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Enhancing the bearing capacity of friction anchor bolts through cementitious concrete injection for reinforced support in Imiter underground rock masses

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A B S T R A C T

Friction anchor bolts are commonly used to provide support in underground structures by relying on frictional forces between the bolt and the surrounding rock. This study proposes a method to enhance the efficiency of these bolts by injecting a cement-based mixture comprising cement, sand, and additives. The injection of this mixture into the bolt results in internal expansion, which reinforces the friction and bearing capacity of the bolt. The increased volume exerts a radial force, leading to improved adherence, load transfer, and void filling. Pullout tests were conducted on various rock masses to evaluate the performance of the anchor bolts. The results demonstrate increased pullout resistance with higher rock mass quality and longer cemented bolts. Additionally, the use of a silicate-based additive accelerated the curing time of the cement, enhancing the strength of the bolts. The study also highlights the significant influence of groundwater on the bearing capacity of the bolts. These findings indicate the effectiveness of cemented concrete injection in strengthening friction anchor bolts and their anchorage in underground structures.

Keywords: *Friction anchor bolt, Cemented concrete injection,Additives, Pullout resistance*

Introduction

Friction anchor bolts play a critical role in providing support and stability to underground structures by utilizing the frictional forces between the bolt and the surrounding rock. However, there is a need to enhance the performance of these bolts to improve their bearing capacity (BC) and overall effectiveness. This study introduces a novel approach to enhance the efficiency of friction anchor bolts through the injection of a cement-based mixture (Li et al., 2016).

The proposed method involves injecting a cement-based mixture comprising cement, sand, and additives into the hollow profile of the friction anchor bolt. This injection leads to internal expansion, resulting in increased volume and reinforcing the frictional interaction between the bolt and the rock. The radial force exerted by the expanded concrete improves the bolt's adherence, load transfer, and void filling capacity, thereby strengthening the anchor bolt and improving the stability of the support system (Liu et al., 2021).

Pullout tests were conducted on various rock masses to evaluate the performance of the cemented friction anchor bolts. These tests considered different rock mass qualities and bolt lengths to examine their impact on pullout resistance. The results revealed a positive correlation between rock mass quality and pullout resistance, indicating that higher-quality rock masses exhibit improved bearing capacity.

In addition, the curing time of the injected cement plays a crucial role in the effectiveness of the cemented friction anchor bolts. To address this, a silicate-based additive was incorporated into the cement mixture, accelerating the curing process.

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This additive shortened the curing time, thereby enhancing the strength of the bolts and enabling immediate support.

Furthermore, the study investigated the influence of groundwater on the bearing capacity of the cemented bolts. It was found that groundwater significantly affects the performance of the bolts, emphasizing the importance of considering groundwater conditions in the design and application of cemented friction anchor bolts.

In conclusion, the proposed cemented concrete injection technique offers a promising approach to enhance the strength and anchorage of friction anchor bolts in underground structures. The findings of this study demonstrate the effectiveness of the cemented bolts in improving pullout resistance, bearing capacity, adherence, load transfer, and overall stability.

The incorporation of a silicate-based additive accelerates the curing time, further enhancing the strength of the bolts. Consideration of groundwater conditions is crucial for ensuring optimal performance. These results contribute to the understanding and advancement of friction anchor bolt technologies, offering potential benefits for the design and construction of underground structures.

1. Methods

1.1.Mine location

The Imiter silver mine is an underground mine situated in the Anti- Atlas Mountain range of Morocco, approximately 120 km southeast of the City of Ouarzazate. Located at an elevation of 1600 meters above sea level in a remote desert region, Imiter is the largest silver producing mine in Africa.

The extensive underground workings at Imiter reach depths exceeding 600 meters below surface across 11 production levels. The principal extraction methods employed are cut-and-fill and longhole open stoping. Significant geotechnical challenges encountered in the mine include high in-situ stresses and generally poor rock mass quality requiring extensive ground support.

The study site discussed in this paper is situated at the 500 meter level of the Imiter mine. The rock types encountered are dominantly volcano-sedimentary in origin. Prominent foliation planes strike nearly uniformly east-west across the rock mass. Multiple discontinuity sets are present, with frequent intersection of the various fracture orientations.

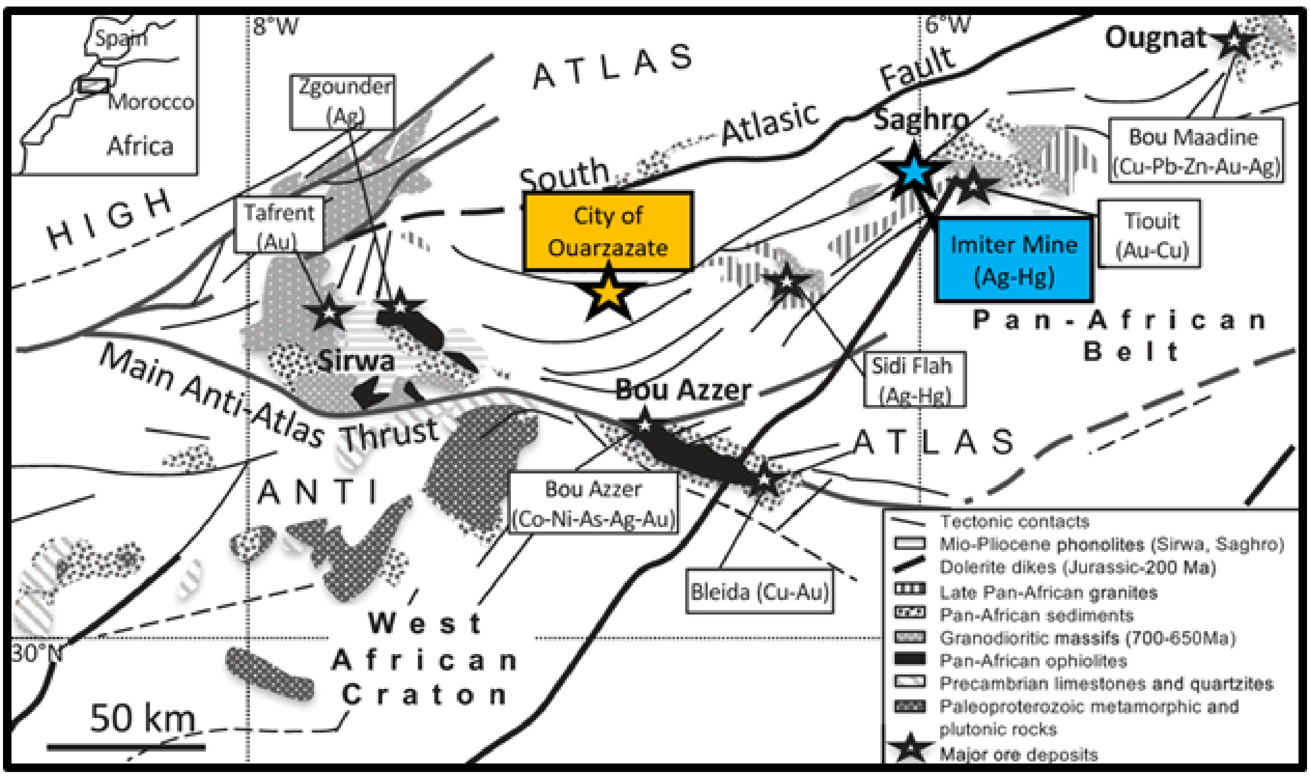


Fig.1. *Geological Sketch map of the location of the major deposit and the mine location*

1.2.Tested friction anchorage bolt

Friction bolts are hollow and thin metal profiles brought into intimate contact with the rock along their entire length, allowing for friction-based anchoring, their effectiveness is immediate. The Split Set (Figure 2.a) is a friction anchorage bolt for rocks that is inserted within seconds by simple percussion into a hole slightly smaller in diameter than the tube. The straightness of the hole is not important. The bolt conforms to the irregularities of the terrain, provides significant friction through radial pressure along its entire length (Figure 2.b), and ensures immediate anchoring (Li et al., 2017).

a)

b)

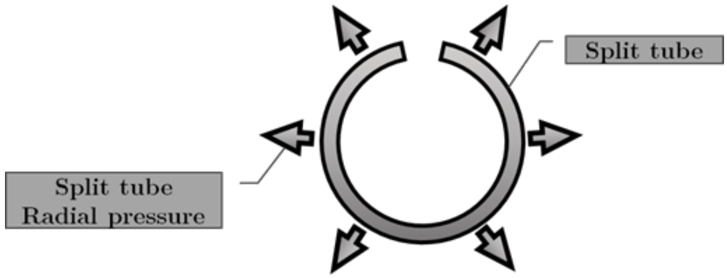


Fig.2. *a) Friction bolt / Split set (Hoek, 1993) b) Radial pressure of the friction bolt*

1.3. Principle of the test

The anchorage force of the anchorage bolt is generally evaluated using an extraction test, and the anchorage behavior of the anchorage bolt has been studied based on the load-displacement curves from the extraction test. An extraction load is applied to the outer end of the anchorage bolt, and the displacement of the anchorage bolt is then measured.

The traction jack (Figure 3) consists of two main units: a mechanical part (grip, bell, threaded bar, spacer, and nut) and a hydraulic part (jack, pump, pressure gauge).

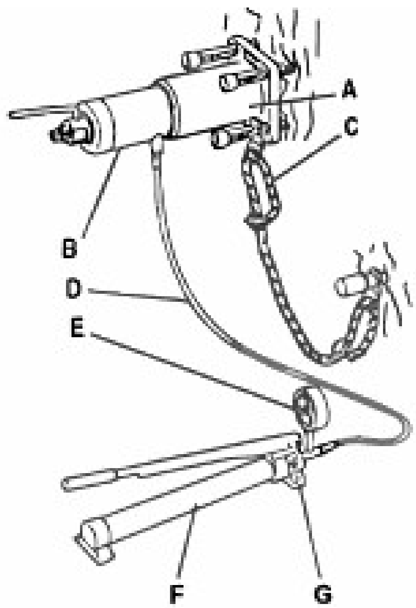


Fig.3. *Pull-out test setup (A: Charging case - B: Jack - C: Safety chain - D: Hydraulic hose - E: Manometer - F: Hand pump - G: Valve)*

The hole for an anchorage bolt is typically drilled perpendicular to the tunnel excavation surface. The drilling hole for the split set was drilled with a length of 1.8m, and a friction bolt was installed. The grout used was a mixture of ordinary Portland cement and sand in a 1:1 ratio. Sand with a maximum particle size of 2 mm was used.

2. Theory

2.1 Enhancing Friction Bolt Adherence

By combining the pressure generated through the diameter difference between the holes and the bolt, our proposal aims to enhance the bolt's adherence to the rock mass by introducing a cementitious mixture consisting of cement, sand, and two additives. This mixture will be injected into the friction bolt to ensure internal expansion, with the objective of improving friction and consequently the load-bearing capacity of the bolt. When the pressures generated by the expansion of the cemented mixture and the diameter gap between the bolt and the hole are combined (Figure 4).

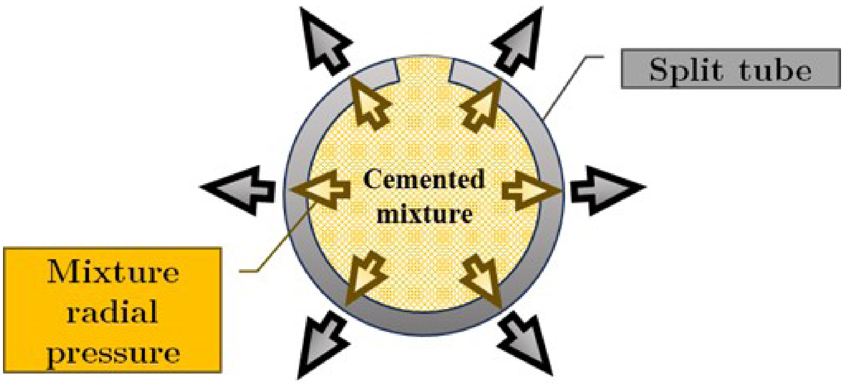


Fig.4. *Radial pressure of cementation mixture.*

Our tensile strength is naturally enhanced by confinement. When a friction anchor bolt is inserted into a hole in a rock mass, the rock exerts a radial confinement force on the bolt when it is tensioned. This force results from the elastic deformation of the surrounding rock (Figure 5). The radial confinement increases the pressure exerted on the bolt, thus improving the friction between the bolt and the rock. This increased friction enhances the bolt's resistance to pull-out. Consequently, the anchorage is more stable and can better withstand external loads.

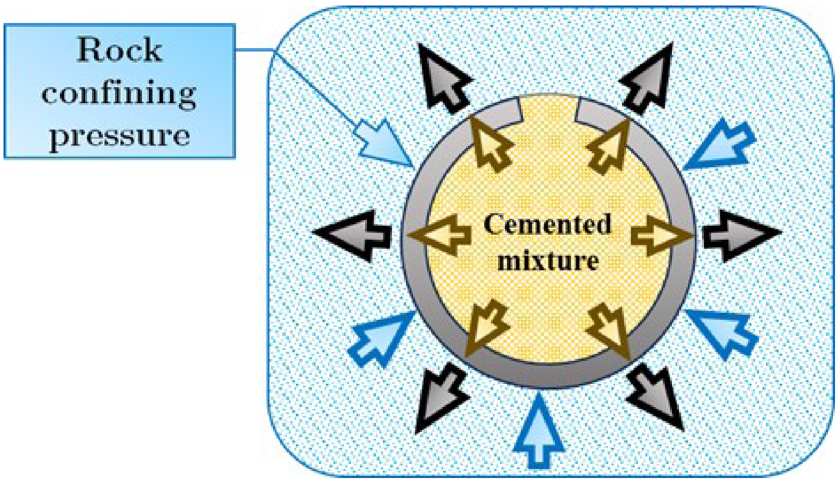


Fig.5. *Radial confining pressure of rock mass*

2.2 Cementitious Mixture Injection

In the present study, we propose the injection of friction bolts with concrete and two types of additives for two objectives. Firstly, to accelerate the consolidation of concrete in a very short time, and secondly, and most importantly, to enhance the increase in volume of concrete as a function of consolidation over time. These additives are designed to induce controlled expansion of the concrete, leading to a specific volume increase.

Silicate-based additives: Alkali silicates can also be used to accelerate concrete consolidation. These additives react with cement components to form reaction products that promote faster setting.

Gypsum-based expansive additives: These additives contain gypsum (calcium sulfate dihydrate), which reacts with water present in the concrete to form expansive crystals. These crystals create internal pressure that increases the volume of the concrete. Gypsum-based additives are often used to compensate for subsequent plastic shrinkage of the concrete.

When our concrete is injected inside a bolt anchored in rock, its volume increases over time due to chemical hydration reaction and the gypsum-based additive.

This increase in concrete volume exerts a radial force inside the bolt, directed towards the rock mass. This radial force has several beneficial effects on the bolt's pull-out resistance:

Increased adhesion: The radial force exerted by the increased volume of concrete promotes better adhesion between the bolt and the rock mass. This improved adhesion strengthens the bolt's ability to resist pull-out forces.

Load transfer: The radial force transmitted by the concrete expansion helps transfer applied loads on the bolt to the rock mass. This reduces local stresses on the bolt and contributes to a better distribution of forces, enhancing overall pull-out resistance.

Void filling: During concrete injection, voids may exist inside the bolt and between the bolt and the rock. Concrete expansion helps fill these voids and ensure closer contact between the bolt and the rock, thus improving anchorage efficiency.

Increased stability: The increase in concrete volume can also contribute to greater overall stability of the support system. By reinforcing the bolt anchorage, the concrete reduces undesired movements or deformations of the bolt and rock mass, thereby improving the strength and durability of the support structure.

In summary, the volume increase of concrete injected into an anchored bolt promotes adhesion to the rock mass, transfers loads, fills voids, and enhances the overall stability of the support system. These combined effects contribute to strengthening the bolt's pull-out resistance and ensuring effective anchorage in the rock.

3. Results and discussion

3.1 Behavior of bolts in a dry rock mass

The Rock Mass Rating (RMR) system was developed by Bieniawski in the 1970s to provide a quantitative estimate of rock mass quality based on six parameters: uniaxial compressive strength of intact rock, RQD (rock quality designation), spacing of discontinuities, condition of discontinuities, groundwater conditions, and orientation of discontinuities. The six parameters are rated and summed to give an overall RMR value between 0-100 which is correlated with rock mass classes and estimated engineering properties. A higher RMR indicates better, more competent rock mass conditions (Bieniawski, 1988).

The Q-System was developed by Barton, Lien, and Lunde in the 1970s to complement the RMR system. It aims to quantify the quality of the rock mass to provide estimates of support requirements. It involves rating six parameters on a logarithmic scale: RQD, joint set number (Jn), joint roughness number (Jr), joint alteration number (Ja), joint water reduction factor (Jw), and stress reduction factor (SRF). The sum of the six parameters gives the Q-value, which ranges from 0.001 to 1000. A higher Q indicates better quality rock mass with lower support requirements (Barton et al., 1981).

To investigate the anchoring and traction behavior of an anchorage bolt in a dry rock (Figure 6), several field tests were conducted at the Imiter mining site in Morocco. This section includes nine pull-out tests on three anchors in each rock mass RMR=40, RMR=60, and RMR=80. The primary rock component is sandy siltstone, and the joint spacing is classified as dense, with soft filling materials.

Fig.6. *Pullout test*

The behavior of anchorage bolts was studied by analyzing the load-displacement relationship in the extraction test. The effect of each dry rock mass on the behavior of the anchorage cemented bolt was examined by comparing the extraction resistance and displacement at the yield limit. The Figure 7 depict the relationship between extraction load and displacement for each rock condition. The extraction resistance was determined following ASTM standard D443513e1.

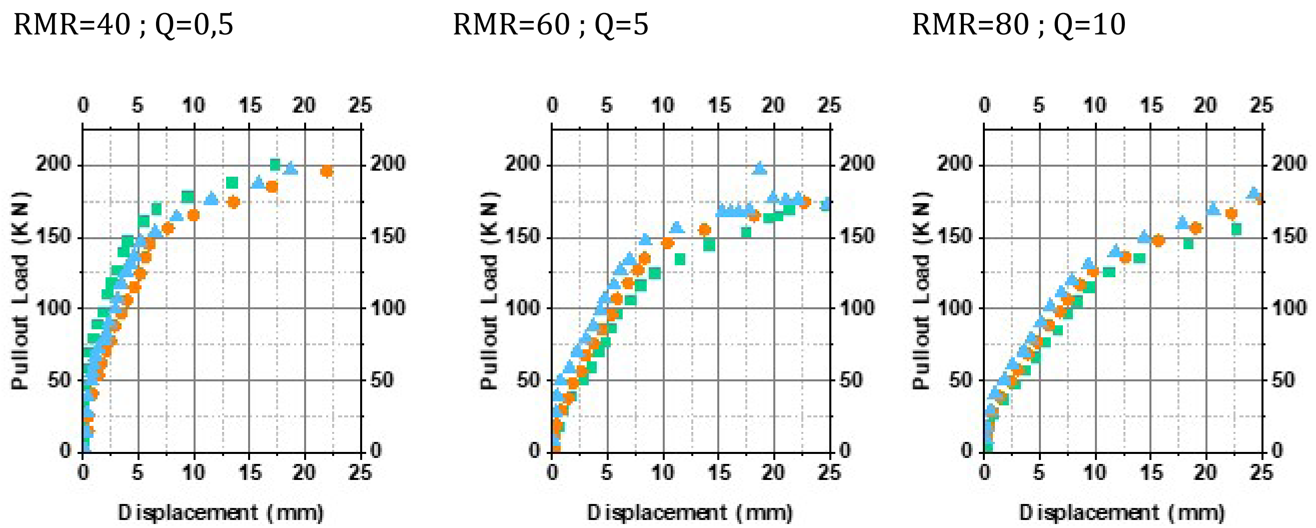


Figure 7.*a) Pullout load-displacement for RMR=40; b) Pullout load-displacement for RMR=60; c) Pullout load-displacement for RMR=80*

The test results demonstrate that the slope of the load-displacement curve increases with the improvement of rock mass quality, leading to an increase in pull-out resistance. This trend was more pronounced when the tested dry rock mass became more competent (stiffer).

The detection of the pullout failure point of cemented friction bolts was achieved by observing the change in slope of the load-displacement curve (Figure 8). The upper (abc) and lower (a'b'c') boundaries were plotted, correlating the two inflection points (bb'), in order to obtain the failure line:

$$BC\ (KN) = 1{,}32RMR + 60 \quad (1)$$

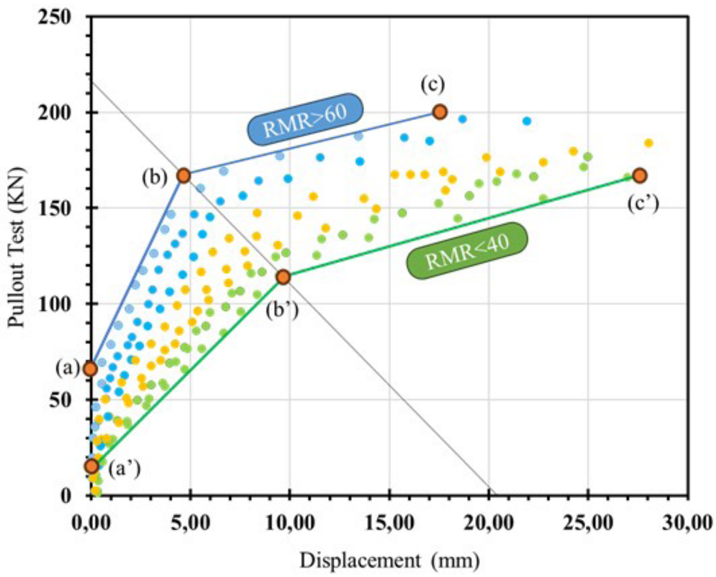


Fig.8. *Pullout load-displacement for RMR=40, RMR=60 and RMR=80*

3.2 Effect of bolt length and Rock Mass Quality

The pullout capacity of friction rock bolts increases with length, but at a diminishing rate. Longer bolts exhibit higher load capacity but lower strength per unit length. The paper provides equations relating bolt length to pullout resistance based on numerical modeling and field pullout tests (Komurlu and Demir, 2019).

The relationship between anchorage bolt length and load-displacement response was investigated in rock masses of varying quality, categorized using Bieniawski's Rock Mass Rating (RMR) system and Barton's Q-system. The influence of cemented anchorage bolt length on traction behavior was investigated in moderate and soft rocks with lengths ranging from 1.8 to 3.5 m. Figure 9 depicts the relationship between pullout load and displacement for various anchorage bolt lengths.

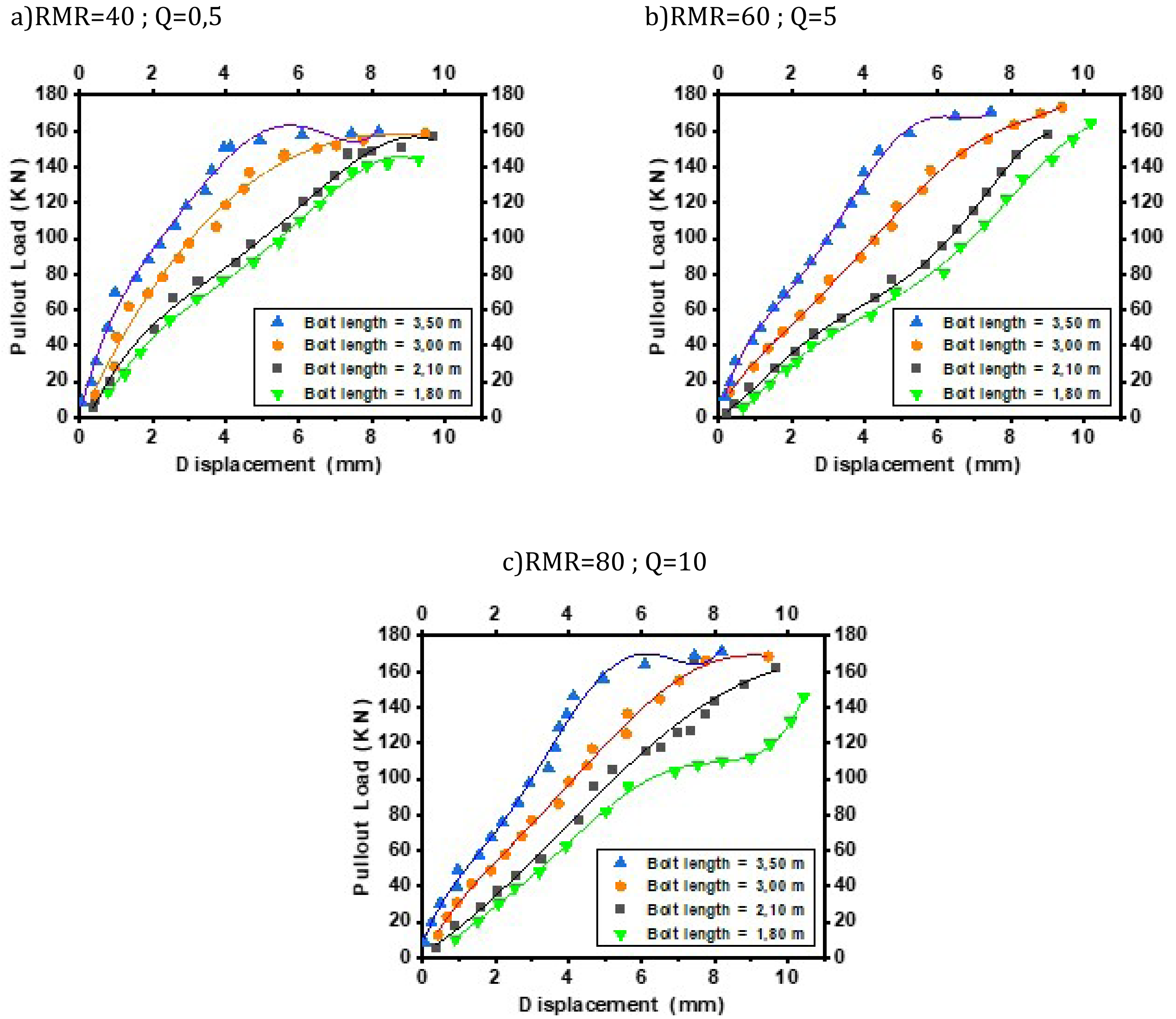


Fig. 9. *Pullout load-displacement with lengths ranging for a) RMR=40 b) RMR=60 and c) RMR=80*

The slope of the load-displacement curve increased with bolt length in rock masses with RMR values of 40 (Q=0.5), 60 (Q=5), and 80 (Q=10). This illustrates an increase in yield limit load capacity linked with longer bolt installations across poor, fair, and good quality rock masses. The study emphasizes the advantages of longer anchor lengths, especially in short bolts, for increasing load capacity (Figure 9).

To prevent having a negative residual value (b<0) in the regression equations ($y=a.Bl^b$) for different rock mass qualities, a constraint was imposed requiring zero bearing capacity at negligible bolt lengths. This origin-passing condition forces all regression lines through the point (0,0) on the plot of bolt length versus capacity. Anchoring the regressions at zero eliminates the possibility of a negative y-intercept term (b), which is non-physical given that bolts cannot provide negative support. Extrapolating the regressions to zero length must correspond to zero capacity for consistency with expected mechanical behavior. Constraining the regressions to intersect (0,0) also enhances fit and predictive performance by eliminating unrealistic negative residuals (Figure 10).

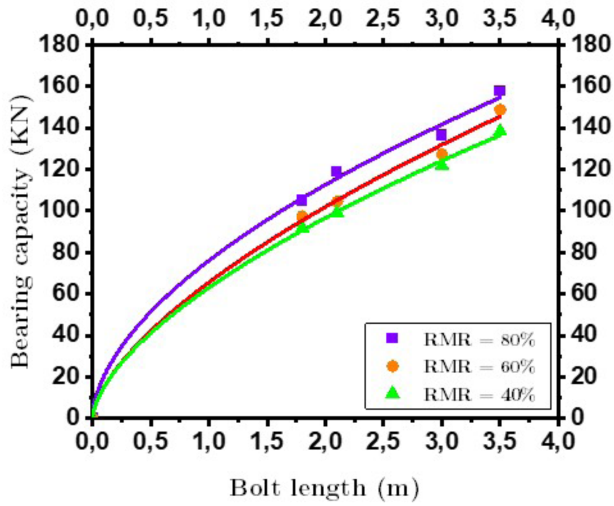


Fig. 10. *Pull-out bearing capacity with lengths ranging*

Overall, requiring the regression lines to pass through the origin provides a sensible bounding condition that improves representation of the relationship between bolt length and bearing capacity across different rock masses. To estimate the carrying capacity of cemented friction bolts, taking into account the cemented bolt length and the quality of the rock mass, the following expression is proposed:

$$BC_{Bl}\ (KN)=a.Bl^{b} \qquad (2)$$

Where:

BC: bearing capacity (KN)

Bl: cemented bolt length (m)

Table 1. *Parameter of adjusted exponential model*

Parameters	**Optimized Values**		
	RMR=80	**RMR=60**	**RMR=40**
a	76,12 ± 5,59	65,63 ± 4,7	63,04 ± 2,6
b	0,56 ± 0,07	0,63 ± 0,07	0,61 ± 0,04
r²	0,95	0,96	0,98

To account for the combined effect of both fully grouted bolt length and rock mass quality (RMR) on bearing capacity, a 3D surface plot was generated interpolating between available measurement points. This allowed visualization of bearing capacity as a function of the two parameters of interest. The 3D representation captures how bolt length and RMR quality interact to influence capacity, generating the interpolated surface enabled continuous prediction of bearing capacity across varied bolt lengths and rock mass ratings based on the measured data.

The 3D interpolation and surface plotting methodology enable straightforward interpretation of capacity trends in response to concurrent changes in bolt geometry and rock mass characteristics. Fitting the following proposed model allows representing the combined effect of length and RMR on capacity in a closed-form equation.

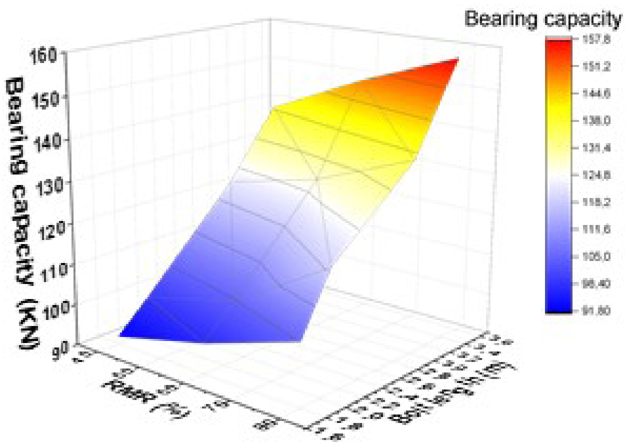
$$BC_{(RMR,Bl)}(KN)=A+\frac{B}{\left[1+e^{\left(\frac{C-RMR}{D}\right)}\right]\left[1+e^{\left(\frac{E-B1}{F}\right)}\right]} \qquad (3)$$

Where:

BC: bearing capacity (KN)

BL: cemented bolt length (m)

a)



b)

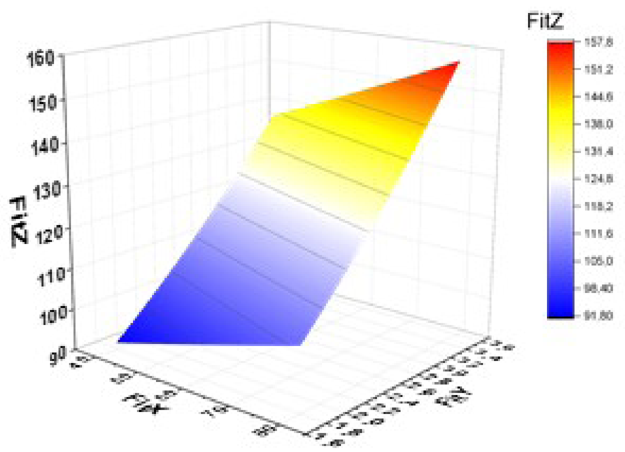


Fig. 11. *a)3D surface interpolation from pullout measurement points, b)3D surface plotting of fitted exponential model*

Multiple regressions were performed to identify the coefficients values that maximized the Pearson correlation coefficient (r^2=0,96) , thereby ensuring acceptable prediction accuracy compared to measurements.

Table 2. *Parameter of adjusted regression model*

Parameters	Optimized Values
A	-1,88 ± 106,8
B	3827,16 ± 59261,9
C	236,61 ± 4209,6
D	236,61 ± 4209,6
E	10,7 ± 49,3

The proposed exponential formulation with optimized coefficients provides a predictive relationship able to capture the interactive effects between bolt lenght and rock mass quality based on the empirically measured capacities. This exponential model enables straightforward estimation of bearing capacity across the range of tested bolt lengths and rock mass ratings.

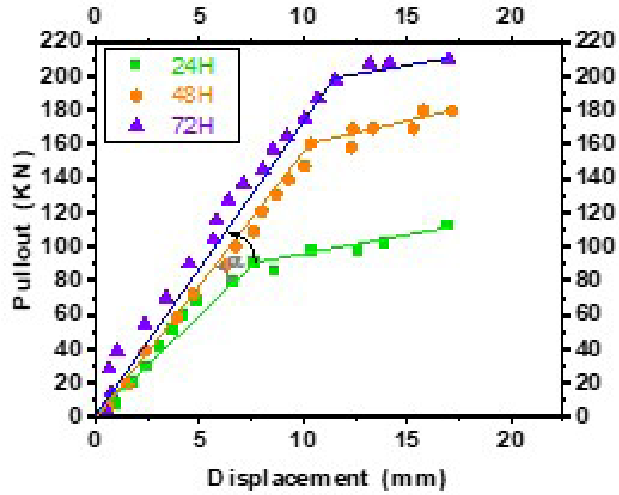
3.3 Effect of Curing Time on Cemented Anchor Bolts

The setting time of injected cement is an important issue in the application of cemented anchor bolts. It affects the stabilizing capacity of the bolts. Cement takes time to set and harden; therefore, cemented bolts cannot be used for immediate support.

Kilic et al. conducted traction tests on eight groups of bolts with the same length and mortar with a water-to-cement ratio of 0.4. They were tested to determine the effects of curing time on bolt bond strength. Each group of bolts had a different curing time. The results showed that during the first 7 days, the bond strength of the bolts and the maximum traction load increased rapidly. After 7 days, the tests continued to increase but at a slower rate (Kılıc et al., 2002).

To address the issue related to setting time, a decision was made to add a silicate-based admixture to accelerate the consolidation process. Subsequently, a series of pull-out tests was conducted on six cemented bolts, distributed in two different types of rock masses characterized by quality indices RMR=40 and RMR=60. The displacements of the installed bolts were then recorded at three distinct time intervals: after 24 hours, 48 hours, and 72 hours (Figure 12).

a)RMR=60 ; Q=5



b)RMR=40 ; Q=0,5

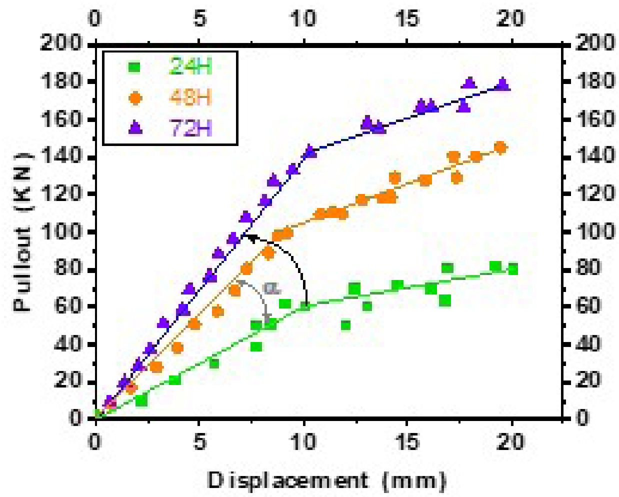


Fig. 12. Pull-out bearing capacity with lengths ranging a)RMR=60 b)RMR=40

For an RMR=40 rock mass, it is evident that the bearing capacity experienced a significant increase, rising from 80 kN to 160 kN after a period of 72 hours following the installation of the cemented bolt.

The results obtained clearly demonstrated a significant increase in bearing capacity after the installation of the cemented bolt over a 72-hour period. Initially, the bearing capacity was 100 kN, but it increased significantly to reach 200 kN. In other words, we observed a 100% improvement in bearing capacity between the first and third day.

The first observation regarding Figure 11 is that within the same RMR class, the slope of the pull-out-displacement curve increases as a function of curing time. Furthermore, quantitative analysis reveals a decrement in the angular divergence α between directing slopes of pullout-displacement curves as RMR score improves. In other words, the pullout-displacement lines converge angularly over time when moving from lower to higher RMR values. This suggests a closing of the angular separation between pullout-displacement relationships as curing duration increases, particularly for rock masses of greater quality per the RMR classification.

The diagram depicted Figure 13 illustrates the correlation existing between the bearing capacity and curing time for two distinct classes of Rock Mass Rating (RMR), to estimate the bearing capacity of cemented friction bolts, taking into account the curing time and the quality of the rock mass, the following expression is proposed:

$$BC(KN)=1{,}7Ct+1{,}3\ RMR - 25 \qquad (4)$$

Where:

BC: bearing capacity (KN)

Ct: curing time (hours)

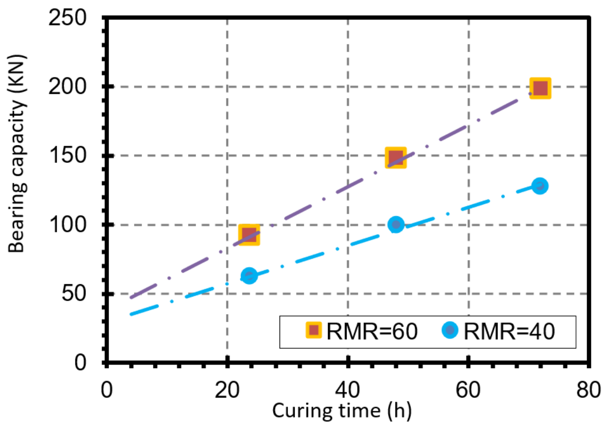


Fig.13. *Pull-out bearing capacity with Curing Time*

These results indicate that the setting time plays a crucial role in enhancing the strength of the cemented bolt. The analysis of the obtained data significantly confirms the positive effect of setting time on the strength of the cemented bolt.

3.4 Impact of groundwater on bearing capacity

Zhang et al. studied the impact of groundwater on the load-bearing capacity of anchor bolts in a coal mine, using the rating of water condition (Rw) index of the RMR classification to estimate the water flow in the underground structures of the mine. The results showed that the presence of groundwater had a significant impact on the load-bearing capacity of the anchor bolts (Zhang et al., 2017).

The Rw rating of water condition is a parameter used in the Rock Mass Rating (RMR) system for rock mass classification. It was introduced by Z.T. Bieniawski in 1973 and provides a quantitative estimate of the quality of water seeping through rock discontinuities. The Rw value ranges from 0 to 15 and depends on the water pressure, flow rate and chemical activity. Higher values represent drier conditions with low water pressure and flow, while lower values are assigned to wet rock with active water seepage and high pressure (Aziz et al., 2017).

Water present in rock masses can have a significant influence on the bearing capacity of friction anchor bolts used in underground structures. To quantify this impact on the bearing capacity of the bolts, we estimated the water flow rate in the underground structures of the mine using the Rw index of the RMR classification shown in Table 3.

Table 3: *Parameter of water presence in the RMR index*

Inflow per 10m length (l/m)	0	<10	10-25	25-125	>125
Condition	dry	Damp	Wet	Dripping	Flowing
Rw Rating	15	10	7	4	0

To investigate the impact of groundwater presence in imiter rock mass on the load-bearing capacity of cemented bolts, we recorded the pull-out displacements of four bolts installed in four mining sectors (Imiter 1, Imiter 2, ImiterSud, and Igoudrane). These sectors exhibit varying levels of groundwater presence. The four mining zones under study share the same overall rating of RMR=60; however, the rating of the Rw parameter, representing the groundwater presence in the mass, varies across the zones (Figure 14).

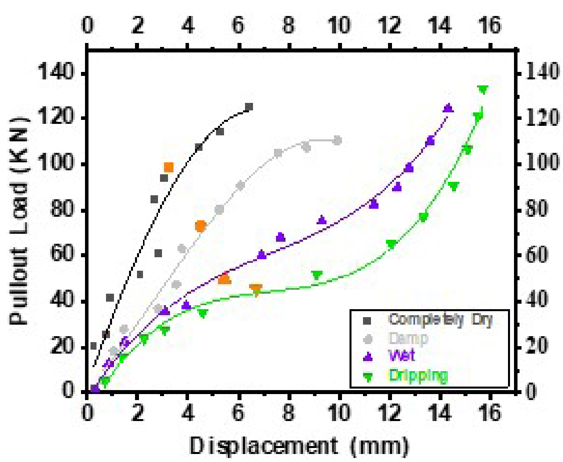


Fig.14. *Pullout load-displacement with groundwater factor for RMR=60*

To establish a correlation between the load-bearing capacity of cemented bolts and the presence of water in the rock mass, we graphically represent the values of the load-bearing capacity as a function of the rating of the Rw parameter, which characterizes the groundwater presence according to the RMR index (Figure 15).

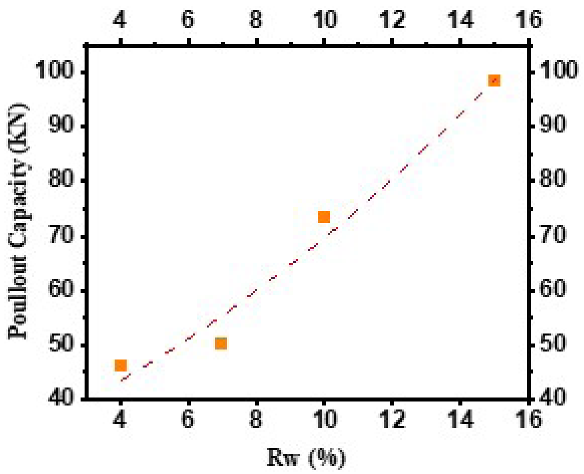


Fig.15. *Pull-out bearing capacity with groundwater factor for RMR=60*

To quantify the correlation between the tensile strength and the Rw index, the following expression is proposed:

$$BC(KN)=32{,}83\ e^{0{,}074 \cdot R_w} \ ; R^2 = 0{,}97 \quad (5)$$

The analysis of the results leads to the conclusion that the pull-out load capacity of cemented friction bolts decreases proportionally with the presence of water in the rock mass. Here are some proposed explanations for this impact:

Reduction of friction: When water infiltrates into cracks and joints in the rock, it can reduce the friction between the anchor bolt and the rock wall. This can weaken the holding capacity of the bolt, resulting in a reduction in load-bearing capacity.

Rock erosion: Water can cause erosion of the surrounding rock, weakening the overall structure of the rock wall. This can decrease the rock's ability to support the load exerted by the anchor bolt, thus reducing its load-bearing capacity.

Corrosion of the anchor bolt: Water can also lead to corrosion of the anchor bolt, especially if it is made of steel. Corrosion weakens the bolt, diminishing its strength and load-bearing capacity.

Rock swelling: In certain situations, when water penetrates into the rock, it can cause the rock to swell. This swelling can act like a lubricant on the anchor bolt, thus reducing its load-bearing capacity.

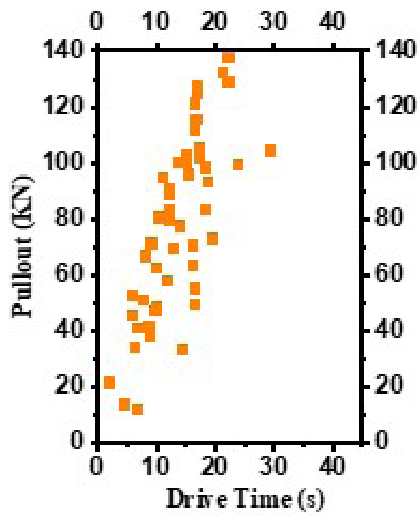
To mitigate the effects of water on the load-bearing capacity of friction anchor bolts, several measures can be taken, such as using corrosion-resistant materials and implementing drainage systems to remove water.

3.5 The effect of Rock Bolt-Drilled Hole diametrical difference on pull-out resistance

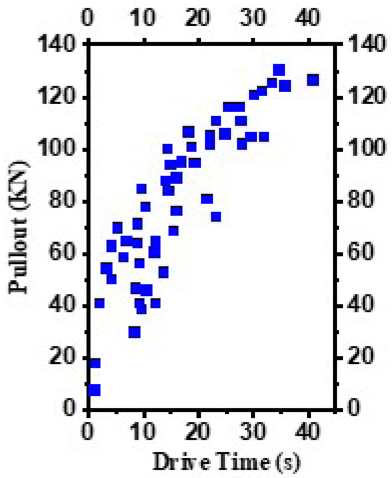
The installation time of rock bolts into boreholes can be used as an indicator of the difficulty encountered by the drilling equipment during the bolt insertion process. This installation time parameter can be linked to Bolt-Hole diametrical difference (BHDD) then be correlated with the force required to extract the rock bolt from the borehole in pull-out testing.

An experimental investigation was conducted to determine the influence of rock bolt installation rate on the pull-out resistance for varying bolt-borehole diametrical differences. The study involved installation of 34 mm, 36 mm, and 38 mm diameter rock bolts into 33 mm diameter boreholes drilled in a rock mass of moderate quality, with an RMR of 60 and Q-value of 5. The insertion time was measured for each bolt diameter and correlated to the maximum pull-out load obtained from extraction testing. The results shown in Figure 16 demonstrate that longer installation times, corresponding to slower drive speeds, lead to higher ultimate pull-out loads for increased diametrical differences between the bolt and borehole diameters examined. Excluding anomalous outliers, a clear trend is observed where slower insertion s, and therefore higher bolt-borehole diametrical differences, produce increased pull-out resistance.

a) BHDD=1mm



b) BHDD=3mm



c) BHDD=5mm

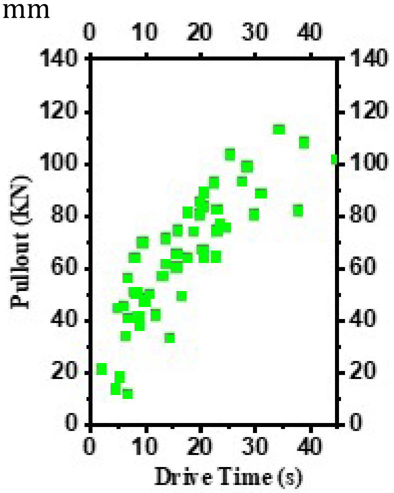


Fig.16. *Pullout load-displacement with drive time for a) D =34 mm, b) D =36 mm and c) D =38 mm*

Results from field pull-out tests demonstrate that the more the drilled hole is smaller than the rock bolt diameter the more the bolt necessitate a longer drive time for placement into the borehole. This increased duration of the rock bolt insertion process for reduced bolt diameters directly relates to an increase in the measured pull-out resistance. This observation suggests that increasing the rock bolt diameter leads to greater friction and mechanical interlock between the bolt and the borehole wall.

The regression curves of the drive time for each Bolt-Hole diametrical difference (BHDD) are given by the following expressions:

$$UC_{(BHDD=1mm)}=53\ \ln(Dt) - 56.3 \tag{6}$$
$$UC_{(BHDD=3mm)}=32.56\ \ln(Dt) - 4 \tag{7}$$
$$UC_{(BHDD=5mm)}=32.1\ \ln(Dt) - 18.7 \tag{8}$$

Overlaying the regression curves of each Bolt-Hole diametrical difference on a single graph provides a clear understanding of the pull-out resistance domains based on the drilling advancement speed (Figure 17).

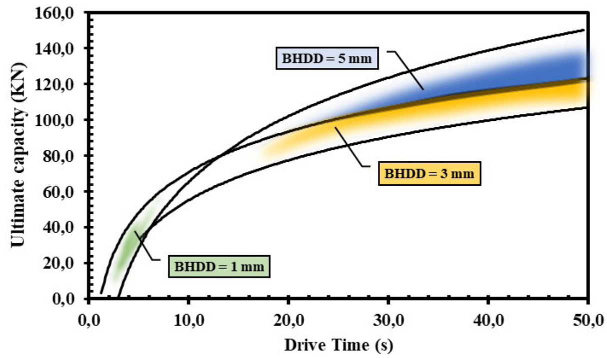


Fig.17. *Pullout load-displacement with drive time*

By utilizing the provided regression equations for the different bolt diameters, it becomes possible to estimate the pull-out resistance based on driving time and Bolt-Hole diametrical difference. This estimation can be used to evaluate bolt performance under specific conditions and make appropriate decisions regarding design and safety.

3.6 Impact of Water-to-Cement Ratio on Rock Bolt Resistance

As the water increases in a water-cement ratio, the strength and durability of cured concrete will decrease (Aziz et al., 2017), This is due to an increase in water particles between the cement particles, as the water evaporates over time air will replace the water, leaving the concrete porous (Wong and Buenfeld, 2009). These pores offer littles structural support and therefore will reduced the strength of the concrete structure.

The water-to-cement ratio (w/c) is the most important factor in concrete mix design as it controls the mechanical properties and durability of hardened concrete. The water-to-cement ratio represents the mass ratio of water to cement in freshly prepared concrete, and it is defined by dividing the amount of water in the mix by the weight of cement, both of which are fixed in the same concrete mix.

$$WCR = \frac{w}{c} \tag{9}$$

A pullout test was conducted on four bolts installed with four different water-to-cement ratios, after 28 days from the date of their installation. In order to avoid the influence of water presence and the quality of the rock mass, it was decided to install the bolts in dry blocks with an RMR rating of 60 (Figure 18).

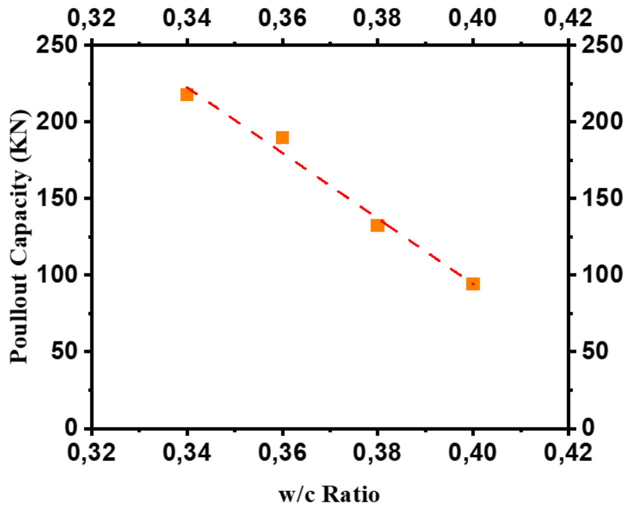


Fig.18. *Pull-out bearing capacity with WCR ratio (RMR=60; Curing time=28 Days)*

We propose the following model:

$$BC_{WCR}\,(KN)=a+b.WCR \tag{10}$$

Table 3. *Parameter of adjusted linear model*

Coefficients	Optimized Values
A	950,7 ± 69,18
B	-2141,5 ± 186,63
R^2	0,98

Experimentally, a ratio of 0.34 provides the best bolt-rock resistance; however, other issues arise with this ratio. The pumpability of the grout decreases, and several difficulties arise during application. Pumpability increases as the ratio becomes higher, which facilitates the filling of the boreholes. However, this reduces the bond strength.

4.Conclusion

In conclusion, the study demonstrates the effectiveness of cementitious concrete injection in enhancing the bearing capacity of friction anchor bolts and reinforcing their anchorage in underground structures. The injection of a cement-based mixture comprising cement, sand, and additives into the bolt leads to internal expansion, resulting in increased volume and improved frictional interaction between the bolt and the rock mass. The main conclusions and advantages of this method can be summarized as follows:

Increased Adherence: The radial force exerted by the expanded concrete enhances the adhesion between the bolt and the rock mass, improving the bolt's ability to resist pull-out forces.

Enhanced Load Transfer: The radial force transmitted by the expanded concrete aids in transferring applied loads from the bolt to the rock mass, resulting in reduced local stresses on the bolt and better distribution of forces, thereby enhancing overall pull-out resistance.

Void Filling: The expansion of the concrete helps fills voids inside the bolt and between the bolt and the rock, ensuring closer contact between the bolt and the rock. This improves the efficiency of anchorage.

Overall Stability: The increase in concrete volume contributes to the overall stability of the support system by reinforcing the bolt anchorage. It reduces undesired movements or deformations of the bolt and rock mass, enhancing the strength and durability of the support structure.

Silicate-Based additive: The incorporation of a silicate-based additive accelerates the curing time of the cement, enhancing the strength of the bolts. This allows for immediate support after the injection process.

Influence of Groundwater: The study highlights the significant influence of groundwater on the bearing capacity of cemented bolts. It emphasizes the importance of considering groundwater conditions in the design and application of cemented friction anchor bolts.

The pullout tests conducted on various rock masses demonstrate that higher rock mass quality and longer cemented bolts result in increased pullout resistance. The length of the anchorage bolt plays a significant role in the bearing capacity, with longer bolts exhibiting higher tensile strength and pull-out resistance. The proposed empirical equations provide estimates for the bearing capacity based on the rock mass quality and cemented bolt length.

Overall, the cemented concrete injection technique offers a promising approach to enhance the strength and anchorage of friction anchor bolts in underground structures. It provides specific advantages such as increased adhesion, load transfer, and overall stability of the support system. The use of a silicate-based additive accelerates the curing time, further enhancing the strength of the bolts. Considering groundwater conditions is crucial for optimal performance.

While this study demonstrates the potential of cementitious concrete injection to enhance friction anchor bolts, there remains significant scope for further optimization through ongoing research. Comparative analysis against traditional bolting solutions will help refine the technique and quantify potential disadvantages to be mitigated. The installation of hollow split rockbolts requires additional procedural steps compared to traditional bolting methods. These extra operations reduce the purported technological superiority of split bolts over conventional supports. Moreover, the lower elastic modulus of a cement mortar bolt relative to a hollow bolt may have detrimental effects. The reduced elasticity could lead to worsening of adhesion properties at the bolt-rock mass interface as blasthole diameter enlarges resulting from progressive rock fracture during mining activities. This potential adhesion deterioration and loss of friction should be thoroughly examined.

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