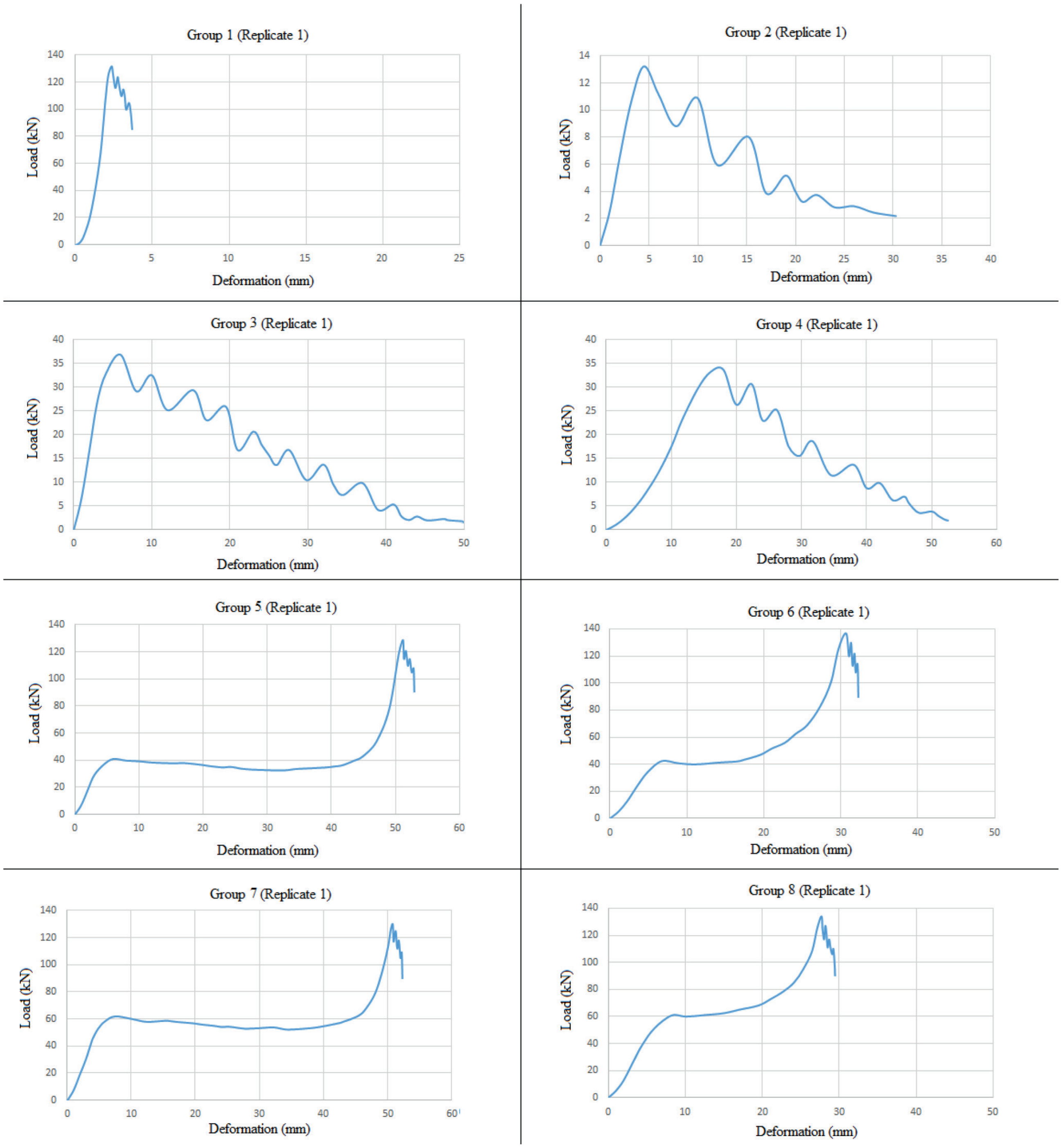


Fig. 5 Load and displacement graphs of different specimen groups

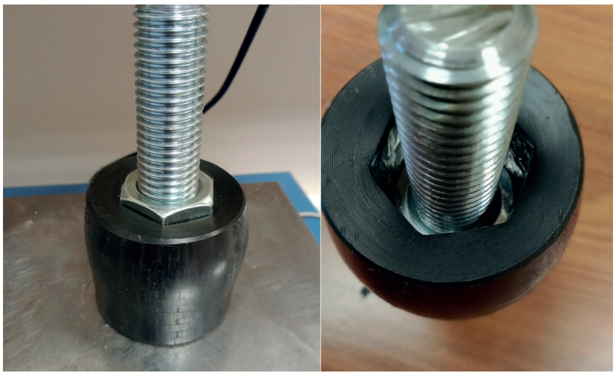


Fig. 6 steel nut embedding in the polyamide nut

after the steel nut embedding in the polyamide. However, the displacement limits of the sixth group were found to be relatively low compared to the fifth group specimens.

As shown in Fig. 7, all the specimens with both polyamide and steel nuts had four stages of polyamide compression, embedding in the polyamide nut, stiffening and the breaking of steel nut threads in their load displacement graphs. Among the samples whose test results have been mentioned above, the highest energy absorption capacity values were found in the fifth group. However, it was thought that the energy absorption capacity can be still improved in case of increasing the embedding load. To increase the load values during the embedding of the steel nut in the polyamide, circular washers with the outer diameter of 39 mm and the inner diameter of 23 mm were used between the polyamide and steel nuts in the seventh and eighth group specimens. According to the results, the seventh group specimens have the highest energy absorption capacity among all specimen types tested in this study. The mean energy absorption capacity of the 7th group specimens is 3340 Joule. In the case of only steel nut usage as in the first group specimens, the average energy absorption level was measured as 361 J. It can be noted herein that the use of polyamide material in the plate fixing designs was determined to supply a good amount of increase in the energy absorption capacity property.

4 Site study

A site study was carried out in a motorway tunnel construction with the squeezing problem. Although there was no collapse in the rock mass around the tunnel, shotcrete liners were broken as seen in Figs. 8 and 9. Additionally, rock bolt plates were bended and sometimes bolt heads failed as a result of the squeezing convergences. The new bolt plate fixing designs with polyamide energy absorber nuts were estimated to work well in this tunnel construction with the squeezing problem. To examine this estimation, the seventh group's plate fixing mechanisms were tested with the rock bolts used in the tunnel construction. As seen in Fig. 10, stiff support systems are not preferred in the squeezing rock zones because support pressure and ground pressure equalize unnecessarily early and relatively high support pressures are needed to stop convergences. Failed bolt heads in the stable tunnel confirm that the support reaction was not convenient for the relevant ground reaction and an unnecessary support pressure was supplied by the support system. It was understood that a rock bolt design that can allow more deformation is required.

The new plate fixing design was used with the same bolt shanks in the tunnel construction. As same with those used in the experimental study, the bolt diameter was 20 mm. The bolts with the length of 2.5 m were inserted into the holes drilled by using a 36 mm diameter bit, and grouted by the same cement mix used in the tunnel construction.

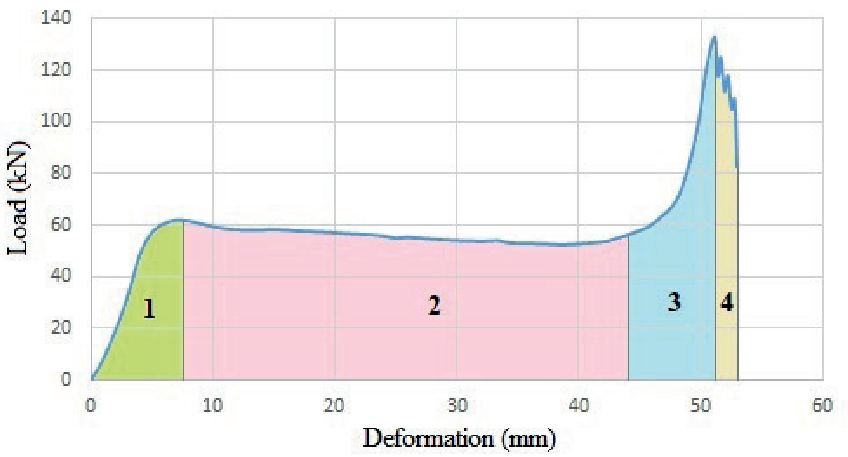


Fig. 7 Load displacement characteristics in the group 7 specimens
(1: compression of polyamide nut, 2: embedding in the polyamide nut, 3: stiffening, 4: the breaking of steel nut threads)

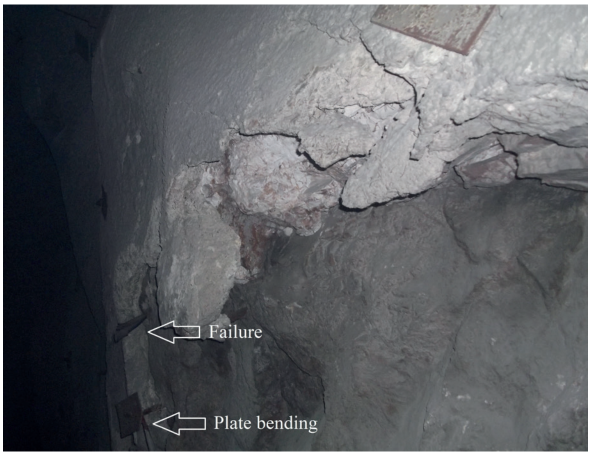


Fig. 8 A shown of damages (bolt head failure and bending) resulting from the squeezing problem in the case study tunnel

Fig. 9 Cracked shotcrete liners and bended bolt plates due to the squeezing problem of the tunnel construction

The in-situ condition of the bolts with the polyamide absorber was examined within the observations during the ongoing tunnel construction. There was no plate bending and no breaking in the rock bolt heads with the polyamide absorber. The embedding depths of the steel nuts were measured to be about 30 mm in the polyamide absorbers. The embedding depth was measured regularly during a month in the tunnel construction period. Convergences of the investigated bolting location were found to stop within a week after the insertion of the bolts. Because the steel nut was not totally embedded in the polyamide, the load level at the stop of the convergences were estimated to be about 55 kN considering the load-displacement data obtained from the laboratory tests. The new plate fixing design was assessed to be usable in the squeezing zones to supply deformability while having no decrease in the bearing capacity. The new polyamide energy absorber nuts were found advantageous to let squeezing deformations, to protect plate parts against high level of convergences and to supply a safe and undamaged bolts after the squeezing convergences. An embedded steel nut in the site study is shown in Fig. 11.

5 Discussions

Polyamide materials have lower strength values compared to steel materials. Therefore, their use as a direct alternative to steel materials is not suitable in terms of load bearing capacity needs in many rock bolting applications.

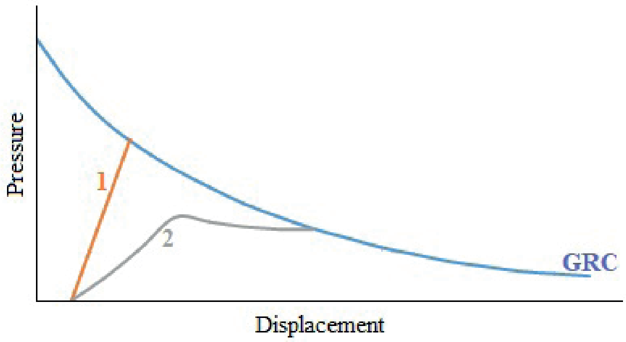


Fig. 10 Ground reaction curve (GRC) and support reactions (No. 1 support reaction shows early pressure, No. 2 can supply stability with relatively low support pressure)

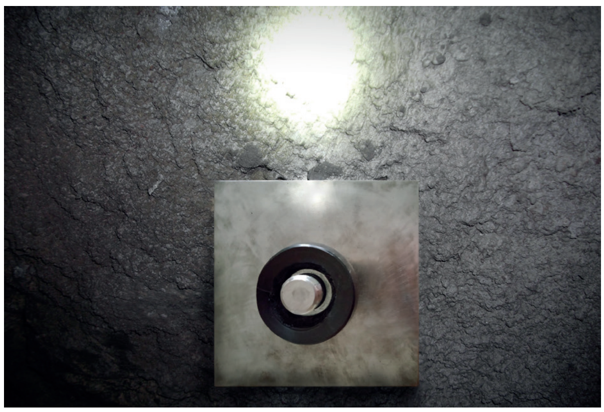


Fig. 11 An embedded steel nut in the polyamide absorber

As confirmed by this study, there is a significant difference between the load bearing capacities provided by polyamide and steel nuts of the same size and geometry. How-ever, good energy absorption capacities can be achieved due to the higher deformability and ductility properties of polyamide materials in comparison with the steel ones. Load bearing capacity is not a sufficient parameter in rock bolting designs. Also, the energy absorption capacity parameter should be considered for the performance of rock bolts [32–35].

It was determined that it is advantageous to use polyamide materials together with steel nuts for having high energy absorption capacities instead of using them alone as a nut material. In rock masses with various problems like clay swelling, rock squeezing and rock bursting, the use of rock bolts with high energy absorption capacity has a critical importance [36–38]. Therefore, the extra costs of polyamide nuts should not seem unnecessary. Because of increasing rock bolt performances, some tolerable and extra costs can be economical to be paid. Choosing right materials supplies economical solutions by eliminating the need for repair costs [39–41]. Economy and safety should be considered together in engineering designs. However, when a choice has to be made between them, the most important consideration in engineering designs must be the safety.

Polyamide materials approximately have seven times lower density values than typical construction steel materials [42, 43]. Although prices of typical polyamide materials per kilogram are 2–2.5 times more expensive than those of the typical steel materials, polyamides are cheaper compared to steel elements for the same dimensions. In addition, the easiness of processing and shaping polyamide materials provides an important advantage for their use in manufacturing.

Considering the total energy absorption capacity values, the seventh group specimens with non-conical polyamide nut, steel washer and steel nut were found to be the best choice within different designs investigated in this study. Compared to the standard steel nut usage (1st specimen group), seventh group specimens have more than 9 times higher energy absorption capacity values. The use of a washer supplied better energy absorption capacity values as the embedding load increases as a result of increasing in the contact area on the polyamide nut. The use of washer was found to improve the energy absorption capacity for about 35% according to the comparison of the results obtained from the fifth and seventh group non-conical specimens. The conic polyamide nuts were found to be advantageous for supplying load increase during the embedding in the polyamide nut. However, energy absorption capacity and displacement limits are relatively low for the conic polyamide nuts, because a part of the conical nut is already inserted into the plate hole.

Use of polyamide nuts without steel nuts was found to cause low load bearing capacity values during their slide on the bolt. Nevertheless, proper energy absorption capacity values can be supplied depending on the polyamide nut sizes. It has been determined that the use of polyamide absorber nuts with steel nuts and washers instead of using them alone provides much higher load bearing and energy absorption capacity. New engineering polymers have provided revolutionary benefits in solving many problems in rock bolting applications [44–46]. As seen in this study, polyamide type polymer materials can also provide various advantages for the fixation of rock bolt plates.

The plate part has an important role in the anchorage mechanisms of rock bolts. A plate that fails early affects the bearing performance. The site study confirmed that the polyamide nuts work well in the rock masses where the high deformability property is needed. For instance, the squeezing convergences of the case study tunnel was investigated and found to not cause damages of the bolt plates with the polyamide absorber. The newly designed plate mechanisms were evaluated to let increased deformation limits which are unacceptable for ordinary plate mechanisms.

6 Conclusions

As conclusion, it can be noted that polyamide nuts can be usable to improve displacement and energy absorption capacity values of the rock bolt plates. Polyamide nuts are effective to be used as energy absorbers between steel nuts and plates. Instead of using only polyamide nuts, good energy absorption capacity values can be obtained by using polyamide nuts between steel nuts and plates. The most effective method was found to use the seventh group design with both steel nuts and washers in addition to non-conical polyamide nuts. Steel washers are suggested to use with the nuts to obtain better load bearing and energy absorption capacity properties of bolt plates. This study is a preliminary one carried out to investigate the use of polyamide nuts and energy absorbers in the bolt plate fixing mechanisms. Further analyses will be highly beneficial to improve new plate fixing designs. Different size and geometries can be tested to make bettered polyamide nut and energy absorber designs in future studies. Polyamide nuts and energy absorbers are thought to have a good potential to be popular in rock bolting applications in near future.

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