Servo-Controlled Direct Shear Tests on Phyllites

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ABSTRACT: The results from several sets of direct shear tests performed with both constant normal load and constant normal stiffness on various phyllites are discussed. Tests were performed both parallel and perpendicular to the foliation with different boundary conditions. The results are discussed focusing on the differences in behavior associated with the different boundary conditions and the rock sample quality.

1. INTRODUCTION

Servo controlled direct shear tests using variable feedback channels for test control provide the opportunity to implement different boundary conditions to the sample during testing [1]. This paper describes the results of several sets of tests performed on phyllites for different tunneling projects in Austria. The shear behavior of phyllites under both constant normal load (CNL) and constant normal stiffness (CNS) test conditions have been investigated.

Shear tests are typically performed to evaluate the strength and mechanical properties of preexisting discontinuities such as foliation planes or joints, while compression tests are used for intact samples. For highly anisotropic and weak rocks such as phyllites, the acquisition and preparation of samples for compression tests often results in a highly biased selection of stronger samples due to difficulties in specimen preparation. The preparation effort is much less for direct shear testing, thus allowing the testing of the weaker material, as well as the highly competent material using the same procedures.

To evaluate the anisotropic behavior, a sample can be placed at any orientation within the shear box to evaluate the strength and failure processes associated with a shear direction that is not directly parallel to the preexisting discontinuity structures.

To properly evaluate the strength of a material the appropriate boundary conditions should be used. Low porosity crystalline rocks as well as rough joints tend to dilate during failure as new cracks form. If the normal load is much less then the rock or joint strength-dilation characteristics then the entire system will be lifted, but if the normal stress is significant then the dilation is resisted and local changes to the stress state will occur often resulting in new fractures. For underground excavations where the normal stress will typically be high enough to resist dilation the stiffness of the surrounding rock mass will control the increase in normal stress during shear displacement. In order to better represent the boundary conditions for underground excavations Constant Normal Stiffness (CNS) testing procedures should be used [1,2].

There are currently no guidelines for determining the stiffness to be used for a given CNS investigation program. Many CNS testing apparatuses use springs to simulate the stiffness and are thus rather limited. While state-of-the-art apparatuses using hydraulic servo controlled test systems allow any stiffness to be applied, and even provide the opportunity vary the stiffness with calculated control modes, for example a portion of the stiffness can be controlled by the horizontal displacements. Choosing the appropriate stiffness is important as the measured peak strength is a function of both the initial load and normal stiffness [2]. The normal stiffness should approximate the expected in situ rock mass stiffness. However, one must consider that if there is a soft zone just outside of the excavation this could dramatically reduce the local rock mass stiffness thus effecting the available shear resistance on a critical joint surface. If an infinite stiffness is used (simple shear) then the "Ultimate Shear Strength" of the sample can be determined. This value is not the maximum shear resistance, but the maximum strength that the specimen possesses. Currently research is in progress to determine the relevance of this value and what it really represents.

2. DIRECT SHEAR SYSTEM

2.1. Test Frame and Control

All the tests were performed using a direct shear test system developed in cooperation with MTS System Corporation in 1996. A detailed description of the test system can be found in [1]. The system has a maximum normal force of 500 kN and a maximum shear force of +250/-160 kN. Two horizontal LVDT's and 4 vertical LVDT's are attached directly to the shear box allowing very accurate measurements of the normal and shear displacements as well as the rotations. All normal displacements reported in this text are contraction positive, dilation negative. The system is operated with the MTS TestStar II digital control system.

3. TEST RESULTS

3.1. Sample Description

All of the specimens reported in this paper are phyllites with different compositions that were tested as part of investigation programs for various tunnel projects in Austria. The majority of the samples are quartz phyllite and chlorite phyllite, graphite phyllite. When a specific test or test series is referred to a general description of the sample(s) will be given.

3.2. Graphite Phyllite

Five samples were tested in a series of tests performed on graphite phyllite samples acquired by diamond core drilling as part of the rock mass characterization for a railroad tunnel in the Semmering region of Austria. The samples came from a depth between 57 and 67 m. Typically 20 cm core lengths were used for the direct shear samples. Constant normal load multiple state failure test procedures were used for this characterization. . This results in 3 to 6 failure points per sample per test. Additionally, a pair of tests with CNS test procedures were performed on a hand sample (graphite phyllite) from a nearby pilot tunnel. This sample was acquired from within a major fault zone in the Semmering region.

Figure 1 shows the failure points for these tests. It can be seen that most (8 tests) of the failure points cluster along the lower strength envelope associated with a residual friction envelope even though several of the samples were intact.

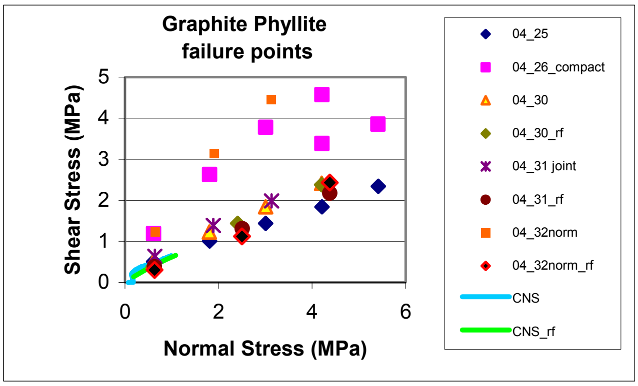

Figure 1. Mohr stress space summary plot of the failure points for the graphite phyllite tests.

The results from two of the tests have a much higher failure envelope. One of these samples (04_32) was sheared normal to the foliation and the other (04_26) was described as a compact sample and possessed a less developed foliation on the sample scale.

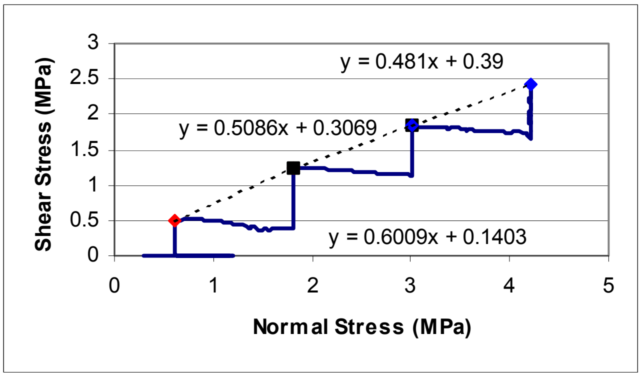

Figure 2. Stress path for a intact sample sheared parallel to the foliation.

Figures 2 and 3 show the stress path and shear stress and normal displacement vs. shear displacement, respectively for a test performed on a intact sample sheared parallel to the foliation (04_30).

As can be seen in Figure 2, for each increase in normal load and the subsequent shear displacement there is a small drop in the friction angle from 31° to 25°. This is a common phenomenon when performing multiple failure state tests on a single sample. What it shows is that depending on the initial normal stress level the initial dilation and cohesion are blended together while sliding friction is mobilized. It is suggested that with preexisting joint surfaces that tilt tests be performed before the direct shear test to quantify what is the initial dilation due to joint roughness and what is due to cohesion or shearing through the asperities. This information is generally not available if different samples are used at each load level (single failure test) and combined to determine the failure envelope.

Figure 3 shows the corresponding stress vs. displacement plot. It can be seen that during the test there was initially neither dilation or contraction but after the first load step a continuous contraction was observed during shear. For the intact sample this is related evolution of the shear plane geometry. In softer samples, such as this test, whether this is related to compaction of the entire sample or to a break down in the preexisting structure during shear is not distinguishable. The consolidation during the increase in normal stress is allowed to finish before the next shear increment.

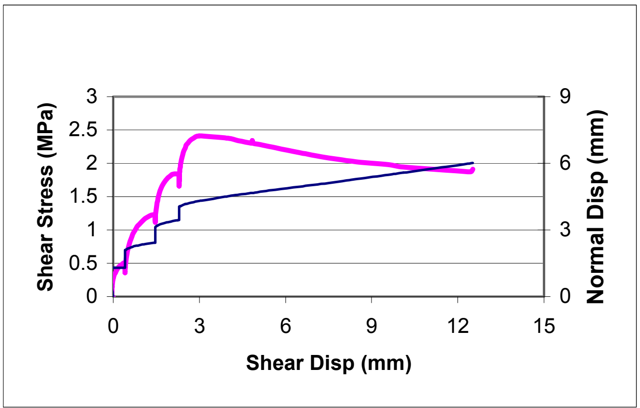

Figure 3. Stress displacement plot for parallel shearing. Thick line is the shear stress and thin line the normal displacement.

Figures 4 and 5 show the results of a test performed on an intact sample that was sheared perpendicular to the foliation (04_32). It can be seen in Figure 5 that there is a dramatic rise in the apparent friction angle from 30° for parallel shearing to 56° for the perpendicular shearing. This sample also dilates significantly during the first two load cycles, but at increasingly smaller rates. During the third load cycle there is initially a dilational stage followed by steady shearing, then the sample begins to contract. This is the point at which a through going shear plane developed in the sample resulting in a rapid drop in the required shear stress during this period. The sample is also much stiffer then the parallel sheared sample as noted by the magnitude of consolidation with the same relative increase in stress. This is expected as most foliated rocks are stiffer when compressed parallel to the foliation.

3.3. Chlorite Phyllite

The next series of tests were conducted on chlorite phyllite samples acquired during the excavation of a tunnel located in a major shear zone in the Semmering region of Austria.

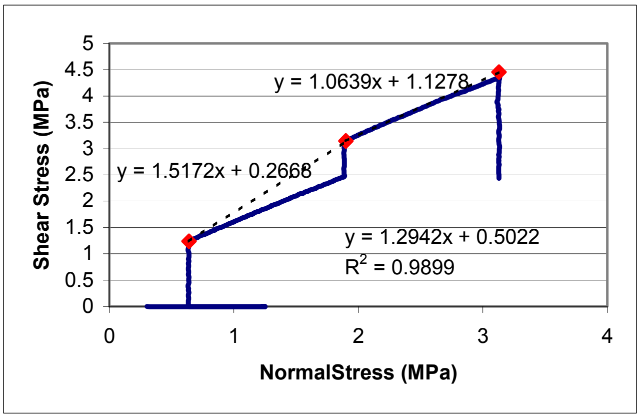

Figure 4. Mohr stress plot for an intact sample sheared perpendicular to the foliation. The friction angle decreases from 56° to 46° while the average value is 52°.

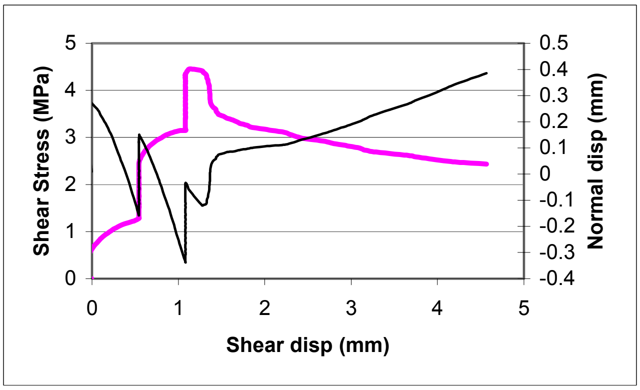

Figure 5. Stress vs. displacement for perpendicular shearing. Note the rapid drop in required shear stress with the localization of shear on a through going shear plane.

The first two tests discussed were from a local shear zone from within the major fault zone, the tunnel experienced absolute vertical deformations in the range of 12 to 18 cm with an overburden of approximately 40 m. Tests were again performed with a CNL multiple failure state procedure.

Figures 6 and 7 show the results from a test performed parallel to the foliation. The behavior of these samples are slightly different then the graphite phyllites. Figure 6 shows the Mohr stress plot for this test. The four failure points defining the failure envelope are almost perfectly linear. As mentioned above this material was extremely weak and tectonically sheared. It has been suggested by Habimana et. al. [3] that with an increase is tectonisation a weak rock will change behavior from a nonlinear failure envelope to a linear one as the internal structure and cohesion are broken down and the sample becomes more like a soil.

Figure 7 shows a similar normal displacement behavior to that of the graphite phyllite sheared parallel to the foliation. Initially there is steady sliding with neither dilation or contraction and with additional normal load and shearing the sample contracts.

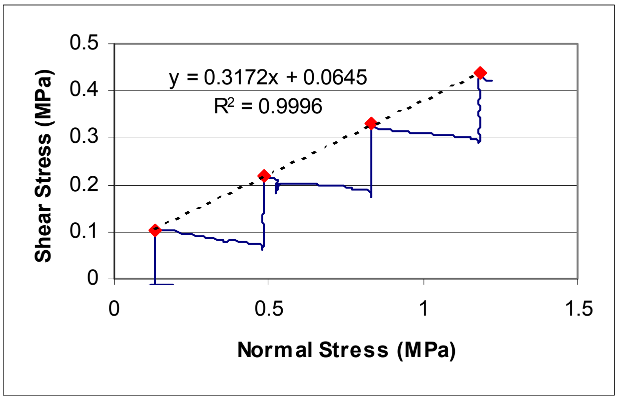

Figure 6. Mohr stress plot for the intact chlorite sample sheared parallel to the foliation. Friction angle is approximately 17.5°.

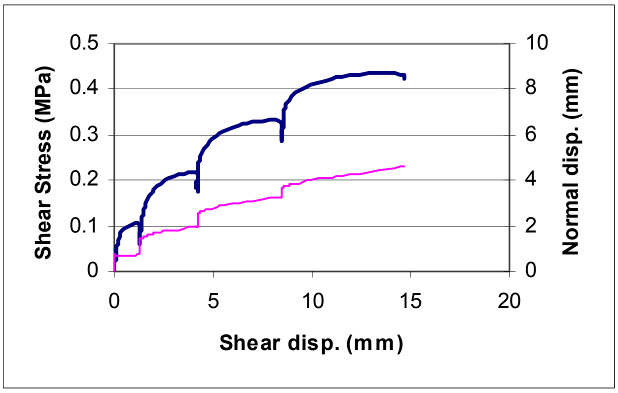

Figure 7. Stress displacement plot for the above test. Thick line is the shear stress while the thin line is the normal displacement.

Figures 8 and 9 show the results of a CNL multiple failure state test performed perpendicular to the samples foliation. This sample behaves extremely different then the graphite phyllite under the same boundary conditions. Figure 9 shows the Mohr stress plot for this test. Again the failure points are practically linear. Only the second point is off the line and the load cycle was probably not extended far enough. Choosing this point during the test is one of the most difficult aspects of multiple failure tests.

If the shear displacement is too large for a given normal load then a different failure envelope is followed as the breakdown of the shear surface progresses. This is shown by the last two failure points for test 04_26 in Figure 1, the friction angle approaches the residual friction angle with increased deformation in any one cycle. If the cycle is ended prematurely then a failure point with a lower shear stress may be recorded then if slightly more deformation had taken place.

Comparing these two samples it seems that with increased tectonisation the inherent strength anisotropy of the system is removed as the internal structure is broken down.

Figure 9 shows the stress displacement characteristics for this test. It can be seen that the contractual behavior of this sample was much greater then the sample with the foliation parallel to the shear direction. This is related to the different mode of shear displacements. Instead of pure sliding on a foliation surface the foliation planes are folded and rotated due to the soft nature of the chlorite and mica mineral particles until a new mineral preferred orientation is obtained.

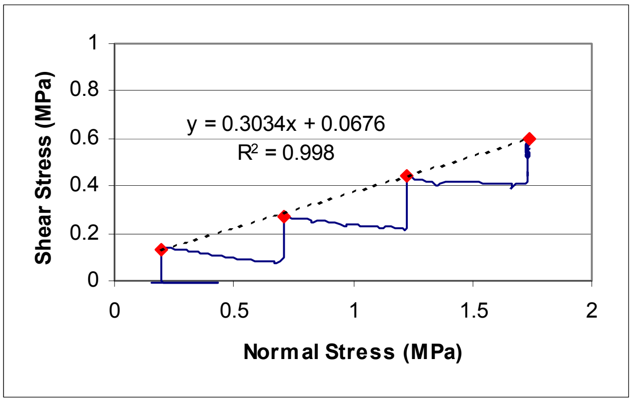

Figure 8. Mohr stress plot for the intact chlorite sample sheared parallel to the foliation. Friction angle is approximately 17°.

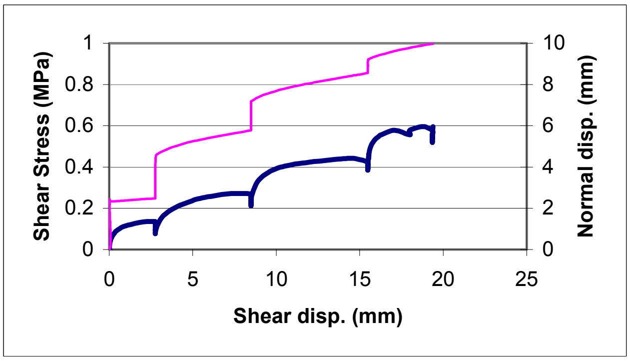

Figure 9. Stress displacement plot for the above test. Thick line is the shear stress while the thin line is the normal displacement. Note the drops in shear stress at higher stress levels related to the breakdown of the internal structure.

The next two tests are again performed on chlorite phyllite hand samples acquired from the same tunnel but in an area with better rock mass conditions. The overburden was approximately 15 to 20m and the displacements were only in the 4 to 7 cm range.

These next two tests were performed under infinite normal stiffness (simple shear). However, due to the weak and contractive nature of the sample sheared parallel to the foliation a second CNL Multiple failure state procedure was also used.

Figures 10 and 11 show the results from the test performed parallel to the foliation. The initial normal load for this test was 5 kN corresponding to a stress of 0.3 MPa (slightly less then the in situ vertical stress). At this load, the sample was contractive in nature and to prevent the loading system from lifting off of the shear box a second control procedure was implemented once the ultimate shear strength was reached.

For comparison the stress paths from both the parallel shear and perpendicular shear tests are shown in Figure 10. The lower loop is the stress path for the CNS test procedure and the stepped sequence the CNL procedure. The initial normal stress dropped continuously with the shear displacement and a peak was reached at a stress level of (0.13,0.12) MPa. The procedures were changed and the normal load was increased to the original level while the shear stress was lowered to zero. Then a CNL multiple shear test was performed as shown. The results from both tests were combined to develop the failure envelope. Which was again almost perfectly linear, even with the change in the boundary conditions.

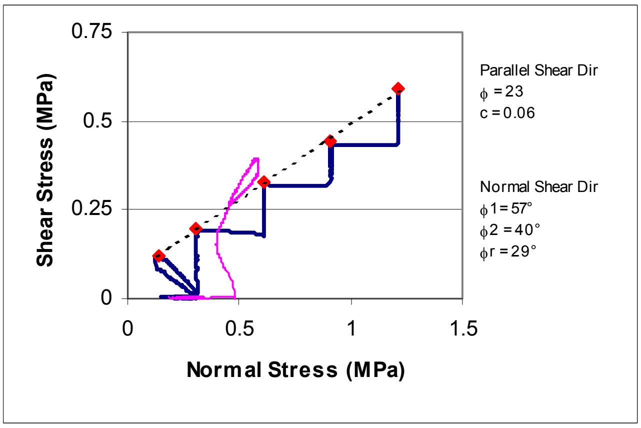

Figure 10. Mohr stress plots for both the CNS and CNL test procedures performed parallel to the foliation (thick line) and the CNS test performed normal to the foliation. Friction angles are displayed on the plot.

By using an infinite normal stiffness, you can test a rocks natural strength in shear. If this value is too low for the given projects boundary conditions, then additional procedures can be used to evaluate the frictional strength at the appropriate stress levels. The CNS procedures are most appropriate for dilating samples, but also can define the failure envelope for contracting samples as long as the initial normal load is sufficiently high. Figure 11 shows the stress displacement plot for the test parallel to the foliation.

Figure 12 shows the stress displacement diagram for the CNS test performed normal to the foliation.

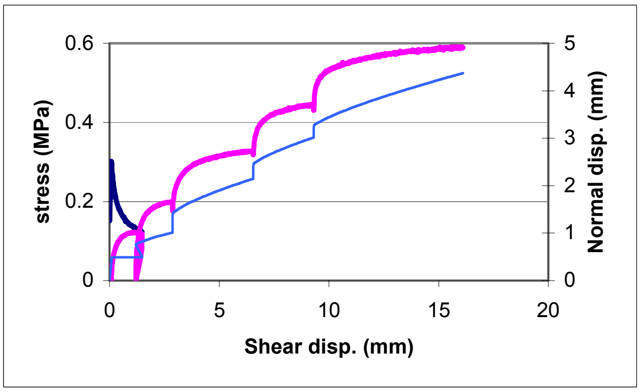

Figure 11. Stress Displacement plot for the parallel sheared sample. The thick lines are the stress lines. The normal stress is only shown for the CNS portion of the line (Drops from 0.3 to 1.5). The dilational characteristics are very similar to the previous test shown in Figure 8.

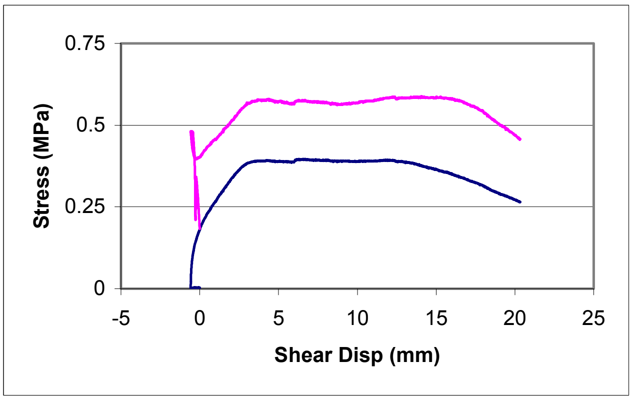

Figure 12. Stress displacement plot for the CNS test with infinite stiffness e.g. zero normal displacement during shear. Once the peak stress is reached the deforms at a constant load before beginning to soften.

It can be seen in this test that once the failure envelope is reached the sample deforms at a constant friction angle. This is represented in the Mohr stress plot as the point at the peak of the loop in Figure 10. This deformation was not concentrated on a single plane but involved a zone in which folding and rearrangement of the internal structure was taking place under constant load conditions. Figure 13 shows a photo of the sample still in the shear box after deformation. The shear direction was dextral (top to the right). The folding of weaker foliation zones around stiffer inclusions can be seen showing that the sample was deforming in a complex mode and not shearing on a plane as would be assumed by the Mohr Coloumb friction law. To determine the friction angles during this test the load line was separated into three quasi linear sections to determine the apparent friction angle. After initial seating during shear the behavior is linear up to a normal stress of 0.475 MPa. This region was characterized by an apparent friction angle of 57°.

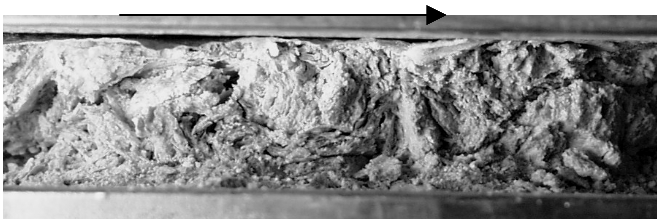

Figure 13. Close up of the shear zone developed during the CNS test perpendicular to the foliation. Sample View is approx. L = 8 cm, H = 1.8 cm. Shear direction was dextral (top to the right). Note the folded mica layers surrounding more competent inclusions indicating a complex deformation band and not simple sliding.

The next section extended from a normal stress of 0.53 to 0.56 MPa and was characterized by a friction angle of 40°. After the peak was reached and the stresses started to drop the line became linear in its approach to zero. This apparent friction angle was determined to be approximately 29°. It can be seen in Figure 14 (a detail of Figure 10) that the convergence of the stress path from the perpendicular test meets with the failure line of the test performed parallel to the foliation. The value of 29° degrees was calculated using a majority of the residual load line and with smaller segments near the end of the test could be less then that indicated as possibly shown with the convergence in Figure 13.

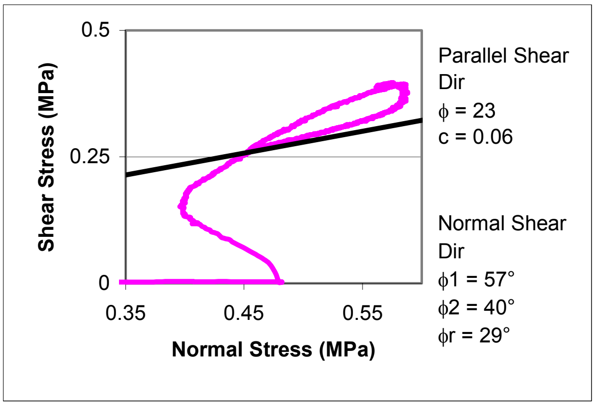

Figure 14. Detail of 10 showing the convergence of the residual line with the failure envelope (strait line) from the test performed parallel to the foliation. The initial contraction of the sample is obvious before dilation begins to occur.

These two samples were taken from the same bulk sample. And therefore should posses the same residual strength envelope. This is shown nicely by the convergence of the two tests Mohr stress plots. The additional load carrying capacity in a direction normal to the foliation is acquired by the different boundary conditions used in this test compared to the results for the CNL tests described earlier. There is still anisotropy measured in the natural strength, but not in the frictional response.

3.4. *Quartz Phyllite*

The last set of tests presented were performed under infinite CNS test conditions. Two of these samples were acquired from diamond drill cores as part of the investigation for a short railroad tunnel in central Austria, the other was a hand sample acquired during the excavation. The one sample contained a higher mica content then the other two, which were predominantly quartz with thin 0.2 to 1 mm thick mica foliations. Figure 15 shows the sample used for the CNS test perpendicular to the foliation. The test was performed shearing the right side down in this photo.

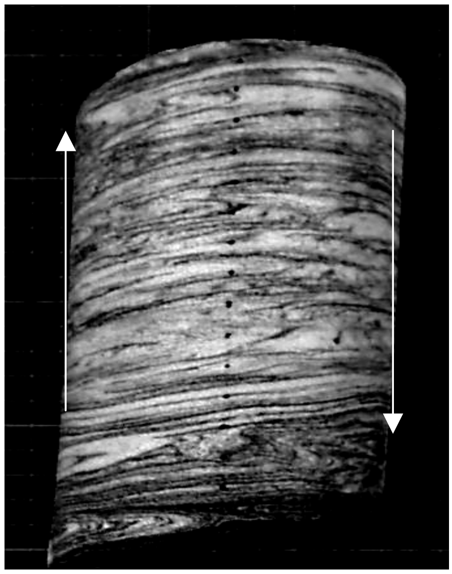

Figure 15. Sample of quartz phyllite (quartz = light, mica layers = dark). Showing the ductile flow structures that dominate these samples. Points are 1 cm intervals. The foliation surfaces are crenulated with consistent properties wavelength 0.5 mm and height approximately 0.05mm.

To compare the more competent materials to the weaker fault rocks shown previously, tests performed both parallel and perpendicular to the foliation will be described. Figure 16 shows the stress paths the two tests performed parallel to the foliation. That there is a quite complex post failure behavior that is not observed during CNL conditions. Figure 17 shows the corresponding stress displacement plot.

The initial failure point occurs at nearly the same stress level even though the samples started at different normal stresses. The hand sample (thin line) was determined to have an apparent friction angle of 53° from the initial slope. This sample then shows a drop in the shear stress after a period of increasing normal stress (dilational behavior) accompanied by a small amount of contractual behavior. This is representative of the shearing of an asperity or delamination of a foliation plane associated with normal cracks forming through the stiffer quartz foliations forming a stepped failure surface in the direction of shear. The normal and shear stress then begin to increase again in short linear segments accompanied by a stress drop (asperity shearing) until the sample begins its residual stress path towards zero. Linear segments were measure and friction angles between 23° and 38° gradually increasing until the residual line is followed.

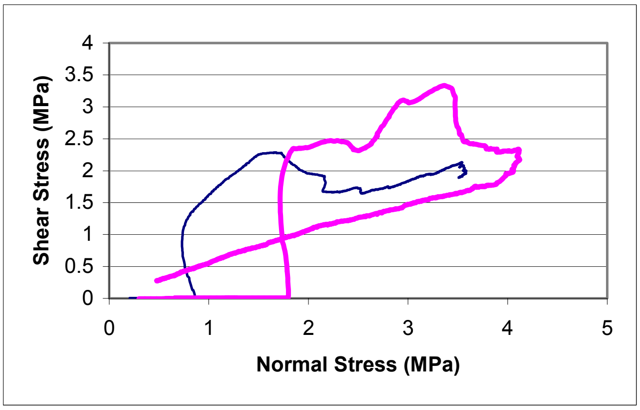

Figure 16. Mohr stress paths for the two tests performed under Infinite CNS parallel to the foliation, the thicker line represents the sample with a higher quartz content.

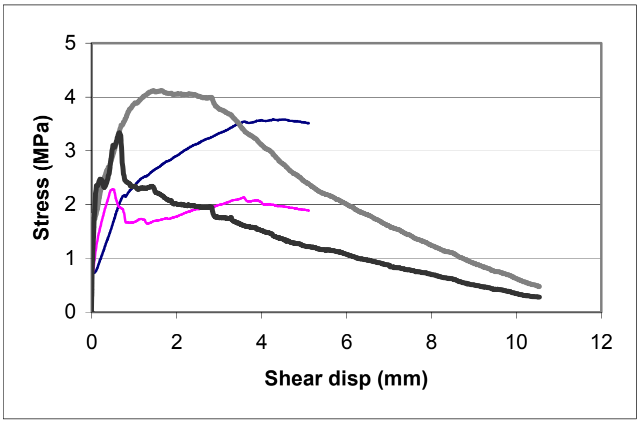

Figure 17. Stress vs. Displacement for the CNS tests parallel to the foliation. Thicker lines represent the stresses for the sample with a high quartz content. The more rounded lines are the normal stresses while the shear stresses show a distinct peak and drop.

After the initial failure the second sample (thick line) shows increased dilation and stronger asperities as both the normal and shear stresses increase. There is a small decrease in the shear stress before a rapid increase in both stress components. This section of the graph is characterized by two slopes which correspond to apparent friction angles of 67° and 43° respectively. The sample then reaches its peak shear stress and begins to shear soften while the normal stress continues to rise due to the dilative nature of the failure plane. Once all of the asperities have sheared though the sample follows a slightly concave upwards path toward zero. This portion of the stress path results in a apparent friction angle of approximately 21°. There is a slight change at a normal load of 2.1 MPa. And the remainder of the stress path results in an apparent residual friction angle of 27.5°. The failure plane in both of these tests was a mica rich layer that had a stepped surface as the quartz layers were fractured in tension and then slid along the lower foliation surface. Often when the samples are removed from the shear box several of these surfaces are delaminated forming thin wafers.

As can be seen with these test results development and degradation of the cohesive and frictional resistance of an intact sample is quite complex. Work is continuing to quantify these relationships in relation to the joint roughness for preexisting joints and to the rock texture at the sample scale. The relationships between the mineral grain shape, size, and preexisting damage combine to form a complex system that forms both the observed joint roughness on preexisting planes and the shear planes in intact rock. Beginning to quantify these relationships would considerably improve our understanding of surface roughness and the shear behavior of rocks.

The last test discussed was performed on the sample shown in Figure 15. This sample was directly next to the sample tested parallel to the foliation. Figure 18 shows the stress path and stress displacement relationships.

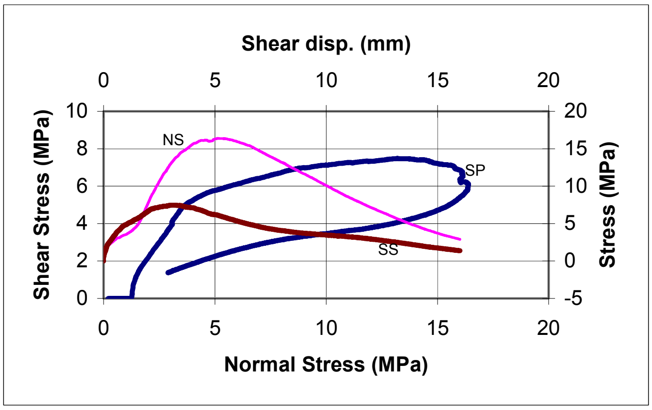

Figure 18. Stress path for the sample sheared perpendicular to the foliation. The stress displacement plots (NS,SS)correspond to the right and upper axis while the stress path (SP) corresponds to the lower and left axis. Note the smooth increase and decrease in the shear and normal stresses.

It can be seen that there is a dramatically different behavior. This type of behavior is quite common with a rapid increase in stress followed by a gradual increase to the peak shear stress. A decrease in shear stress occurs until the maximum normal stress is reached, then the sample follows the residual line towards zero. Initially this sample has an apparent

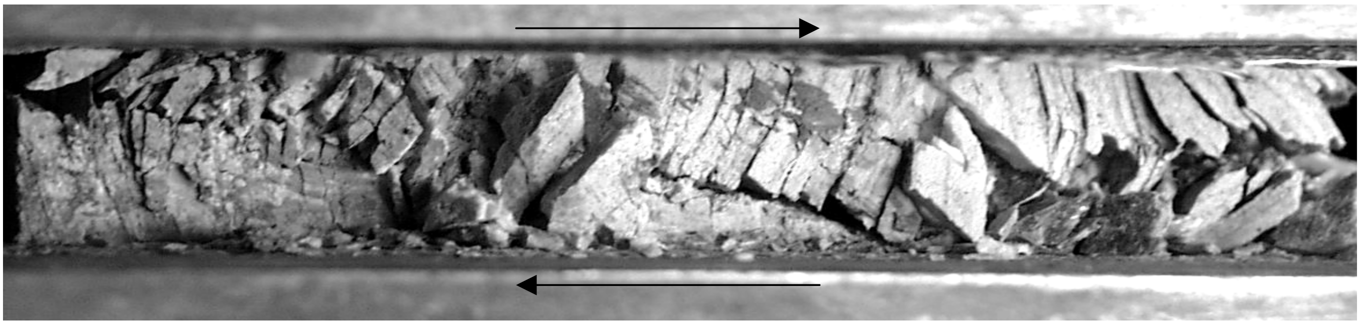

Figure 19. Sample after shearing 2 cm under infinite normal stiffness. Note the through going shear plane from upper left to lower right. Initial foliation was slightly against the shear direction which was dextral. The failure mode was bookshelf type shear. Sample size is approx. L = 13cm, H = 1.9 cm.

friction angle of 60°. The second section is characterized by an apparent friction angle of 17°. This seems quite surprising given that the foliation parallel residual friction was approximately 21° to 27°. Only the end of the residual path is used to calculate the residual friction angle. This results in a value of 22°. This is similar to the lower value measured in the previous tests.

However, this sample did not break along a single plane but involved complex failure kinematics not typically associated with typical rock testing procedures. Therefore, the calculated friction angles are representative of the failure mode and kinematics and may not be directly applicable to a typical constitutive relationship. Figure 19 shows a photo of the sample before it was removed from the shear box. We classify this failure as an antithetic rotation on preexisting weaknesses (foliation planes) that due to the boundary conditions (zero dilation) were forced to bend and dilate parallel to the shear direction [4]. Mandl presents a full description of the complex stress states associated with this failure. This behavior is the brittle semi-ridged counterpart to the soft faulted material shown in Figure 13.

4. CONCLUSION

The results were shown and discussed for several tests performed on various phyllites both perpendicular and parallel to the foliation. When performing a laboratory investigation program the project specific boundary conditions should be simulated as well as possible in the laboratory. The use of computer controlled servo hydraulic testing equipment can greatly increase the flexibility of the tests performed, resulting in a better understanding of the rock behavior.

Several tests were shown with complex failure and deformation mechanisms. The initial strength is influenced by a complex interaction between sliding friction, dilation, and cohesion. The breakdown of these factors to a residual strength is not easily defined. This interaction continues through the entire straining process to different degrees. It has been shown that the use of sophisticated testing procedures can begin to quantify the processes.

One parameter that is extremely difficult to quantify is the shear stiffness. This parameter is highly nonlinear and controlled by the interaction of the above mentioned factors. As this is a typical input parameter in many numerical models the development and degradation of this parameter is currently being more thoroughly investigated.

These tests give light to some of the more complex natural deformations observed in high stress environments. The use of CNL direct shear tests do not really test the rock strength but the resistance to shear at a certain normal load. The use of infinite CNS testing procedures can be used to define a samples "Ultimate Shear Strength" which is the samples natural response to simple shearing. This value is typically much less then the uniaxial compressive strength and seems like a realistic long term value strength value when compared to the excavation behavior during tunneling, but more work needs to be done and other samples investigated order to better understand this strength.

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