Cementitious Grout Method Application on Tunnel Rockbolts and its Effect on Bond and Load Carrying Capacity. A Real-Scale Pull Out Test on Fan River HPP Power Tunnels

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ABSTRACT

This paper presents the investigation of 144 in situ rock bolt pull-out tests conducted during the construction of Fan River hydropower plant's power tunnels. The pull-out tests are performed on 22 and 25mm diameter; 3, 4 and 6m usually full grouted rock bolts installed in different parts of the tunnel with different angles to gravitational direction. The pull-out tests were performed to analyze the bond and load carry capacity of rock bolts based on their installation angle and grouting efficiency. To optimize the rock bolt performance, two different grouting methods have been used. The results indicate that rock bolts' bond strength declines as the installation angle goes closer to the gravitational direction and majority of the failure cases are due to grouting problems.

Keywords: *Cement grouted rock bolts, pull out test, bond, and load-carrying capacity.*

INTRODUCTION

The stability of the excavated tunnel sections is mainly affected by the geological conditions and the dynamic load caused by the blasting process in the drilling and blasting tunnel construction method. The blasting process creates distortions and cracks in the surrounding rock mass, weakening the perimeter of the tunnel. Rock bolts limit rock deterioration to rock mass by transferring loads to solid rock. The nature of the load transfer is driven by three main elements: the type of bolt system, the properties of the cement grout material and the suitability of the rock adjacent to the bolt. [1,2]. According to anchoring systems, rock bolts can be divided into three main groups such as: mechanically fixed rock bolts, friction anchored rock bolts and fully grouted rock bolts. [3]. Flexibility, ease of installation and low cost makes fully grouted rock bolts a method of choice in tunnel engineering [4]. Fully-grouted rock bolts are divided into three standard types SN (Stor Norfors) rock bolts, PG (Post Grouted) rock bolts, IBO (injection bore bolts) rock bolts [5]. For the purpose of our research, only fully grouted SN and PG rock bolts have been tested, the bearing capacity is mainly provided by the shear resistance at the bolt–grout or grout–rock interfaces [6,7]. The length, pattern and severity of the rock bolts are determined based on rock mass quality. Standard rock mass classification for tunnel engineering is the Rock-Mass Rating (RMR) system, Rock-Mass index (RMi), and rock-quality index (Q) system [8]. In the present study, the rock-quality index (Q) system was used to determine the rock mass quality. All the direct support of tunnel-like, shotcrete thickness, wire mesh, steel or plastic fibers, steel ribs, umbrella arches, rock bolts, etc. are determined on-site based on Q value.

Typical SN and PG rock bolt elements and installation are shown in Figure 1. The elements of rock bolt, shown on the left, are hex nut, beveled washer, bearing plate, and steel anchor. A fully grouted rock bolt is shown on the right.

Figure 1. Typical SN and PG rock bolt elements and installation.

Mahrenholtz et al. studied the failure mechanism of post-installed reinforcing bars as end anchorage or as a bonded anchor. The research states that that the failure of a reinforcing bar, post-installed in a hole drilled into a base material like concrete or rock, may occur as a result of: steel failure (rupture or yielding of steel), concrete cone failure (concrete breakout), bond failure (pull-out) and splitting failure (cracking of concrete cover) [9].

Moosavi et al. studied the bond capacity of cement grouted steel bars under constant radial pressure by testing the specimen with a modified Hoek cell. They concluded that grout quality directly affects the bond capacity, emphasizing the importance of quality control of grout preparation and its application [10].

Kılıc et al. analyzed the effect of bar shape on fully grouted rock bolts' pull-out capacity. They have performed laboratory pull-out tests in 24 types of fully grouted rock bolts, out of them: in 3 types or 12.5% steel bar failure occur, in 1 type or 4.17% steel bar-grout failure occur, in 19 types or 83.33% grout failure occur [3].

Clay et al. summarized some practical problems encountered in rock bolts' site applications. They have concluded that only rock bolts that are not adequately grouted may fail in lower forces than the designed ones [5].

As shown also from the abovementioned literature, rock bolt method is a widely used technique for supporting underground excavations or stabilize damaged or cracked rock masses [11]. Their behavior and failure mechanisms are still an important topic of research. Worldwide laboratory tests show that failure of fully grouted bolts is more likely to happen at the bolt-grout interface because of a deboning process that begins when the axial force of the rod exceeds a critical value [4]. Ideally, the bolt is designed and implemented so that the bolt anchored to the solid rock will extend as the cracked rock mass moves towards the open/excavation site [12]. Thus, the bond capacity is the crucial element that makes the system work as designed which is also the main focus of this study.

TESTING MATERIALS

This paper investigates the bond capacity of rock bolts applied to different: rock mass qualities, bolt lengths and bolt inclination angles. Elements affecting bond capacity are rock bolt, grout, and surrounding rock/soil. The rock bolt support systems can be divided into three types: Continuous Mechanically Coupled (CMC) system, Continuous Frictionally Coupled (CFC) system, and Discreetly Mechanical and Frictionally Coupled (DMFC) system [13,14]. The CMC system is widely used among the three, as it is faster, simpler, needs less labor and is cheaper than the others. Also, within the CMC system there are several techniques, from which the cement grout system is the most common [15].

Rock Bolts

The rock bolts in this study were made of standard steel rebar, as shown in Figures 1 and 2 of B500C grade and only two diameters of rock bolts, such as: Φ22 and Φ25 were used. An atomized machinery was employed to arrange the length and properties of the thread. The average mechanical properties of tested rock bolt are shown in Table 1.

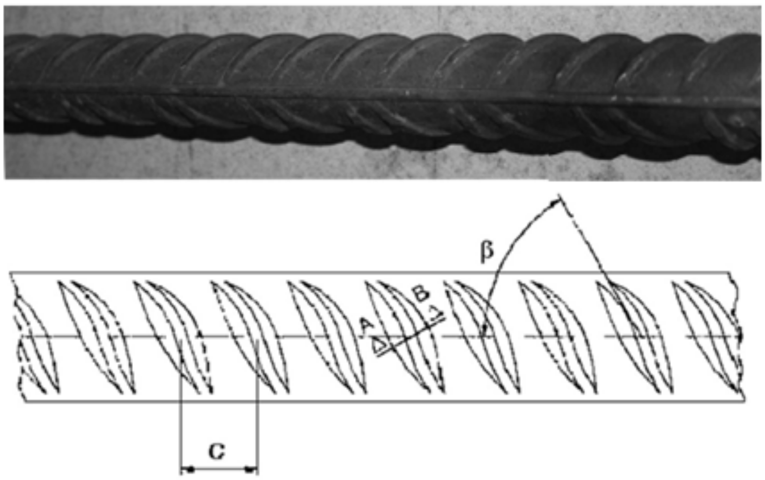


Figure 2. B500C grade steel bar material of which rock bolt is produced, adapted from [4].

Table 1. Rock bolt mechanical properties.

Rock bolt	Effective diameter (mm)	Yield capacity (N/mm^2)	Tensile capacity (N/mm^2)	Relative Extension (%)
Φ25	25.09	552.13	664.5	21.20
Φ22	22.15	531.96	632.5	19.55

Cementitious Grout

The grout used in this study is a cement-based mixture that protects the rock bolt from corrosion and transfers the bolt's acting forces to the surrounding rock mass [16]. The mix design of cementitious grout, Portland cement, water and necessary admixtures proportions were defined based on site and weather conditions and grouting pump capacities. The laboratory test performed on cementitious grout are: (a) Marsh funnel viscosity, (b) strength, (c) Vicat needle setting time and (d) Bleeding, as shown in Figure 3. The average values of compressive and flexural strength are reflected in Table 2.

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

Figure 3. Laboratory test performed on cementitious grout.

Table 2. Properties of cementitious grout and surrounding rock/soil.

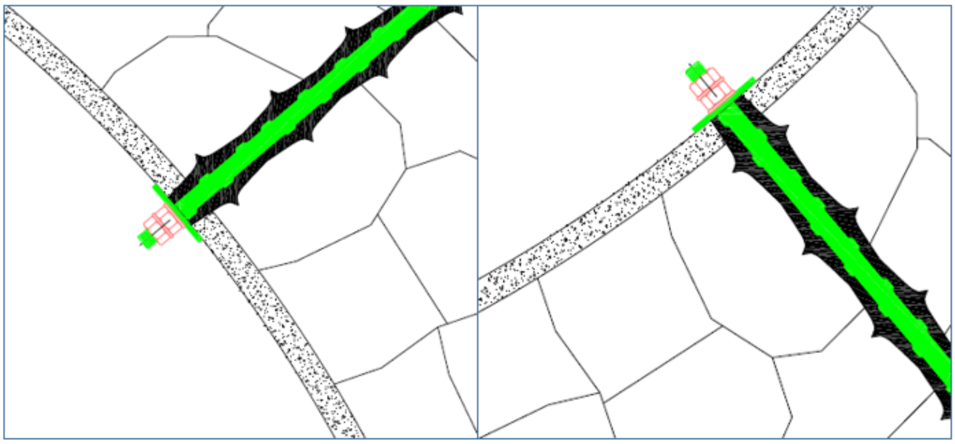
	Compressive Strength (MPa)	Flexural Strength (MPa)
Grout (7 days)	32.31	4.73
Grout (28 days)	43.56	6.67
Rock/soil	64.87	

Surrounding rock/soil

The tunnel axis passes through ultra-basic and basalt rocks. For this study purpose, 16 samples of surrounding rock are tested, and the results are presented in Table 2. Laboratory tests show that the average uniaxial compression strength of rock is 64.87 MPa with a standard deviation of 11.03 [17].

EXPERIMENTAL PROGRAM

The pull-out tests were performed on 22 and 25mm diameter; 3, 4 and 6m usually full grouted rock bolts installed in different parts of the tunnel with different specific angles to gravitational direction.



(a) Bolt inclined upwards (b) Bolt inclined downwards

Figure 4. The direction of rock bolts in a tunnel section.

The rock bolt installation in a specific tunnel section can be of two different directions, bolt inclined upwards and bolted inclined downwards, as shown in Figure 4. The bolts installed in the top head of the tunnel, from 0° to 180°, are inclined upwards, and bolts installed in the bench of the tunnel, from 180° to 360°, are inclined downwards. The tested rock bolts are installed on drilled holes in surrounding rock/soil of 50mm diameter and 3, 4 and 6m depth. The average uniaxial compressive strength in the tested rock is 64.87 MPa. The grout was mixed in a water-cement ratio varying from 0.35 to 0.40. Initially, the rock bolts were grouted as SN, and then the pull-out test was performed.

(a) (b)

Figure 5. Rock bolt pulls out test apparatus.

The pull-out test was performed with the apparatus shown in Figure 5. composed of (a) hydraulic jack and (b) hand pump. Hydraulic jack is composed of housing, cylinder, claw, spindle, bushing and nut, while the hand pump is composed of pump, gage and hose. The manual gauge shown in Figure 5 (b) is connected to a 30 tons' capacity hydraulic jack shown in Figure 5 (a).

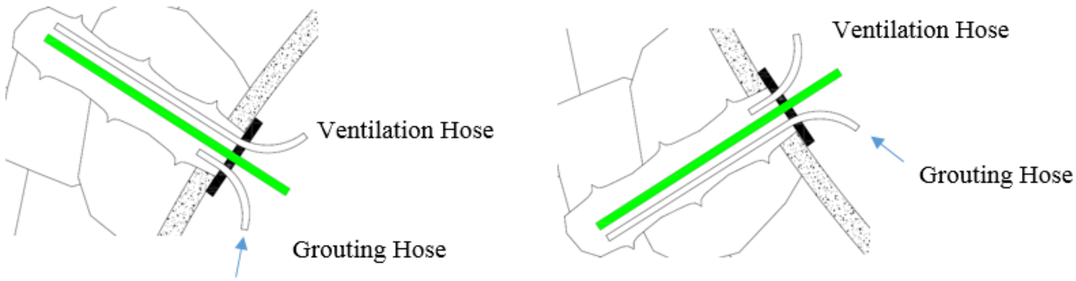
(a) (b) (c)

Figure 6. Rock bolt pull test performed on-site.

Real scale test on bond strength and force carrying capacity of rock bolts is presented in Figure 6. During this study there were performed two types of tests: one defined by technical specifications of construction works of water utilization and project implementation HPP of Fani i Madh and Fani i Vogel river

[18], and another one to determine the ultimate capacities of rock bolt anchors. Figure 6 (a) shows the central hole hydraulic jack bonded on the rock bolt and fixed in the central hole of a 20 mm thick steel plate placed on the shotcrete surface. Figure 6 (b-c) shows the performed test's recording process. The pull-out load is indicated on the loading gauge. An external dial gauge was fixed to measure the displacement of rock bolt with regard to the applied load, and a stopwatch measured the precise experimental time.

The testing procedure is done in compliance with ASTM D4435–08, Standard Test Method for Rock Bolt Anchor Pull Test [19].



(a) Bolt inclined upwards, (b) Bolt inclined downwards

Figure 7. Arrangement of grout for a PG rock bolt.

At the beginning of the investigation and the experimental program, SN rock bolts, also known as mortar embedded anchors, were applied. From the first experimental results, it was observed that all the rock bolts failed at low applied loads, due to bolt-grout bond. In the upward inclined bolts, this phenomenon was even more evident. So, it was decided to test the PG (post grouted) rock bolts as well. The grouting implementation for a PG rock bolt inclined upwards and downwards is shown in Figure 7.

The grout mechanism for upward inclined rock bolts is shown in Figure 7 (a), and for the downward inclined rock bolts are shown in Figure 7 (b). There were used two hoses for each type of rock bolts, one for grouting and the other to release the air out of the drilled hole without creating any pressure. The application process starts with drilling the 50 mm diameter holes up to the respective rock bolt depth. Attach two hoses in the rock bolt, and place them in the drilled hole. For safety reasons during the application process, there were used two different colored hoses; the one used for grouting is transparent while the one used to release the air out is black. After the rock bolt and the attached hoses are inserted, the hole entrance is closed with a plaster. As the plaster is hardened enough, the cement grouting is injected from the grouting hose till some grout came out from the ventilation hose. After that, the hoses are blocked, and the process is completed.

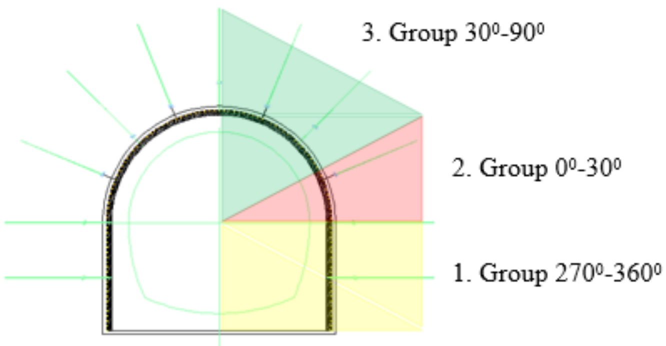


Figure 8. Typical rock bolt application pattern in a tunnel cross-section.

The typical rock bolt application pattern in a tunnel cross-section is shown in Figure 8. The rock bolts are symmetric according to the vertical axis passing from the center of the tunnel, so the details of one half apply in the same way to the other half. At the beginning of this study, we found that the inclination angle directly affects the SN type rock bolt capacity, so we grouped the tested rock bolts into three groups. Rock bolts of the first group, applied in the yellow part of Figure 8, are inclined downwards; second and third groups, applied in the red and green part of Figure 8, are inclined upwards. Upward inclined rock bolts are divided into two groups because the grouting shows different behavior as the inclination angle increases.

RESULTS AND DISCUSSIONS

Table 3. Pull out test results of SN type rock bolts.

Rock Bolt				Grout (w/c)	Rock Type	Failure Load (kN)	Max. Displacement(mm)	Failure Type
Type	Φ	Lenth (m)	Group					
SN	22	3	1	0.37	Moderate	116.54	21	Grout Failure
				0.36	Weathered	112.13	20	Grout Failure
SN	25	3	1	0.38	Moderate	118,27	22	Grout Failure
				0.35	Weathered	115,12	21	Grout Failure
SN	22	3	2	0.35	Moderate	68.45	8	Grout Failure
				0.36	Weathered	67.81	10	Grout Failure
SN	25	3	2	0.39	Moderate	71.24	21	Grout Failure
				0.38	Weathered	69.52	20	Grout Failure
SN	22	3	3	0.36	Moderate	48.36	-	Grout Failure
				0.35	Weathered	46.81	-	Grout Failure
SN	25	3	3	0.39	Moderate	51.29	-	Grout Failure
				0.37	Weathered	50.24	-	Grout Failure
SN	22	4	1	0.38	Moderate	124.58	24	Grout Failure
				0.36	Weathered	120.51	21	Grout Failure
SN	25	4	1	0.38	Moderate	125.68	25	Grout Failure
				0.37	Weathered	125.01	22	Grout Failure
SN	22	4	2	0.37	Moderate	66.28	15	Grout Failure
				0.39	Weathered	65.98	14	Grout Failure
SN	25	4	2	0.36	Moderate	70.59	17	Grout Failure
				0.35	Weathered	71.53	12	Grout Failure
SN	22	4	3	0.38	Moderate	50.27	-	Grout Failure
				0.36	Weathered	52.01	-	Grout Failure
SN	25	4	3	0.37	Moderate	51.98	-	Grout Failure
				0.35	Weathered	52.87	-	Grout Failure
SN	22	6	1	0.36	Moderate	132.52	29	Grout Failure
				0.36	Weathered	133.25	32	Grout Failure
SN	25	6	1	0.35	Moderate	135.69	31	Grout Failure
				0.38	Weathered	137.84	28	Grout Failure
SN	22	6	2	0.38	Moderate	68.51	21	Grout Failure
				0.37	Weathered	67.48	20	Grout Failure
SN	25	6	2	0.36	Moderate	67.21	19	Grout Failure
				0.36	Weathered	68.09	20	Grout Failure
SN	22	6	3	0.37	Moderate	58.83	-	Grout Failure
				0.36	Weathered	56.18	-	Grout Failure
SN	25	6	3	0.36	Moderate	59.37	-	Grout Failure
				0.35	Weathered	55.14	-	Grout Failure

The pull-out test results of SN type rock bolts are shown in Table 3. There are three different rock bolt lengths; for each bolt length, there are three types of arrangement as shown in Figure 8, and for every arrangement there are three types of the rock mass. In total there is a number of 36 cases. For SN bolt types, there was tested one bolt for each case, so 36 tested bolts.

Table 4. Pull out test results of PG type rock bolts.

Rock Bolt Type	Φ	Length (m)	Group	Grout (w/c)	Rock Type	Failure Load (kN)	Max. Displacement (mm)	Failure Type
PG	22	3	1	0.35	Moderate	124.87	32	Grout Failure
				0.35	Weathered	122.36	30	Grout Failure
PG	25	3	1	0.36	Moderate	126.53	28	Grout Failure
				0.37	Weathered	126.04	27	Grout Failure
PG	22	3	2	0.35	Moderate	121.74	27	Grout Failure
				0.35	Weathered	120.35	28	Grout Failure
PG	25	3	2	0.38	Moderate	120.58	26	Grout Failure
				0.38	Weathered	121.98	24	Grout Failure
PG	22	3	3	0.33	Moderate	121.42	28	Grout Failure
				0.35	Weathered	121.35	26	Grout Failure
PG	25	3	3	0.36	Moderate	122.01	26	Grout Failure
				0.37	Weathered	120.94	25	Grout Failure
PG	22	4	1	0.35	Moderate	132.56	34	Grout Failure
				0.35	Weathered	131.48	32	Grout Failure
PG	25	4	1	0.36	Moderate	131.52	32	Grout Failure
				0.37	Weathered	130.78	32	Grout Failure
PG	22	4	2	0.35	Moderate	128.96	33	Grout Failure
				0.36	Weathered	129.04	29	Grout Failure
PG	25	4	2	0.36	Moderate	127.04	30	Grout Failure
				0.35	Weathered	126.89	31	Grout Failure
PG	22	4	3	0.37	Moderate	128.78	30	Grout Failure
				0.36	Weathered	128.05	32	Grout Failure
PG	25	4	3	0.35	Moderate	130.09	31	Grout Failure
				0.35	Weathered	128.56	31	Grout Failure
PG	22	6	1	0.36	Moderate	142.52	38	Grout Failure
				0.36	Weathered	143.25	36	Grout Failure
PG	25	6	1	0.38	Moderate	142.04	39	Grout Failure
				0.37	Weathered	142.52	39	Grout Failure
PG	22	6	2	0.36	Moderate	141.86	38	Grout Failure
				0.35	Weathered	141.25	36	Grout Failure
PG	25	6	2	0.35	Moderate	142.87	37	Grout Failure
				0.36	Weathered	140.65	37	Grout Failure
PG	22	6	3	0.35	Moderate	141.89	36	Grout Failure
				0.35	Weathered	141.57	35	Grout Failure
PG	25	6	3	0.36	Moderate	140.12	38	Grout Failure
				0.35	Weathered	140.36	37	Grout Failure

The pull-out test results of PG type rock bolts are shown in Table 4. Similar to SN type bolts, there are three different rock bolt lengths; for each bolt length, there are three types of arrangement as shown in Figure 8, and for every arrangement, there are three types of the rock mass, so there are 36 cases. For PG bolt types, there were tested three bolts for each case, so in total, there are tested 108 bolts. The comparison of average values of Table 3 and Table 4 are shown in Table 5.

Each value shown in Table 3 is the value of the pull-out test results carried in a single rock bolt, each value shown in Table 4 is the average value of the pull-out test results carried in three different rock bolts, each value shown in the SN columns of Table 5 is the average value of the pull-out test results carried in four different rock bolts and each value shown in the PG columns of Table 5 is the average value of the pull-out test results carried in twelve different rock bolts.

Table 5. Comparison of results.

Length (m)	Group	Failure Load (kN)		Max. Displacement (mm)		Increase in Load Cap. (%)	Increase in displacement (%)
		SN	PG	SN	PG		
3	1	114.34	124.95	21.00	29.25	9.28	39.29
	2	69.25	121.16	14.75	26.25	74.96	77.97
	3	49.17	121.43	-	26.25	146.96	-
4	1	123.95	131.58	23.00	32.50	6.16	41.30
	2	68.60	127.98	14.50	30.75	86.56	112.07
	3	51.78	128.87	-	31.00	148.88	-
6	1	134.82	142.58	30.00	38.00	5.76	26.67
	2	67.82	141.66	20.00	37.00	108.88	85.00
	3	57.38	140.98	-	36.50	145.70	-

There were tested 36 different SN type rock bolts out of which 12 were inclined downward, and 24 were inclined upward. Half of the upward inclined rock bolts were installed in Group 2. (between 0^0 and 30^0) and the other half have installed in Group 3. (between 30^0 and 90^0). The highest ultimate load capacity/(failure load) and maximum displacement measured in downward inclined ones are respectively 137.84 kN and 32.00 mm. While there was possible to take some values for the downward inclined rock bolts, it was not the same for the upward inclined ones. The lowest ultimate load capacity/(failure load) measured on upward inclined is 46.81 kN (34% of the highest one), and there could not be taken any record in the displacement of the Group 3. upward inclined rock bolts.

The majority of rock bolts installed in tunnel construction, as shown in Figure 8, are upward inclined, so it is crucial to be sure that they are correctly installed and fully grouted. As previously mentioned, the failure of fully grouted bolts most likely occurs at the bolt-grout interface; in our study, 100% of failure occurred at the bolt-grout interface.

Rock bolt load carry capacity depends on two main elements: 1. grout mechanical properties 2. bolt diameter and length. Increasing the values of these two parameters will directly increase the bolt carry capacity; however, it must be emphasized that the bolt upper limit is the ultimate tensile strength of the bolt materials.

The results show that rock bolt load carry capacity decreases as the angle of upward inclined bolts increases. This explains that the application of SN rock bolts, especially for the upward inclined ones, causes problems in proper grouting; consequently, the bolt–grout interface is not well achieved. It can be easily seen in Table 4 that there are significant differences in load carry capacity of the same rock bolts having opposite incline direction. A downward inclined rock bolt has a load carry capacity more than two times higher than an upward inclined rock bolt in the same bolt type, grout, and rock properties. To achieve a better bolt–grout interface, the SN rock bolts were replaced with PG ones.

The results of PG bolt pull out test results are better, as shown in Table 4. By applying PG bolts, we achieved much better results in load carry capacity and bolted maximum displacement, as shown in Table 5. Replacing SN bolts with PG ones increased the load carry capacity to 148.88% and maximum displacement until the 112.07% level.

CONCLUSION

This study is critical because it was conducted in a real-scale rock bolt application and working environment. The study tested 144 rock bolts with a total length of 624m size, which is impossible to perform in the laboratory or small or medium projects.

The rock/soil on which the tunnel is built, and the rock bolts installed must be tested at representative intervals. Although basalt and ultrabasic rock formations have an ultimate compressive strength capacity (USC) above 100 MPa, in our case, the rock has an average (USC) 64,87 MPa.

In their entirety, the tested SN bolts have low values in bearing capacity and small displacement. SN bolts that are inclined upwards have an even smaller bearing capacity and almost zero displacements; this is due to an improper grouting method that fails to fill the drilled hole.

The change of the grouting method from SN to PG has dramatically improved their bearing capacity and maximum displacements. The bearing capacity of the bolts has increased to values ranging from 5.76% to 148.88%, and the maximum displacements have increased to values ranging from 26.67% to 112.07%

In our study, the bolt-grout interface's failure of grouted bolts occurred due to the deboning process and/or grout failure. This clearly expresses the importance of grouting as a material, its mechanical properties, and its application in the field.

It is suggested that PG should be set as a conditional grouting method for tunnel rock bolts. Our study proved that it filled the drilled hole fully, leading to a better bolt-cement-rock bond.

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