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FACTORS TO ANALYSE STRENGTH OF MINERAL INFILLED ROCK MASS DISCONTINUITIES

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ABSTRACT: In primary rock mass, with high intact strength and a small or null presence of open discontinuities, the rock mass strength depends on the volumetric distribution and mechanical properties of veinlets filled with different minerals. Vein properties can be used to obtain an index for rock mass characterization and classification into geotechnical domains, or they may be used directly in wedge analysis or in complex numerical models. A mineralized vein presents shear and tensile strength. These properties were measured, and the scale effect was approached by using 150 mm diameter samples for direct shear and indirect tensile tests. Vein properties were also obtained from triaxial compression tests in 48mm diameter samples. The test methods used are analyzed and the values of the mechanical properties of veinlets per mineralogy are given.

KEYWORDS: Rock mass strength, Rock mass characterization, El Teniente.

1 INTRODUCTION

One of the major geological features of the hard primary rock mass at El Teniente mine is the presence of mineral-filled veins which control its failure mechanism . The caving of the competent primary rock is controlled by the presence of these discontinuities, facilitating or hindering the gravity breakage of the rock mass.
The vein characteristics controlling the caving progress of El Teniente Mine were deeply studied by Brzovic and Villaescusa (2007), who used the Mohs scale to evaluate the strength of the infilling material.
Likewise, these veins are part of the rock mass where the operational infrastructure is constructed, which needs to remain until the production finishes. In both cases, the importance of understanding and characterizing these discontinuities is remarkable. The use of vein properties to classify a rock mass in geotechnical domains is well documented by Brzovic et al. (2014) using the density of weak veins measured in oriented cores. Such definition of the geotechnical domains has proved to be of great practical use for different geotechnical problems in the mine design stages.
This paper is based on the laboratory testing published by Bustos (2011) in partial fulfilment of the requirements for the Master's degree in Geotechnical Engineering.

2 VEINLET STENGTH CHARACTERIZATION

The veinlet strength characterization was undertaken from a series of laboratory tests from a wide range of specimens with different veinlet mineralogies. The vein infilling mineralogy was confirmed through microscopic analysis.
Tensile strength is an important parameter for quantifying the vein strength, as it may control the rock mass failure mechanism. The next measure of vein strength is the shear strength, defined in this work by the Mohr-Coulomb failure criterion: $\tau = c + \sigma * \tan(\phi)$, where τ is shear strength, σ is normal pressure, c is cohesion and ϕ angle of internal friction.

Laboratory tests on 150 mm diameter samples were subjected to shear on the plane of the infilling veinlet. By comparing with the results of shear strength computed from the results of triaxial tests on smaller diameter samples with similar veinlets (same mineralogy), these large samples were chosen as a first stage in studying the scale effect on the shear strength of the infilled discontinuities.

3 TENSILE STRENGTH

3.1 Background

Different testing techniques have been developed to evaluate the tensile strength of materials; the positive and negative aspects of each technique are shown in Table 1. The Brazilian test was selected in our research because it was easier to build a testing equipment for the large diameter samples to be tested. According to Barahona (2013) the tensile strength computed from a Brazilian test can be 1,25 to 10 times larger than the value obtained from direct tensile strength.

Table 1: Advantages and disadvantages of each technique to measure a vein in a rock sample.

Technique	Advantages	Disadvantages
Direct tensile test	Pure tensile stress in all the sample. Failure location may be forced by narrowing the sample in a selected zone.	Difficult sample preparation and set up. Time consuming.
Modify direct tensile test. (Ohoka et al. 1997).	Pure tensile stress in a well-defined volume of the sample.	Limited experience. Elaborate sample preparation.
Brazilian test	Highly used for rock testing. Easy to set up the sample to test a veinlet.	Variable stress distribution; there are zones of compression as well as tension.
Flexural tensile strength test	A laboratory equipment can be easily adapted to do this type of test.	Difficult to prepare prismatic samples.

3.2 Brazilian equipment design for 150 mm diameter simples

The design of the apparatus test for 150 mm hard rock samples with veinlets was conducted following the suggested apparatus from the International Society of Rock Mechanics (ISRM, 1978), The size of the two steel loading jaws follows the proportions of the sample as is shown in Figure 1.

The loading capacity of the equipment was determined from the equation recommended by the ISRM (1978) to compute the tensile strength: $\sigma_T = 0.636\ P/[D \cdot t]$ (MPa), where P is the load at failure (N), D is the diameter (mm) and t the thickness of the test specimen (mm), (ISRM, 1978).

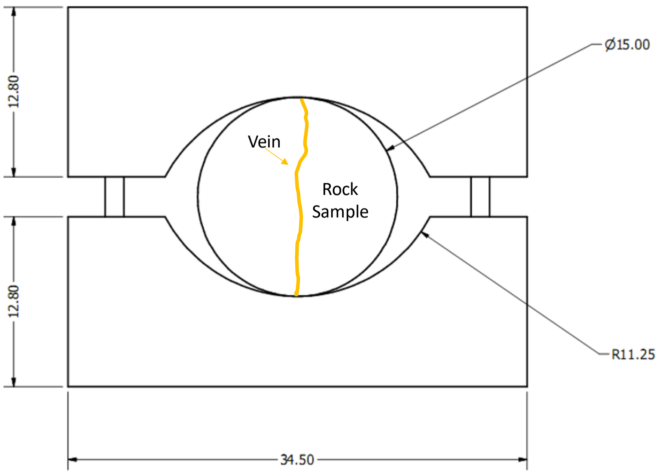


Figure 1: Brazilian equipment designed to test 15cm diameter rock samples with veinlets. All dimensions are in cm.

It was known that the strongest veins tested in NX diameter samples had a tensile strength of 19 MPa. Considering a safety factor of 2.4, the design load was defined as P=1000 kN. The stresses in the loading steel were computed with a 3D finite element model. The Von Misses criteria was used to determine the yield strength requirement of the steel used in the jaws of the equipment. This criteria uses the principal stresses to check the relation $\sigma_y^2 \geq \frac{1}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]$ where σ_y= steel yield tension and σ_1, σ_2 and σ_3 are the principal stresses applied. The maximum stress in the top jaw was 435 MPa. A T1-360 Brinell steel piece was selected, which has a 927 MPa tensile yield capacity.

3.3 Test description

The process followed to conduct this test can be summarized in four steps:

Step 1: specimen preparation, cutting a 75 mm wide rock slice from a 150mm diameter rock sample containing the selected veinlet. Locate the sample with the veinlet as parallel to the applied load as possible (Figure 1).
Step 2: load the specimen to failure at a constant rate of approximately 200 N per second.
Step 3: Describing the failure. The location of the failure surface was described using the proposal of Brzovic and Villaescusa (2007), which defines 4 types of failure:

- V: In the vein infill
- C: At the contact between vein and host rock
- H: In the alteration halo
- IR: Through intact rock, without vein control

The mineralogy of the failure face is also defined at this stage. The results are presented for the mineral visible in more than 50% of the failure plane.

3.4 Results

Overall there were 10 laboratory tests performed, four samples representatives of chalcopyrite present a tensile strength of 4.3 MPa with a standard deviation of 0.5 MPa, which was considered acceptable, their results are shown in Table 2. Two specimens classified as V - TR failure (Table 3), one has a predominant quartz vein and the other has a chalcopyrite vein. Table 4 shows the results of tests with a complex failure, these tests were not considered valid, but they illustrate how complex can become the failure of a rock sample as its diameter increases, let away when we want to evaluate the rock mass strength.
The scale of the sample controls the failure mechanism because the number of singularities can significantly increase in a larger sample and the probability of having only one vein just along the longitudinal axis of the sample is low.

Table 2: Four samples with V failure. Veinlets with high percentage of chalcopirite infill

Sample 13	**Sample 20.4**
Chalcopyrite: 70% Anhydrite: 25% Chlorite:5%	Chalcopyrite: 60% Anhydrite: 20% Chlorite: 10%; Quartz: 5%, Pyrite: 5%
σ_T = 4.7 MPa P= 7.3 MPa	σ_T = 5 MPa P= 7.9 MPa
	
Sample 18.2	**Sample 19**
Chalcopyrite: 80% Anhydrite: 15% Pyrite:5%	Chalcopyrite: 80% Anhydrite: 15% Chlorite: 5%
σ_T = 3.6 MPa P= 5.7 MPa	σ_T = 4 MPa P= 6.3 MPa
	

Table 3: Samples of V and TR mixed failure

Sample 21	**Sample 20**
Quartz: 75% Anhydrite: 10%	Chalcopyrite: 90% Anhydrite: 5% Chlorite: 5%
σ_T = 6.2 MPa P= 9.7 MPa	σ_T 8.3 MPa P= 13 MPa
	

Table 4: Two samples with a complex failure mechanism

Sample 5	Sample 2**0.2**
P=6.1 ton	P=10.6 ton
	
Sample 20.3	**Sample 21.2**
P=13.9 ton	P=5.9 ton

3.5 Comparison with results from the literature

Some results from literature are summarized in Figure 2. The tensile strength tends to decrease as the size of the sample increases. The lowest value (1,5 MPa) comes from a vein filled only with Chalcopyrite. The values were obtained from Padilla (2004) and Willoner (2000).

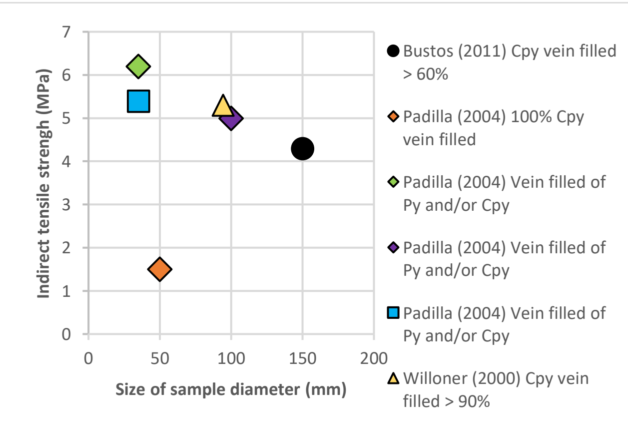


Figure 2. Variation of indirect tensile strength with sample diameter.

4 SHEAR STRENGTH

Usually, two types of laboratory tests are used to evaluate the shear strength of veins. These are the direct shear test and the triaxial compression test. Both types of test were carried out during this research and their positive and negative aspects are discussed next.

4.1 Direct shear test in 143 mm diameter samples

Direct shear tests (ISRM, 1975) were run using two 20x20cm square boxes and placing the veinlet coincident with the middle horizontal plane where shear failure is expected. The line of action of the normal load is fixed in space, it does not advance with the movement of the upper case (see Figure 3).

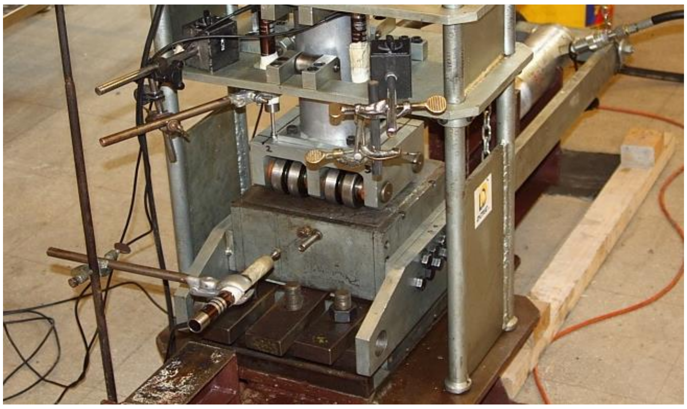


Figure 3. Direct shear tests equipment.

Even when the shear load is applied in the center of the shear zone, the stress in that surface is not uniform and may present border effects. A 2D finite element model was run to study the stress variation in the failure surface and to compare the results with those from a hypothetically modified shear test. Both models are illustrated in Figure 4. The models were constructed in Phase 2 and both have a constant normal load of 0.1MN/m2. The shear load on the left scheme in Figure 4 is applied with a unique lateral load while the right scheme in Figure 4 is loaded with opposite forces that generate the same shear demand on both veinlets. The lateral loads used for this comparison were 0.6 MN/m and 2 MN/m and the 16 mm thick steel box was assigned a modulus of elasticity of 210 GPa. Notice that the average shear stress in the veinlet of the typical test is double that for the modified test.

The models were compared to determine if the distribution of stresses is significantly more constant in the modified version of the test. Figure 5 presents a comparison of the σ_1 distribution in a horizontal line through the vein of the traditional test and through the top vein of the modified test (the bottom vein gives the same results).

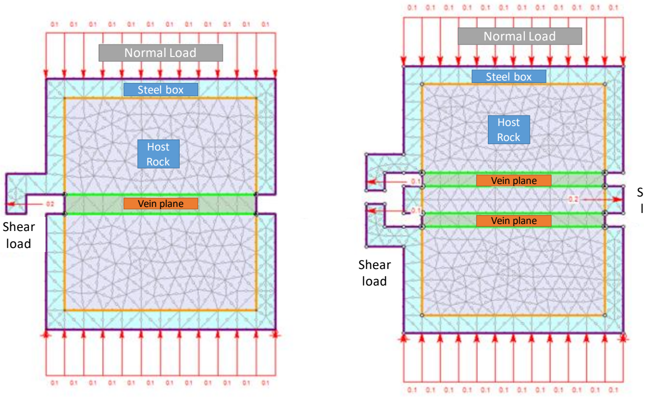


Figure 4: Typical (Left) and modified (right) shear test models

The effect of changing the ratio between the Modulus of Elasticity of the rock and of the vein is illustrated in Figure 5 for an equal ($E_{rock}=E_{vein}$), softer ($E_{rock}=2*E_{vein}$) and stiffer vein ($2*E_{rock}=E_{vein}$) in a 2 MN/m lateral loaded test. The stress distribution is quite irregular in both type of tests and the vein stiffness does not have a relevant impact on the results. Figure 6 compares the stress distribution for a lateral load of 0.6 MN/m and 2MN/m on a sample with a soft vein. It is found that for both tests the variability of the stress distribution increases as the lateral (shearing) load increases. Of course, the probability of finding enough samples with 2 parallel veins is too small for been considered.

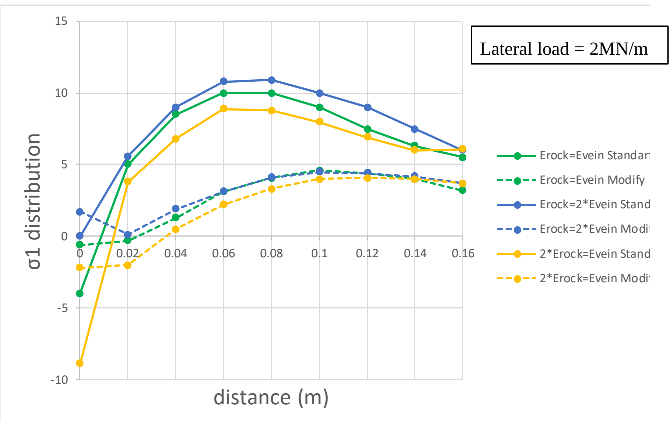


Figure 5: Principal stress distribution through a horizontal line for a standard (continuous line) and modified test (segmented line). Different vein elasticity properties.

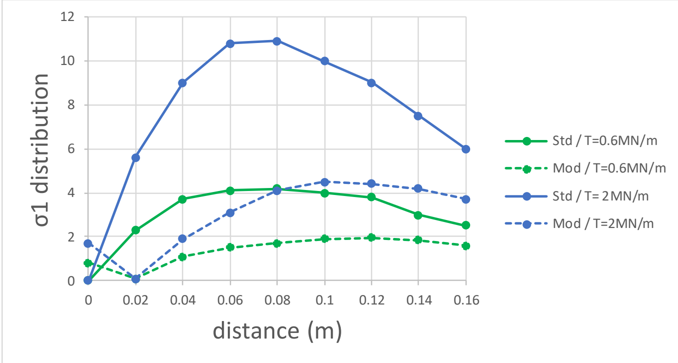


Figure 6: Principal stress distribution through a horizontal line for a standard (continuous line) and modified test (segmented line). Different normal load in a soft vein.

4.1.1 Test description

The process followed to conduct this test can be summarized in four steps:

Step 1: selection of a 150 mm diameter rock sample with an appropriate veinlet specimen.
Step 2: specimen preparation. Since the veinlet is seldom perpendicular to the rock core axis, the core is cut along lines parallel to the veinlet, 8 cm above and below it, to secure a sample which can be firmly cemented in each test box. If the vein orientation is close to the sample axis, a 16cm long specimen was cut to fix in the test box.
Step 3: Additional steps during the preparation of the sample include the following ones:

- The rock specimen is set in a steel box using steel reinforced grout. This process is made twice, firstly on one side of the vein and then the vein is covered with paraffin wax and finally the other side of the specimen is reinforced and grouted too.
- The grout was prepared with a W / C = 0.35 which can reach 40 MPa after 10 days of curing. An 8% of the cement is replaced by micro silica, an addition that accelerates the early strength of the concrete and improves the surface properties. A superplasticizer additive, to improve the workability and an expansion additive to prevent shrinkage of the concrete were also added to the grout
- The cement setting reaction takes about 2 days, after which the steel boxes are disassembled, and the sample submerged in water for 8 days.

Step 4: The test execution starts with an intact specimen which is tested under constant normal load until the maximum shear load is reached. The horizontal displacement is continued for a few centimeters after the peak shear load.

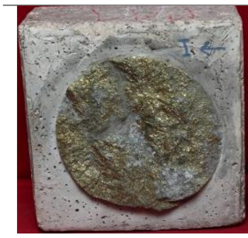
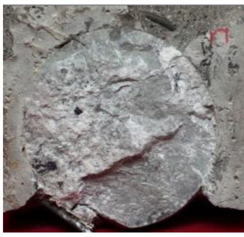
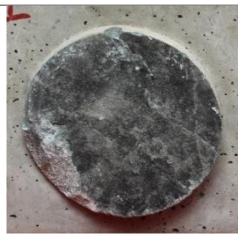
After this test, the fracture surface is cleaned with a smooth brush, the specimen is reassembled in the initial position and the test is repeated but reversing the direction of movement to ensure that dilatation will take place. The horizontal displacement is increased until the rate of reduction of the tangential force is very small, simultaneously it is observed that the vertical displacement (dilatancy) varies very little or at a constant rate. This condition is described as a residual situation. Depending on the hardness of the sample and the level of normal load applied, several repetitions can be made, with different normal loads.

4.1.2 Results

The reliability of results is directly related to the number of samples that contain flat and very similar infilled veinlets. The determination of shear parameters, c and φ, requires performing at least two tests on equal specimens. The probability of finding two equal veinlets is quite low and, to increase the accuracy of the results, it is convenient to cover a relatively wide range of normal pressures over the potential rupture surface.

The limited number of samples required a methodology which was to carry out two tests on each specimen, the first on the intact vein and the second on the sample separated into two halves by the open fracture. In the second test (friction test) the value of the residual friction angle was determined. In the friction test the vertical deformation is measured, which allows to determine the effect of the dilatation (*i*) of the fault plane during the test and applying Patton's correction (Patton, 1966) it is possible to evaluate the residual friction angle, ϕ_r, from the equation $\tau = \sigma_n \tan(\phi_r + i)$. Finally, using the results of the initial test and if the peak friction angle is equal to the residual friction angle, the cohesion can be obtained as $c = \tau_{Test1} - \sigma_{Test1} \tan(\phi_r)$. Since the residual friction is smaller than the peak friction by an unknown value, the procedure can lead to compute cohesion values larger than real ones. To reduce this source of error, the normal stress on the intact sample should be as small as it possible.

Table 5: Result of direct shear strength test

Sample 11	**Sample 12**
Chalcopyrite: 80% Anhydrite: 15%	Chalcopyrite: 55% Anhydrite: 35%
ϕ_r = 16° c= 1.8 MPa	ϕ_r = 25° c= 2 MPa
	
Sample 5	**Sample 6**
Anhydrite: 70% Chalcopyrite: 25%	Anhydrite: 80% Chlorite: 10%
ϕ_r = 41° c= 3.7 MPa	ϕ_r = 43° c= 7.3 MPa
	
Sample 3	**Sample 4**
Tourmaline: 50% Chalcopyrite: 40%	Tourmaline: 70% Chalcopyrite: 20%
ϕ_r = 45° c= 4 MPa	ϕ_r = 45° c= unknown, no intact test.
	
Sample 1	**Sample 7**
Host Rock (Andesite): 50% Chalcopyrite: 30%	Host Rock (Andesite): 80% Chalcopyrite: 10%
ϕ_r = 39° c= 3.9 MPa	ϕ_r = 37° c=4.2 MPa

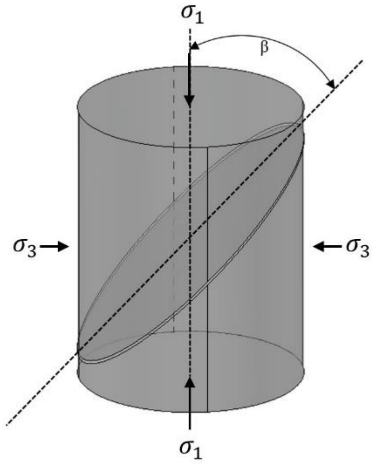


Figure 6: Discontinuity failure in a triaxial test.

4.2 Triaxial test in 55 mm diameter samples

These tests were conducted in a triaxial cell, following the procedures and specifications of the ISRM (1983) on 55 mm diameter specimens, which were re-drilled from 150 mm cores, trying to get the most significant number of samples with veins that could fail. However, the test does not force the specimen to fail in a specific mode. The specimen will always fail through the weakest mechanism, which can be the selected vein, another weaker vein that was not observed, through a group of veins or through the intact rock.

4.2.1 Test description

Only the specimens that failed through a veinlet were considered to calculate the vein's strength parameters. Figure 6 describes a sample with a vein plane where normal (σ_n) and shear (τ) stresses can be calculated with the equations:

$$\sigma_n = \frac{\sigma_1+\sigma_3}{2} - \frac{\sigma_1-\sigma_3}{2} * \cos(2\beta) \quad (1)$$

$$\tau = \frac{\sigma_1-\sigma_3}{2} * \text{sen}\,(2\beta) \quad (2)$$

4.2.2 Results

A trend of failure through very thin anhydrite veinlets was observed even in some cases where another vein was tried to be tested. This was the reason to test the largest number of specimens, regardless of whether they had any visible and favorable oriented vein, since in case there was a weak vein, the test would reflect its presence. This behavior is a reflex how strong can be the influence of vein is on the rock host performance.

The results of measured veins are shown in Figure 7. Although the definition of the plane of rupture was not always easy since in some cases the surface of failure was not exactly flat, a visual estimation of the inclination of the rupture plane was made.

Twenty-three (23) tests were carried out in Andesite host rock, where 18 samples failed through a vein, 13 samples contained an anhydrite vein, generally very planar and thin (0.5-2 mm) whose mineralogy corresponds to a micro-crystallized anhydrite and 5 specimens were chalcopyrite veins. Even in the remaining 5 tests were the failure was through the host rock, a large percentage of disseminated anhydrite was found in the fragments of rupture. This micro-crystallized anhydrite is very easy to clean, a fact to be considered in a mine where the possible reaction of the anhydrite in contact with water could be underestimated.

Twelve Dioritic Porphyry samples were tested (see same Figure 7). One half of the specimens failed markedly by anhydrite veins. Similarly, those which failed through the host rock presented fracture fragments with micro-veinlets of anhydrite as did those samples of Andesite host rock. In the Dioritic Porphyry, no samples were found with visible chalcopyrite veinlets.

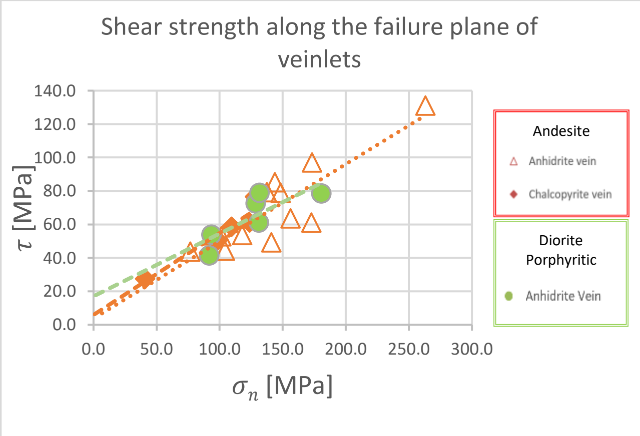


Figure 7: Veinlet strength computed from triaxial tests.

Table 6: Result of shear strength from triaxial tests

Andesite		Dioritic Porphyry
Anhydrite veins ϕ_T = 25° c= 3.7 MPa 	Chalcopyrite veins ϕ_T = 26° c= 5.9 MPa 	Anhydrite veins ϕ_T = 21 to 29° c= 4 to 17 MPa 

4.3 Comparison with results from the literature

Gavia (2005) shows the results of 5 samples of 37 mm diameter anhydrite veins tested in a Mirve test cell. The strength parameters found were 8 MPa for cohesion and 42 ° for friction angle. These results are similar to the samples 5 (ϕr = 41°, c= 3.7 MPa) and 6 (ϕr = 43°, c= 7.3 MPa) shown in the direct shear test section of this document. Santos and Brzovic (2013) present the results of different mineralogies, giving ϕ=43° and c=9.8 MPa for chalcopyrite and ϕ= 58°and c=1 MPa for anhydrite. These results indicate that the strength parameter may be underestimated in this work, however the result shown by Santos & Brzovic (2013) shows a lower coverage of normal stress values which may vary the estimations for this type of test.

5 CONCLUSIONS

- The strength parameters of veinlets classified per mineralogy are given from the results of brazilian (indirect tensile) tests, direct shear tests and triaxial tests.
- A scaling procedure is needed to evaluate the contribution of the veinlets' strength to the rock mass properties.
- The stress distribution along the failure surface in a shear test is quite variable, thus, it seems more reliable and also easier, to measure the shear strength of veinlets through triaxial tests.
- The triaxial test is very convenient as it allows the rupture by the weakest part of each sample, which does not necessarily correspond to the selected oriented vein.
- The shear strength of veins correlates with the type of predominant mineral. Harder minerals (Mohs scale) result in stronger veins. Thus, the Mohs scale can be used as a good indicator of vein strength in practice. The experience at El Teniente Mine confirms this finding: rock mass strength can be well correlated with the density of veinlets and their mineral filling.

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