CHAPTER FOUR

RESULTS OF THE INVESTIGATION

4.1 Basic friction angle

The basic friction angles of a number of rock types were tested in the laboratory. Testing was carried out on NX size core samples of which the shear surface that was saw cut and polished on sandpaper. Three loading cycles were carried out on each sample. Normal stresses of 40 kPa, 70 kPa and 110 kPa were applied. The results of the testing are presented in table 4.1.

ROCK TYPE	BASIC FRICTION ANGLE (Degrees)	COHESION (kPa)
A. Sedimentary Rocks		
Shale (2A)	31,72	4,14
Sandstone (2B)	27,89	6,7
Mudstone (3C)	32,71	9,93
Shale (4A)	31,9	10,46
Sandstone (4B)	34,9	3,34
Sandstone (5B)	35,95	0
Siltstone (5C)	38,19	8,99
B. Igneous Rocks		
Dolerite (Fine) (3A)	33,33	6,7
Dolerite (Coarse) (3B)	36,32	3,03
Granite (5A)	31,11	6,26
Dolerite (5D)	31,03	0
Riolite (6A)	35,03	11,91
C. Metamorphic Rocks		
Quartzite (1A)	30,42	8,59
Quartzite (1B)	27,85	9,36
Tillite (7A)	32,63	2,74
Quartzite (8A)	28,58	1,96

Table 4. 1 **Basic friction angles and cohesion of various unweathered rocks obtained from flat surfaces of important Southern African rock types**

When the basic shear strength is determined no cohesion is present. During testing of this parameter some cohesion was recorded. This cohesion (apparent cohesion) is relatively small and could be attributed to residual roughness of the saw cut surfaces.
The basic friction angle, determined for all rock types during this project, were in the same range as work done by Coulson (1972). The testing programme gave very encouraging results. These values can be used with confidence further in this report.

4.2 Shear strength of rock types tested

Specimens tested with the large shear apparatus during the first two phases are listed in Table 4.2. This table also contains the results of surface characterization, Schmidt hammer tests and testing performed.

Five rock types were tested. These included three (3) basalt samples, three (3) dolerite samples, seven (7) granite samples, three (3) sandstone samples and three (3) mudstone samples. Some specimens were damaged during the first phase of testing and were not available for the subsequent testing programme.

Specimen	Origin	Surface characteristics	Schmidt Rebound	JRC	First phase	Second phase (dry)	Second phase (wet)
Basalt 1	Lesotho	Rough, hard	54	8-10		Yes	Yes
Basalt 2	Lesotho	Rough, hard	56	8-10	Yes	Yes	Yes
Basalt 3	Lesotho	Rough, hard	52	6-8	Yes	Yes	Yes
Dolerite 1	Qedusizi	Rough, hard	46	4-6	Yes	Yes	Yes
Dolerite 2	Qedusizi	Rough, hard	40	2-4	Yes		
Dolerite 3	Qedusizi	Soft clay 1 mm	51	4-6	Yes	Yes	Yes
Granite 1	Driekoppies	Rough, hard	67	2-4		Yes	Yes
Granite 2	Driekoppies	Rough, hard	58	10-12	Yes		
Granite 3	Driekoppies	Rough, hard	60	8-10		Yes	Yes
Granite 4	Driekoppies	Rough, hard	65	8-10	Yes		
Granite 5	Driekoppies	Rough, hard	61	8-10	Yes	Yes	Yes
Granite 6	Driekoppies	Rough, hard	61	8-10	Yes	Yes	Yes
Granite 7	Driekoppies	Rough, hard	56	6-8	Yes	Yes	Yes
Sandstone 1	Natal	Rough, hard	22	6-8	Yes	Yes	Yes
Sandstone 2	Natal	Rough, hard	28	12-14	Yes		
Sandstone 3	Natal	Rough, hard	26	6-8	Yes		
Mudstone 1	Qedusizi	Rough, hard	28	2-4	Yes	Yes	Yes
Mudstone 2	Qedusizi	Rough, hard	40	2-4	Yes	Yes	Yes
Mudstone 3	Qedusizi	Rough, hard	40	2-4	Yes	Yes	Yes

Table 4. 2 **Specimens tested during the first and second phases of testing**

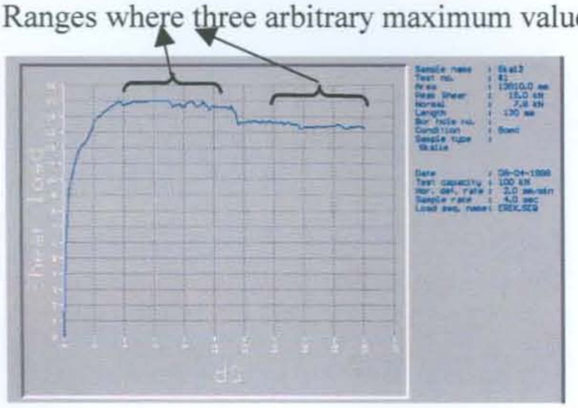
A detailed analysis of the results of the shear tests on large samples was carried out to determine the shear strength of the different rock types as well as the influence of hardness and roughness of the joint surfaces on the shear strength.

Tests were conducted at normal stresses between 0,5 and 1,5 MPa. Normal stresses under a concrete dam are in this order of magnitude. The test method is described in detail in paragraph 3.3.2.1 of this thesis.

Barton and Choubey (1977) have shown that the relationship between shear stress and normal stress for lower stresses (both under 3 MPa) and smooth joints (JRC = 5) are linear. For higher stresses (shear stress up to 6 MPa and normal stress up to 4 MPa) on rough joints (JRC = 20) the relationship is curved. The relationship in all cases originates at 0.

Analysis of the results of tests on each sample involved the selection of three points on the graph of shear load vs. horizontal displacement (see example below) and evaluating the horizontal load (kN) and vertical load (kN) at each of these points. From the graph (Fig 4.2) vertical displacement vs. horizontal displacement, the deviation from horizontal (positive or negative) in degrees was determined to calculate the "corrected" shear load and normal load. The shear and normal stresses were then calculated. The normal stresses for all the samples were then plotted vs. the shear strength (dry and saturated, see Appendix H). Regression plots were then drawn and the coefficient of correlation and slope and X-intercept (c) calculated. (See Appendix F for tables).

Ranges where three arbitrary maximum values measured.



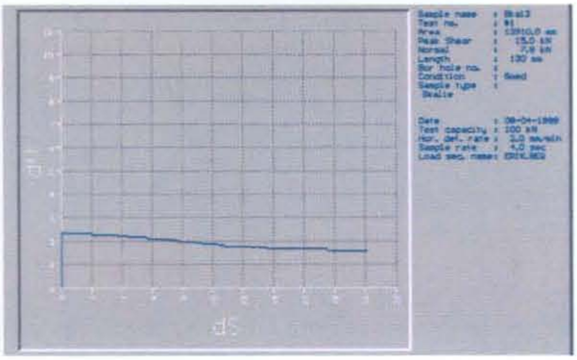


Figure 4.1 Shear load vs. shear displacement showing where readings were taken.

Figure 4.2 Horizontal displacement vs. vertical displacement showing dip angle.

The calculated peak friction angle is the value of the friction angle as calculated with Barton's formula. (See paragraph 2.3.1 of this thesis). The measured maximum p-p friction angle is the friction angle determined by the highest shear load observation points on the shear load vs. displacement graph. The measured minimum p-p friction angle is the friction angle determined by the lowest shear load observation points on the shear load vs. displacement graph. The measured average residual friction angle is the friction angle determined by the average shear load observation points (horizontal part of the graph) on the shear load vs. displacement graph.

4.3 Maximum post peak shear strength - Phase 1

The results obtained during this phase of testing are suspect because the test machine and software controlling the apparatus was faulty. After analysis of the data of phases 1 it was decided to check the large shear apparatus for any possible defects since the results were difficult to interpret. Adjustments were made to the apparatus and amendments to the software controlling the machine were carried out. Adjustments to the apparatus included repositioning of LVDT attachments, while the software was partially rewritten to change the commands regulating the horizontal and vertical forces. During the first phase of testing the shear and normal forces were initiated simultaneously, which meant these forces, increased simultaneously to the set levels. This was changed to allow the normal force to reach its predetermined level before the shear force was initiated. The reliability of the results are in question. It is however discussed as it forms part of the investigation conducted.

4.3.1 Basalt

Two basalt specimens, basalt 2 and basalt 3, were tested during phase 1 of this investigation. The plot of shear stress vs. normal stress for phase 1 is shown in Figure 4.3. Table 4.4 presents a summary of the results obtained for phase1.

Figure 4. 3 **Shear stress vs. normal stress -Phase 1 of shearing for Basalt 2 and 3**

Specimen	Angle of friction (degrees)	Apparent Cohesion (kPa)	Correlation coefficient of observation points on normal- vs. shear stress graph
Basalt 2 - Phase 1 (dry)	32,4	149	0,93
Basalt 3 - Phase 1 (dry)	43,1	461	0,97

Table 4. 3 **Shear strength parameters of basalt as determined during test Phase 1**

Discussion

The maximum post-peak friction angle of basalt 2 is lower than that of basalt 3 due to the rougher joint surface of basalt 3. The value of basalt 2 is low compared to the basic friction angle for basalt has been reported as being between 35° and 38° (Coulson, 1972).

4.3.2 Dolerite

Only one Dolerite specimen was tested during the first phase of shearing. Figure 4.4 illustrates the normal stress vs. shear stress of Dolerite in the first phase of shearing (dry).

Figure 4. 4 **Shear stress vs. normal stress -Phase 1 of shearing (dry) of Dolerite 1**

The test results are listed in Table 4.5.

Specimen	Angle of friction (degrees)	Apparent cohesion (kPa)	Correlation coefficient of observation points on normal - vs. shear stress graph
Dolerite 1 - Phase 1 (dry)	16,4	138	0,86

Table 4. 4 **Friction angle and apparent cohesion for Dolerite 1**

Discussion

The angle of friction of 16,4° is very low for dolerite. This is probably due to the method of testing as described in paragraph 3.3.2.1. These results could not be used with confidence and are presented here only for record purposes.

4.3.3 Granite

Three specimens of Granite were tested through phase 1 of shear testing. These were Granite samples 5, 6 and 7. The shear stress vs. normal stress observations for phase 1 (dry) is plotted in Figure 4.5.

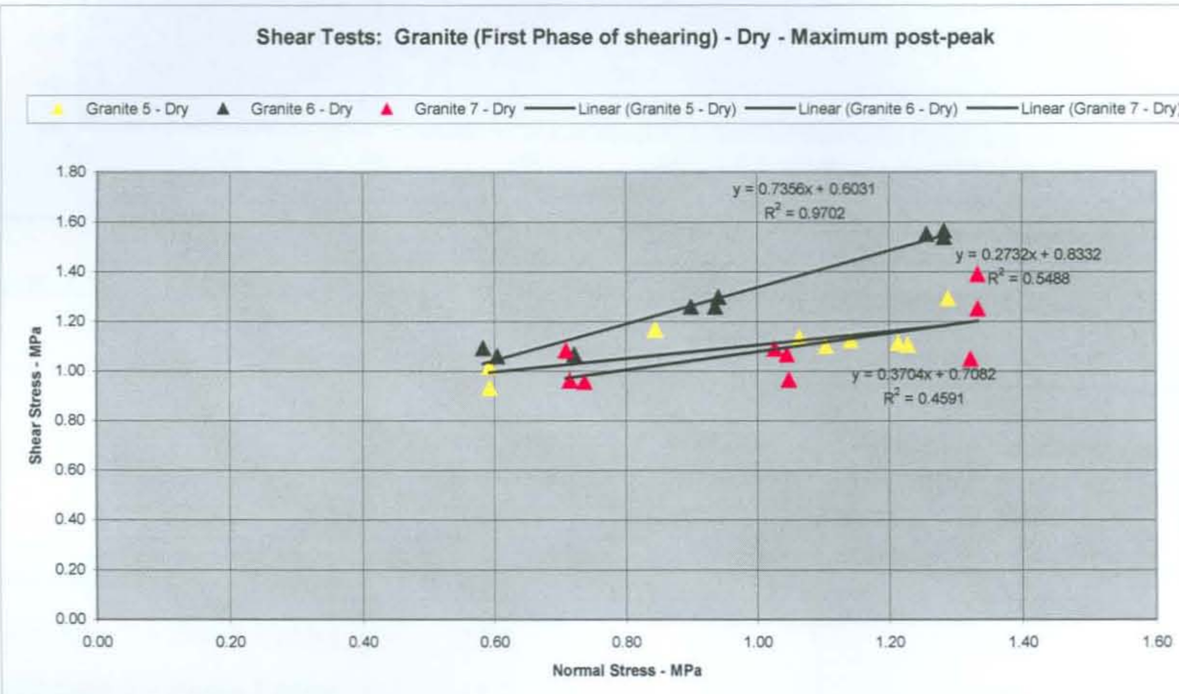


Figure 4. 5 **Shear stress vs. normal stress - Phase 1 of shearing (dry) Granite**

Rock type and test phase	Angle of friction (degrees) Value	Average	Apparent cohesion (kPa)	Correlation coefficient of observation points on normal - vs. shear stress graph
Granite 5 – Phase 1 (dry)	15,3		603	0,55
Granite 6 – Phase 1 (dry)	20,2	23,9	833	0,97
Granite 7 – Phase 1 (dry)	36,3		708	0,46

Table 4. 5 **Shear strength parameters of Granite as determined during Phase 1**

Discussion

The granite specimens were moderately hard with rough surfaces. The friction angles for granite samples 5, 6 and 7 are very low, 15,3°, 20,2° and 36,9° respectively. The basic friction angle for granite is 31° to 35° as reported by Coulson (1972, in Barton and Choubey, 1977).

4.3.4 Sandstone

Three specimens of Sandstone were tested. The shear stress vs. normal stress observations for phase 1 (dry) is plotted in Figure 4.6.

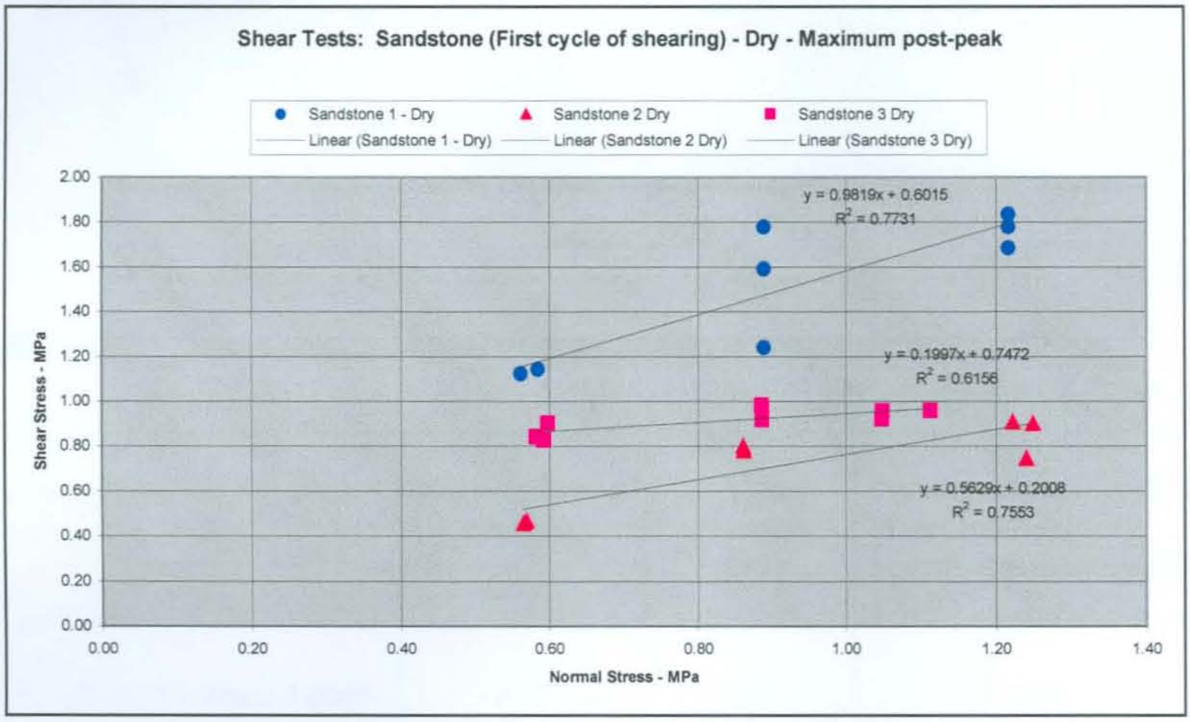


Figure 4. 6 **Shear stress vs. normal stress - Phase 1 of shearing (dry) Sandstone**

Rock type and test phase	Angle of friction (degrees)	Apparent cohesion (kPa)	Correlation coefficient of observation points on normal - vs. shear stress graph
Sandstone 1 – Phase 1 (dry)	44,5	602	0,77
Sandstone 2 – Phase 1 (dry)	29,4	747	0,62
Sandstone 3 – Phase 1 (dry)	11,3	201	0,76

Table 4. 6 **Shear strength parameters of sandstone as determined during Phase 1**

Discussion

These mudstone specimens were tested through Phase 1. Tests on Sandstone 1 gave a very high value for the maximum post-peak friction angle and for Sandstone 2 and 3 very low values.

The basic friction angle for sandstone is 26° - 35° as reported by Coulson (in Barton and Choubey, 1977).

4.3.5 Mudstone

Three specimens of Mudstone (please note: Mudstone is referred to as Shale on the plates in the appendices) were tested, through phase 1. The shear stresses vs. normal stress observations for the first phase (dry) are plotted in Figure 4.7.

Table 4.7 presents the shear strength parameters as determined during this study.

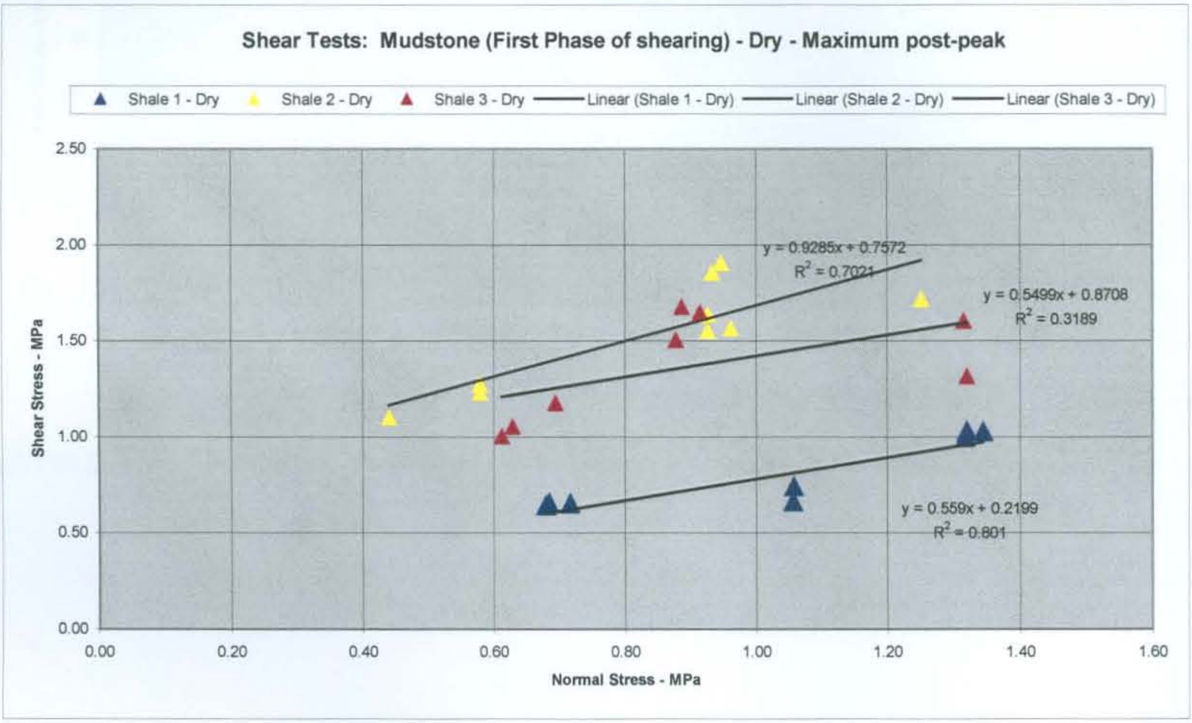


Figure 4. 7 **Shear stress vs. normal stress-phase 1 of shearing (dry) Mudstone**

Rock type and test phase	Angle of friction (degrees)	Apparent cohesion (kPa)	Correlation coefficient of observation points on normal - vs. shear stress graph
Mudstone 1 – Phase 1 (dry)	29,2	220	0,80
Mudstone 2 – Phase 1 (dry)	28,8	871	0,32
Mudstone 3 – Phase 1 (dry)	42,9	757	0,70

Table 4. 7 **Shear strength parameters of mudstone as determined during Phase 1.**

Discussion

Three mudstone specimens were tested. The maximum post-peak friction angle of mudstone 1 and 2 were determined as 29,2° and 28,8° respectively. The peak friction angle of mudstone 3 was determined as 42,9°. The basic friction angle for Mudstone is between 31° and 33° as reported by Coulson, (1972).

4.4 Minimum post-peak shear strength - Phase 2

4.4.1 Basalt

Three basalt specimens were tested, two of which through phases 1, 2A and 2B. The graphs of shear stress vs. normal stress for phase's 2A and 2B are shown in Figure 4.8. The shear strength parameters are listed in Table 4.8.

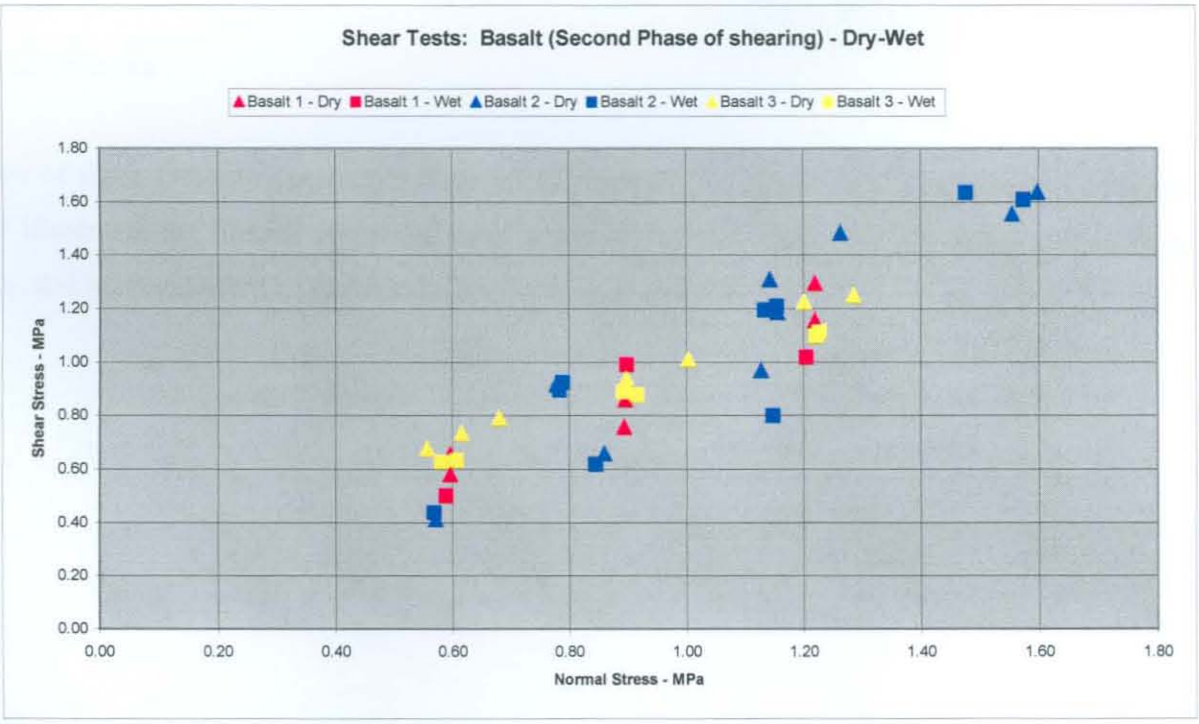


Figure 4. 8 **Shear stress vs. normal stress-Phases 2A and 2B of shearing Basalt 1, 2 and 3**

Specimen	Angle of friction (degrees) Value	Average	Apparent Cohesion (kPa)	Correlation coefficient of observation points on normal - vs. shear stress graph
Basalt 1 - Phase 2A (dry)	44		0	0,93
Basalt 2 - Phase 2A (dry)	49	44	166	0,88
Basalt 3 - Phase 2A (dry)	38		240	0,99
Basalt 1 - Phase 2B (wet)	40		82	0,80
Basalt 2 - Phase 2B (wet)	48	42	137	0,82
Basalt 3 - Phase 2B (wet)	37		190	1,00

Table 4. 8 **Shear strength parameters of Basalt as determined during test Phases 2A and 2B**

Discussion

The average post-peak dry friction angle of 44° seems to be in the order of what can be expected, as the basic friction angle for basalt has been reported as being between 35° and 38° (Coulson, 1972). The average submerged residual friction angle was determined as 42°. This is expected as basalt is a hard rock (UCS or JCS = 200 MPa and Schmidt hardness = 53 - 57) with rough joint surface. The JRC was determined as 9. the reduction of 44° to 42° can also be due to the large cumulative distance of shear.

4.4.2 Dolerite

Two of three Dolerite specimens were tested through the second phase of shearing. Figure 4.9 illustrates the normal stress vs. shear stress of Dolerite in the second phase of shearing (dry and submerged). The test results are listed in Table 4.9.

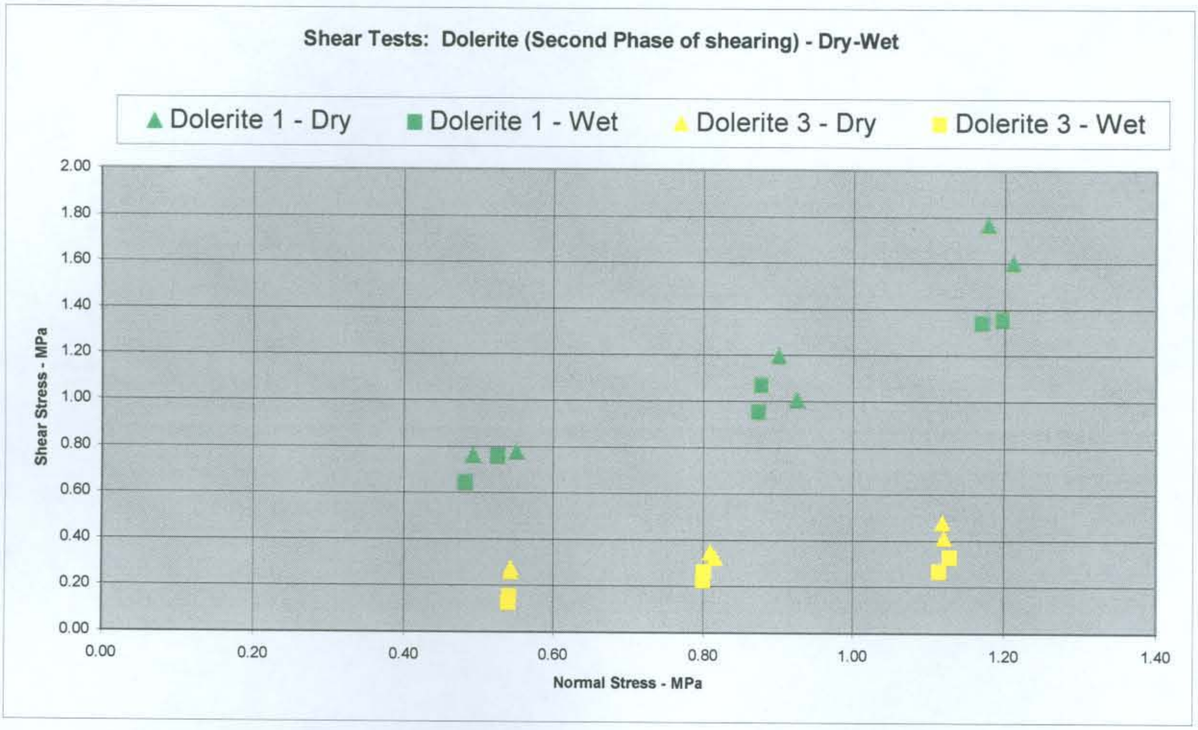


Figure 4. 9 **Shear stress vs. normal stress -Phases 2A and 2B of shearing (dry and submerged) of Dolerite 1 & 3**

Specimen	Angle of friction (degrees)	Apparent cohesion (kPa)	Correlation coefficient of observation points on normal - vs. shear stress graph
Dolerite 1 - Second phase (dry)	52,6	39	0,89
Dolerite 3* - Second phase (dry)	17,0	95	0,82
Dolerite 1 – Second phase (wet)	43,6	205	0,97
Dolerite 3* - Second phase (wet)	14,9	8,5	0,86

Dolerite 3* with 1mm clay layer on joint

Table 4. 9 **Friction angles and apparent cohesion for Dolerite**

Discussion

Two of the three dolerite specimens were tested. There was a distinctive difference between the shear surfaces of the two specimens. Dolerite 1 was a hard, rough surface whilst Dolerite 3 had approximately one millimetre of clay on its surface. Shear strength of the two surfaces can thus not be compared nor correlated.

The minimum p-p angle of friction for Dolerite 1 was determined as 52,6° during phase 2A. This value seems to be high, as the basic friction angle for dolerite is 36°. The maximum post-peak friction angle of Dolerite 1 was determined as 43,6° submerged (test phase 2B). This value seems to be on the high side, however it must be kept in mind that dolerite is a hard rock (UCS = 250 MPa, and Schmidt rebound number: 46). Another factor explaining the medium high friction angle is the roughness of the joint surface. The JRC is between 10 and 12

The minimum p-p friction angle of Dolerite 3 (on the clay filled joint) was determined as 17° dry and 14,9° submerged. These values are low due to the fact that the joint fill is soft clay about 1mm thick. Another factor explaining the low friction angle is the smoothness of the joint surface. The JRC is 4 - 6.

4.4.3 Granite

Seven specimens of Granite were tested, four through phases 1, 2A and 2B of testing. Table 4.10 shows the shear strength parameters obtained. Three other specimens were tested in detail during phase 3 of this project.

The shear stress vs. normal stress observations for phase 2A and 2B (dry and saturated) are plotted in Figure 4.10.

Figure 4. 10 Shear stress vs. normal stress -Phases 2A and 2B of shearing (dry and submerged) Granite

Rock type and test phase	Angle of friction (degrees) Value	Angle of friction (degrees) Average	Apparent cohesion (kPa)	Correlation coefficient of observation points on normal - vs. shear stress graph
Granite 1 – Phase 2A (dry)	35,8	34,6	261	0,81
Granite 5 – Phase 2A (dry)	40,0		231	0,98
Granite 6 – Phase 2A (dry)	27,1		56	0,62
Granite 7 – Phase 2A (dry)	35,3		440	0,97
Granite 1 – Phase 2B (wet)	28,8	29,9	343	0,59
Granite 5 – Phase 2B (wet)	37,5		279	0,99
Granite 6 – Phase 2B (wet)	24,9		230	0,84
Granite 7 – Phase 2B (wet)	28,2		394	0,85

Table 4. 10 Shear strength parameters of Granite as determined during Phases 2A and 2B

.Discussion

Four of the seven granite specimens were tested during the Phases 2A and 2B of testing. The granite specimens were moderately hard with rough surfaces. The basic friction angle for granite, 31° to 35° as reported by Coulson, (in Barton and Choubey, 1977) is in the same order of magnitude as the results obtained during this project. The minimum p-p friction angle of granite was determined as 34,6° dry and 29,9° submerged. These values seem to be as what could be expected as it must be kept in mind that granite is a moderately hard rock (UCS or JCS = 150 MPa and Schmidt rebound number 56 to 65). Another factor explaining the moderately high friction angle is the roughness of the joint surface. The JRC is 8 - 10. The reduction in shear strength from 34,6° to 29,9° is probably due to a combination of saturation and smoothing of the shear surface as a result of shear distance.

4.4.4 Sandstone

Three specimens of Sandstone were tested of which only one was tested through phases 1, 2A and 2B. The shear stress vs. normal stress observations for phase 2A and 2B (dry and submerged) are plotted in Figure 4.11. Results are listed in table 4.11.

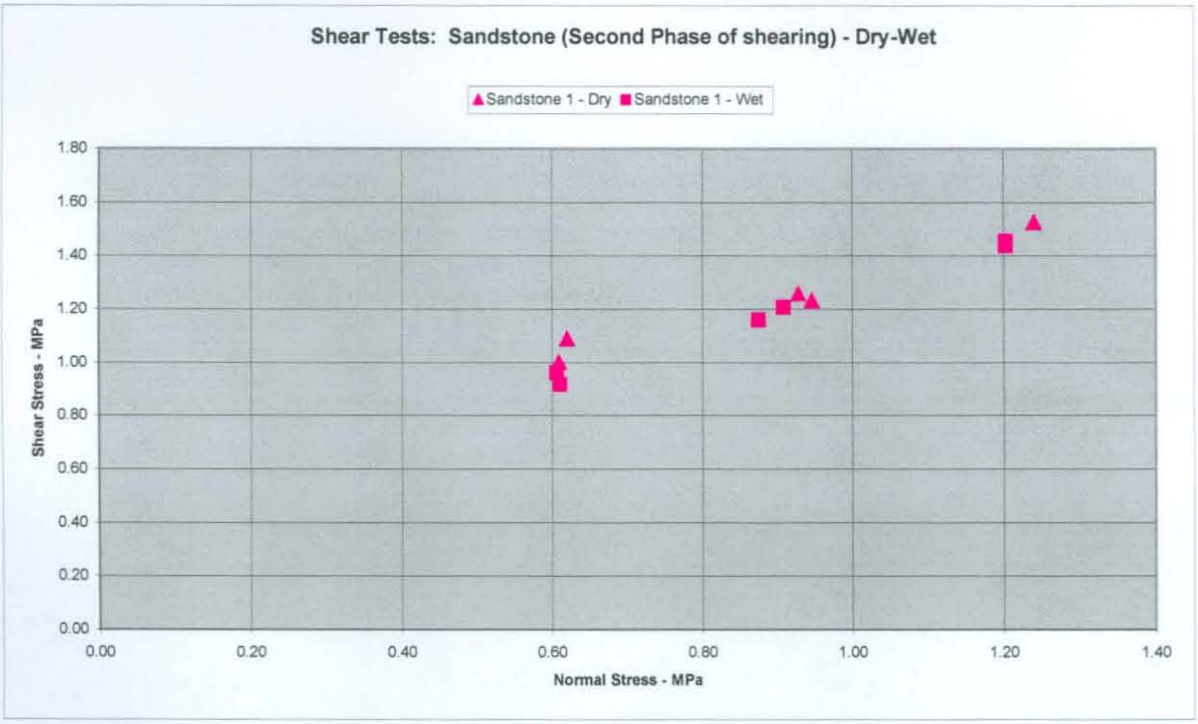


Figure 4. 11 **Shear stress vs. normal stress -Phases 2A and 2B of shearing (dry and submerged) Sandstone**

Rock type and test phase	Angle of friction (degrees) Value	Average	Apparent cohesion (kPa)	Correlation Coefficient
Sandstone 1 – Phase 2A (dry)	37,6	-	558	0,97
Sandstone 1 – Phase 2B (wet)	40,5	-	422	0,99

Table 4. 11 **Shear strength parameters of Sandstone as determined during Phase 2**

Discussion

One sandstone specimen was tested through Phases 1, 2A and 2B. Sandstone 1 had a hard rough surface. The basic friction angle for sandstone is 26° - 35° as reported by Coulson, (in Barton and Choubey, 1977). The minimum p-p friction angle of sandstone 1 was determined as 37,6° dry and 40,5° saturated. These values seem to be moderately high, however it must be kept in mind that sandstone is a hard rock (UCS or JCS = 180 MPa and Schmidt rebound number is 22 - 26). Another factor explaining the high friction angle is the roughness of the joint surface. The JRC is between 10 and 12. The higher value during B2 cannot be explained.

4.4.5 Mudstone

Three specimens of Mudstone were tested, all three specimens through phases 1, 2A and 2B. Table 4.12 presents the shear strength parameters as determined during this study.

The shear stress vs. normal stress observations for the second phases (dry and submerged) are plotted in Figure 4.12.

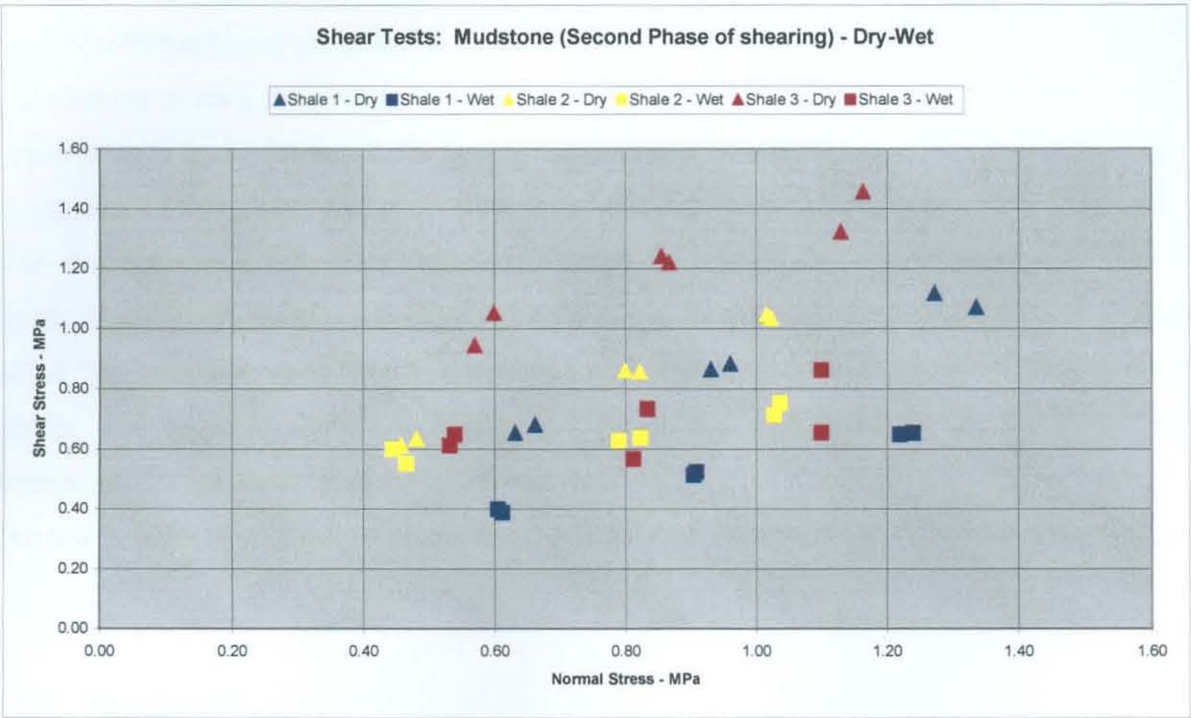


Figure 4. 12 **Shear stress vs. normal stress -Phases 2A and 2B of shearing (dry and submerged) Mudstone**

Rock type and test phase	Angle of friction (degrees) Value	Average	Apparent cohesion (kPa)	Correlation Coefficient of observation points on normal - vs. shear stress graph
Mudstone 1 – Phase 2A (dry)	32,8		257	0,98
Mudstone 2 – Phase 2A (dry)	37,0	34,9	252	0,99
Mudstone 3 – Phase 2A (dry)	35,2		598	0,93
Mudstone 1 – Phase 2B (wet)	22,6		141	1,00
Mudstone 2 – Phase 2B (wet)	14,6	16,8	446	0,85
Mudstone 3 – Phase 2B (wet)	13,2		487	0,32

Table 4. 12 **Shear strength parameters of Mudstone**

Discussion

Three mudstone specimens were tested. The basic friction angle for Mudstone is between 31° and 33° as reported by Coulson, (1972). The minimum post-peak friction angle of mudstone was determined as 34,9° dry and 16,8° submerged. These values seem to be slightly on the high side (not true residual) during dry testing and very low during saturated conditions, however it must be kept in mind that Mudstone is a soft rock (UCS or JCS = 120 MPa and Schmidt rebound number between 28 and 40). The JRC is between 2 and 4.

4.5 Shear strength of joints in Granite - Phase 3

During the interpretation of the test results of Phase 2 it became clear that there were large variations between the calculated (peak) friction angles (see table 4.20) and the tested maximum minimum p-p friction angles. The reasons for this were unclear. It could be that although the cumulative shear distance was in the order 80 mm after the first test and as much as 180 mm after the sixth test, the residual shear strength had not been reached for some samples with hard joint surfaces.

A further set of rock samples were selected and tested with great care and put through a cycle of four tests to try to determine the shear strength more accurately.

The results of this phase (Phase 3) were tested and evaluated. Correction for the shear angle with the horizontal (as described in paragraph 4.2) from the shear load vs. horizontal displacement graph were made (Appendix J). A maximum, minimum and a general average called "intermediate value" were determined and plotted on a shear stress vs. normal stress graphs. The angle of friction, cohesion and correlation coefficient for the trend line was determined for the forward, reverse and wet tests.

The test results of the third phase are discussed for each sample in the following paragraphs.

4.5.1 Granite 1C

Figure 4.13 is a graph of the shear stress vs. normal stress. The diamonds present the forward test result, the triangles the reverse and the circles the saturated test results. In each case a maximum (blue), minimum (red) and intermediate (yellow) value is presented. The results for Granite 1C are summarised in Table 4.13.

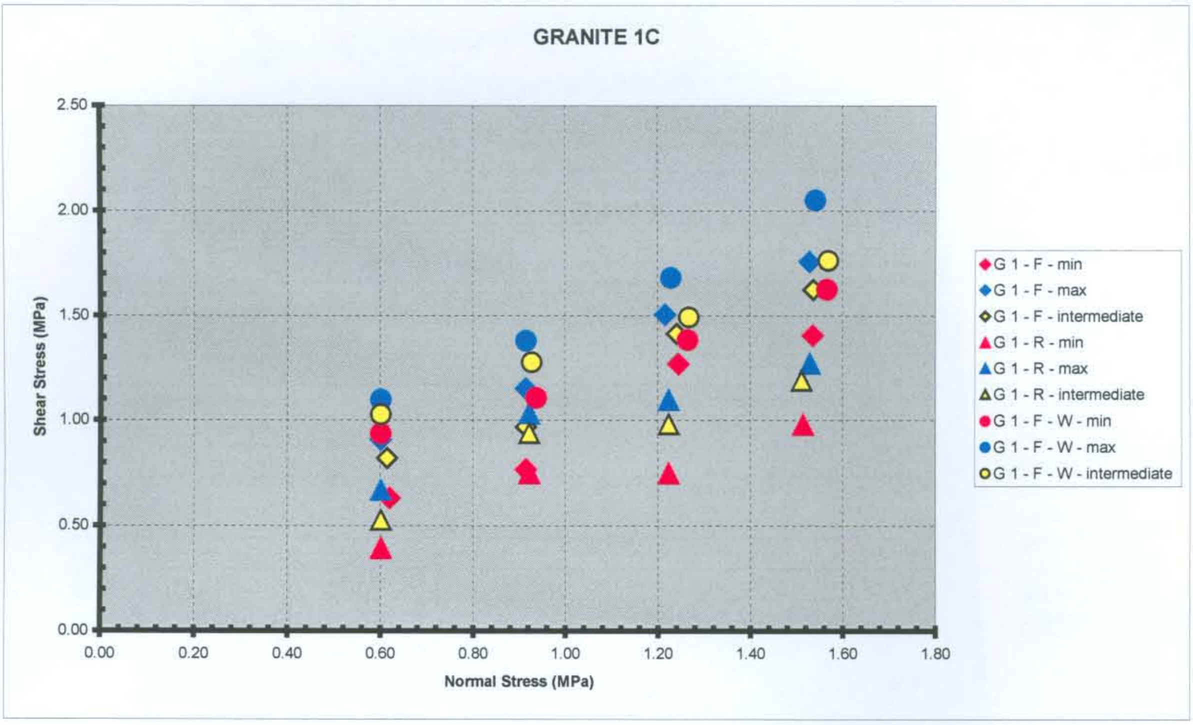


Figure 4. 13 **Shear stress vs. normal stress for Granite 1C**

Shear direction and size	Apparent cohesion KPa	Friction angle Degrees	Correlation coefficient of observation points on normal - vs. shear stress graph
Forward – minimum	228	42,7	0,95
Forward – maximum	333	43,1	0,99
Forward – intermediate	215	42,7	0,97
Reverse – minimum	99	30,3	0,89
Reverse – maximum	369	31,3	0,92
Reverse – intermediate	192	34,0	0,90
Forward (Wet) – minimum	476	35,8	0,99
Forward (Wet) – maximum	471	45,2	1,00
Forward (Wet) – intermediate	575	36,7	1,00

Table 4. 13 **Results of shear testing on Granite 1C**

Discussion

The test in a forward direction yielded an angle of friction of between 42,7 and 43,1 degrees. The value for reverse is approximately 10 degrees lower, between 30,3 and 34 degrees. The value for the saturated sample's minimum and intermediate is between 35,8 and 36,7 degrees. The maximum value of 45,2° is unexpected and no reasonable explanation could be found. The higher values for the forward test can also not be explained.

4.5.2 Granite 2C

Figure 4.14 is a graph of the shear stress vs. normal stress. The diamonds present the forward test result, the triangles the reverse and the circles the saturated test results. In each case a maximum (blue), minimum (red) and intermediate (yellow) value is presented.

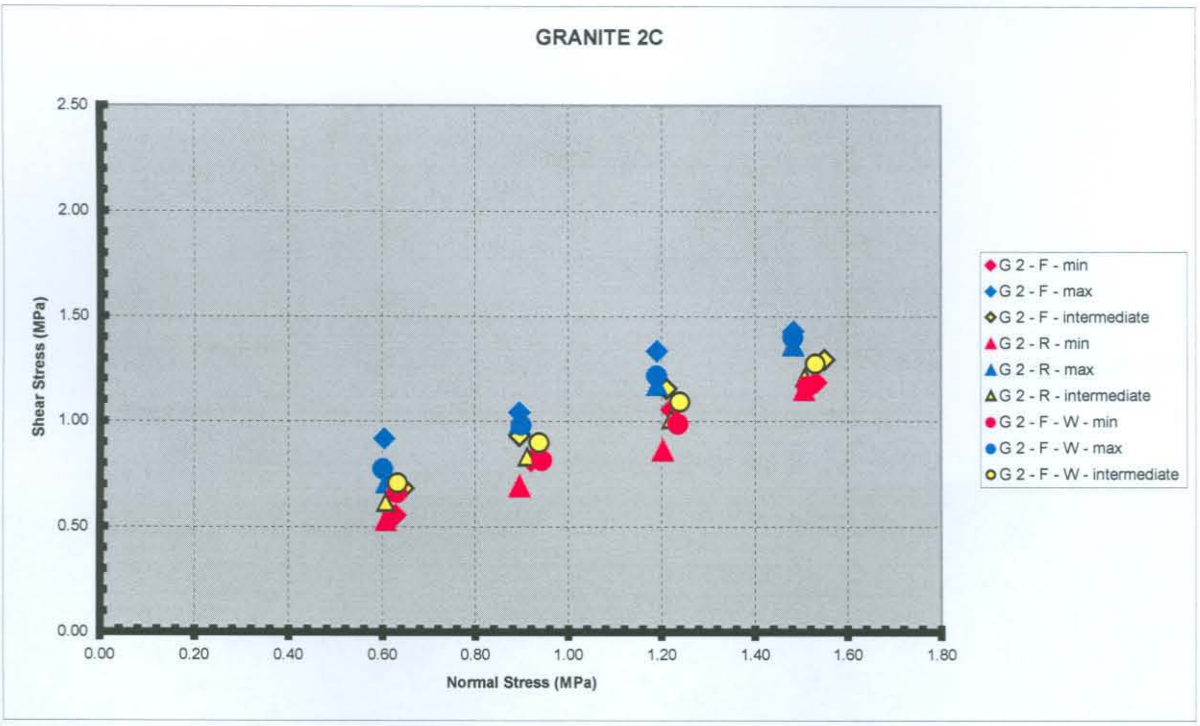


Figure 4. 14 **Shear stress vs. normal stress for Granite 2C**

.

The results for Granite 2C are summarised in Table 4.14.

Shear direction and size	Apparent cohesion kPa	Friction angle Degrees	Correlation coefficient of observation points on normal - vs. shear stress graph
Forward – minimum	145	31,8	0,98
Forward – maximum	536	35,2	0,96
Forward – intermediate	290	34,0	0,97
Reverse – minimum	101	34,0	0,98
Reverse – maximum	297	36,3	0,99
Reverse – intermediate	222	33,2	1,00
Forward (Wet) – minimum	294	29,8	1,00
Forward (Wet) – maximum	350	35,7	1,00
Forward (Wet) – intermediate	309	32,4	1,00

Table 4. 14 **Results of shear testing on Granite 2C**

Discussion

The test in a forward direction yielded an angle of friction of between 31,8 and 34,0 degrees. The value for reverse is approximately the same, between 33,3 and 36,3 degrees. The value for the saturated sample's minimum and intermediate is between 29,8 and 35,7 degrees.

4.5.3 Granite 3C

Figure 4.15 is a graph of the shear stress vs. normal stress. The diamonds present the forward test result, the triangles the reverse and the circles the saturated test results. In each case a maximum (blue), minimum (red) and intermediate (yellow) value is presented.

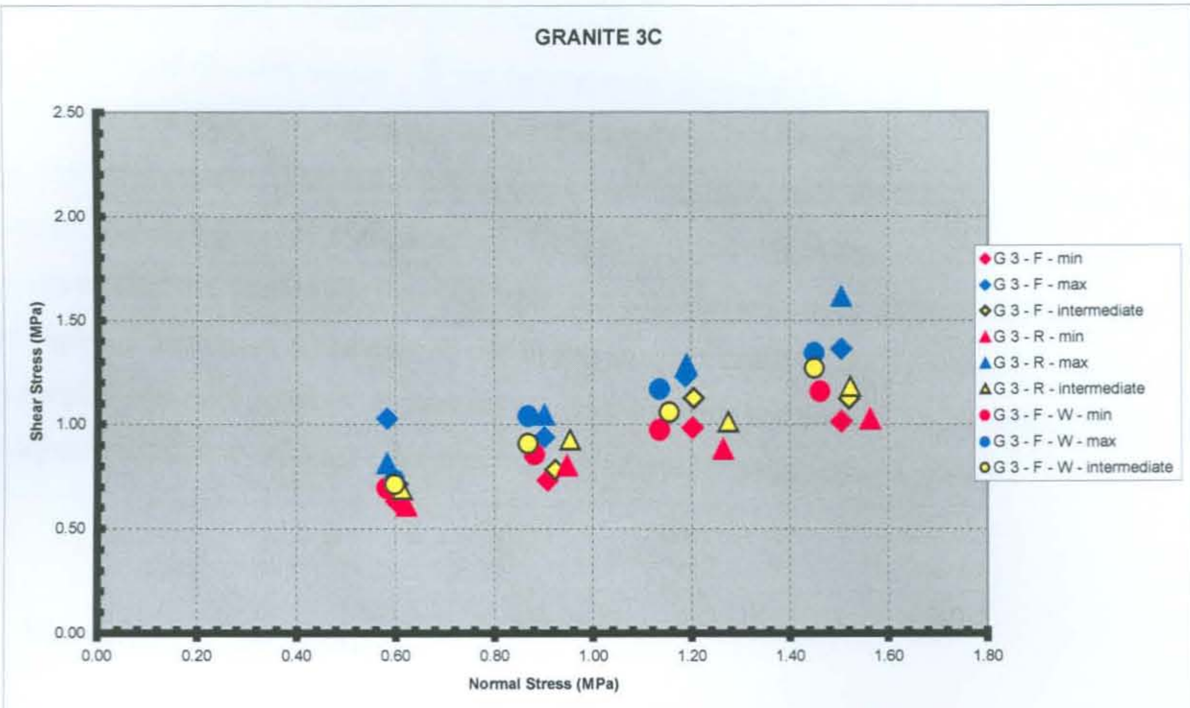


Figure 4. 15 Shear stress vs. normal stress for Granite 3C

Shear direction and size	Apparent cohesion kPa	Friction angle Degrees	Correlation coefficient of observation points on normal - vs. shear stress graph
Forward – minimum	355	24,8	0,92
Forward – maximum	705	22,7	0,74
Forward – intermediate	392	27,1	0,84
Reverse – minimum	382	22,8	0,98
Reverse – maximum	290	40,9	0,99
Reverse – intermediate	393	27,1	0,97
Forward (Wet) – minimum	394	27,5	1,00
Forward (Wet) – maximum	376	34,6	0,96
Forward (Wet) – intermediate	339	32,5	1,00

Table 4. 15 Shear stress vs. normal stress for Granite 3C

Discussion

The joint surface of Granite 3C was covered by approximately 1 mm of joint fill material. The joint fill comprised of a secondary green mineral, probably chlorite in an unweathered form. The joint surface had prominent striations in the direction of shearing. The test in a forward direction yielded an angle of friction of between 22,8 and 27,1 degrees. The values obtained for the reverse tests were 22,8°, 27,1° and 40,9°. The friction angle of 40,9° is very high and cannot be explained. This test result is regarded as credible as the observations on the Normal stress vs. Shear stress graph gave a coefficient of correlation of 0,9930. The values obtained for the saturated sample's minimum is 27,5° and for the intermediate value 22,8°. This could not be explained.

Ideally, calculated peak friction angles (with Barton's empirical formula) should be compared with tested peak friction angles. When testing rock specimens for shear strength in a large shear apparatus where high normal stresses are applied, only the result of the first shear is a true peak test result. The following cycles of testing take place on a surface damaged by previous testing. To obtain the angle of friction (ϕ) and the cohesion of a joint surface at least three (3), but preferably four (4), tests must be carried out at different normal loads. The angle of friction of a test carried out in this manner can thus not be called a "peak". In this chapter post-peak refers to the results obtained as described above. There is thus merit in the argument of comparing the peak and "maximum post-peak" friction angles.

4.6 Discussion of test results

As part of the research project a comparison was made between the calculated peak shear strength according to Barton and Choubey (1977) and the shear strength during testing.

It can be assumed that the effective normal stress (σ_n) under a concrete dam foundation of moderate size is in the order of 1 MPa or 1000 kPa. This was the reasoning for choosing effective normal stresses of 600, 900, 1200 kPa for testing during the phase 2 and effective normal stresses of 600, 900, 1200 and 1500 kPa during the phase 3.

Roughness was determined with a carpenter's comb and compared with Barton and Choubey's (1977) roughness profiles and the joint roughness coefficient (JRC) was so obtained. The hardness of joint surfaces was determined with a Schmidt hammer and the joint wall compressive strength (JCS) calculated using Barton and Choubey's (1977) formula.

4.6.1 Discussion of test results of Phase 1 and 2

The contribution to the angle of friction by roughness and hardness was determined by using Barton's formula (paragraph 2.3.1) and subtracting the maximum post-peak value. By adding the basic friction angle to this value, the total peak friction angle can be determined. Table 4.16 presents these results of this calculation for rock types tested for Phase 2 of the investigation.

Rock type	JRC	JCS (MPa)	Calculated peak friction angle Barton (degrees)	Basic friction ϕ_b *(degrees)* Tested values	Calculated contribution of JRC & JCS to friction angle (degrees)
Basalt 1	9	234	56	35	21
Basalt 3	7	188	51	35	16
Dolerite 1	5	163	47	36	11
Granite 1	5	347	44	31	13
Granite 5	9	280	53	31	22
Granite 6	9	280	53	31	22
Granite 7	7	213	47	31	16
Mudstone 1	3	42	36	31	5
Mudstone 2	3	76	37	31	6
Mudstone 3	3	51	36	31	5
Sandstone 1	7	32	41	31	10

Table 4. 16 **Friction angles for rock types as calculated with the Barton and Choubey (1977) empirical equation for shear strength at normal stress σ_n = 1000 kPa.**

The contribution of hardness and roughness of the joint surfaces to the peak friction angle of the joint plane varied between a minimum of 5° and a maximum of 22°. The minimum values of 5° and 6° are for the Mudstone with smooth and moderately hard joint plane surfaces. The basic friction angle for Mudstone is about 31°. The peak friction angle is thus 36° to 37°. The maximum values of 13° to 22° were found to be that for granite where the joint surfaces were rough and hard. The basic friction angle for Granite is also about 31°. The peak friction angle is thus 44° to 53°.

The calculated peak friction angles were then compared with the maximum post-peak friction angles as determined by testing of joint planes during this study. Table 4.17 presents the results of this comparison. Normally calculated peak friction angles should not be compared with post-peak friction angles. However, in this case they were the maximum values determined with the available specimens.

Rock type	Calculated peak friction angle (Barton) *(Degrees)*	Tested max post-peak friction angle (dry) *(Degrees)*	Difference in friction angle *Degrees*	*Percentage*
Basalt 1	56	44	-12	-21,4
Basalt 2	56	49	-7	-12,5
Basalt 3	51	38	-13	-25,5
Dolerite 1	47	52,6	+6	+12,8
Dolerite 3 (Clay)	48	17	-	-
Granite 1	44	36	-8	-18,2
Granite 5	53	40	-13	-24,5
Granite 6	53	27	-26	-49
Granite 7	47	35	-12	-25,5
Mudstone 1	36	33	-3	-8,3
Mudstone 2	37	37	0	0
Mudstone 3	36	35	-1	-3
Sandstone 1	41	38	-3	-7,3

Table 4. 17 **Difference between the calculated peak and tested residual friction angles for rock types tested during Phase 2. (Calculated peak friction angle = 100 %)**

It is obvious from Table 4.17 that the differences between calculated and tested maximum post-peak friction angles are small, between 0° and 3° for rock with smooth moderately hard joint surfaces (in this case Mudstone 1, 2 and 3). Greater differences, 7° to 13° were found for rock with very hard and rough joint surfaces (Basalt 1,2 and 3) as well as for Granite (phase 2 testing) where the difference varies between 8° and 26°.

An even greater difference was found for Dolerite 3 (see Table 4.17). A peak friction angle of 48° was calculated but the cycle of three tests gave a minimum post-peak friction angle of 17°. This is because Dolerite 3 had a clay layer as joint fill material for which Barton's equation does not make provision.

The conclusion from this research is that Barton's equation can be used to predict maximum post-peak friction for smooth and moderately hard joint surfaces. Higher friction angles were calculated by Barton's equation than were determined in the laboratory for hard rough joint surfaces. It is generally accepted that Barton's formula is not applicable for filled joints.

The effect of water on the shear strength is demonstrated in Table 4.18 where the tested friction angle (dry) and tested friction angle (submerged) are listed.

Rock type	Tested min p-p friction angle $\phi_{(Dry)}$ *(degrees)*	Tested min p-p friction angle $\phi_{(Saturated)}$ *(degrees)*	Difference between dry and saturated friction angles ϕ *(degrees)*
Basalt 1	44	40	-4
Basalt 2	49	48	-1
Basalt 3	38	37	-1
Dolerite 1	52,6	43,6	-9
Dolerite 3 (Clay)	17	14,9	-2,1
Granite 1	35,8	28,8	-7
Granite 5	40,0	37,5	-2,5
Granite 6	27,1	24,9	-2,2
Granite 7	35,3	28,2	-7,1
Mudstone 1	32,8	22,6	-10,2
Mudstone 2	37	14,6	-22,4
Mudstone 3	35,2	13,2	-22
Sandstone 1	37,6	40,5	+2,9

Table 4. 18 **Difference between dry and saturated friction angles**

The effect of water on the friction angles of different rock types is illustrated in Table 4.19. From this table it is evident that as can be expected, rock types with hard, rough joint surfaces are only slightly influenced by the presence of water as far as friction angles are concerned. This is especially true for Basalt (with JRC = 7 - 9 and JCS = 188 - 234 MPa) where the difference between dry and submerged is between 1 and 4 degrees.

The influence of water is the greatest on friction angles of smooth moderately hard joint surfaces JRC = 3 and JCS = 43 - 76 MPa where the differences between dry and saturated is 10,2 degrees for Mudstone 1 and 22 to 22,4 degrees for Mudstone 2 and 3.

The friction angles for clay filled joints is affected by water. The friction angle of a clay filled joint tested for Dolerite 3 is as low as 17°. Submerged in water it falls to 14,9°.

4.6.2 Discussion of test results of Phase 3

To confirm the results obtained in phases 1 and 2, it was decided to investigate a further set of rock samples with great care and through four cycles of testing to try to determine the shear strength more accurately. The test method employed is described on page 3.18 of this thesis. The test results are presented in Table 4.19.

Rock type	JRC	JCS (MPa)	Calculated peak friction angle Barton (degrees)	Basic friction ϕ_b (degrees)	Calculated contribution of JRC & JCS to friction angle (degrees)
Granite 1C	7	185	46,9	31	15,9
Granite 2C	5	190	42,4	31	11,4
Granite 3C	11	205	56,4	31	25,4

<u>Table 4. 19</u> **Friction angles for Granite as calculated with the Barton and Choubey (1977) empirical equation for shear strength at normal stress σ_n = 1000 kPa**

From Table 4.19 it is evident that all three granite samples had the different roughness profiles. The JRC values ranged form 5 to 11. The joint compressive strengths were very much the same, in the order of 200 kPa. The contribution of these two characteristics to the friction angle in all three examples is given in Table 4.19. The calculated contribution was between 11,4° and 25,4°. However, the tested intermediate minimum post-peak friction angle was between 4,2° for Granite 1C; 8,4° for Granite 2C and 29,3 lower than the calculated peak angle of friction. The tested angle of friction is lower than the calculated peak for Granite 3C with joint fill material present. See Table 4.20 for this information.

Rock type	Calculated peak friction angle (Barton) *(degrees)*	Tested maximum post-peak friction angle (dry) (by testing – intermediate) *(degrees)*	Difference in friction angle	
			Degrees	*Percentage*
Granite 1C	46,9	42,3	-4,2	-10
Granite 2C	42,4	34,0	-8,4	-25
Granite 3C	56,4	27,1	-29,3	-108

Table 4. 20 **Difference between the calculated peak and residual friction angles for Granite tested during Phase 3 (Percentages calculated in relation to calculated peak)**

The influence of water on the residual friction angle is shown in Table 4.21. From this table it is evident that water saturated joints have a negative effect on the friction angle. This influence is between 1,6 and 6 degrees. However, during testing of granite 3C (with a secondary mineral as joint fill material) it was found that the presence of water had a positive effect on the angle of friction. The minimum post-peak angle of friction in a saturated state was 5,4° higher than the dry residual friction angle.

Rock type	Tested post-peak friction angle ϕ *(Dry)* *(degrees)*	Tested post-peak friction angle ϕ *(Saturated)* *(degrees)*	Difference between dry and saturated friction angles ϕ *(degrees)*
Granite 1C	42,7	36,7	-6
Granite 2C	34,0	32,4	-1,6
Granite 3C	27,1	32,5	+5,4

Table 4. 21 Difference between dry and saturated friction angles of Granite samples tested

4.7 Relationships investigated.

4.7.1 The relationship between shear displacement and joint roughness.

In theory, it is expected that there should be a relationship between the cumulative shear displacement and residual joint roughness. The farther a joint surface is sheared along a joint plane the smoother that plane becomes as a result of abrasion. If a joint surface is sheared far enough, it should theoretically become a smooth plane (with a residual friction angle equal to the basic friction angle – as described by Rengers envelope) That is if the normal stress is high enough or the joint wall material is so soft that all asperities are sheared. If the asperities are overridden this will not be the case, as part of the sheared asperities will determine the shear strength, probably by rolling, ect. The normal stress acting on the joint plane also has an influence on the distance a joint surface can move before abrasion has removed all asperities and reduced the surface to smooth plane. The higher the normal stress (for a given rock hardness) the shorter the shear displacement. This relationship can be expressed as JCS/σ_n. Where normal stresses are very low, $JCS/\sigma_n > 1000$ and where normal stresses are very high $JCS/\sigma_n \leq 1$.

This principle is presented in Figure 4.16

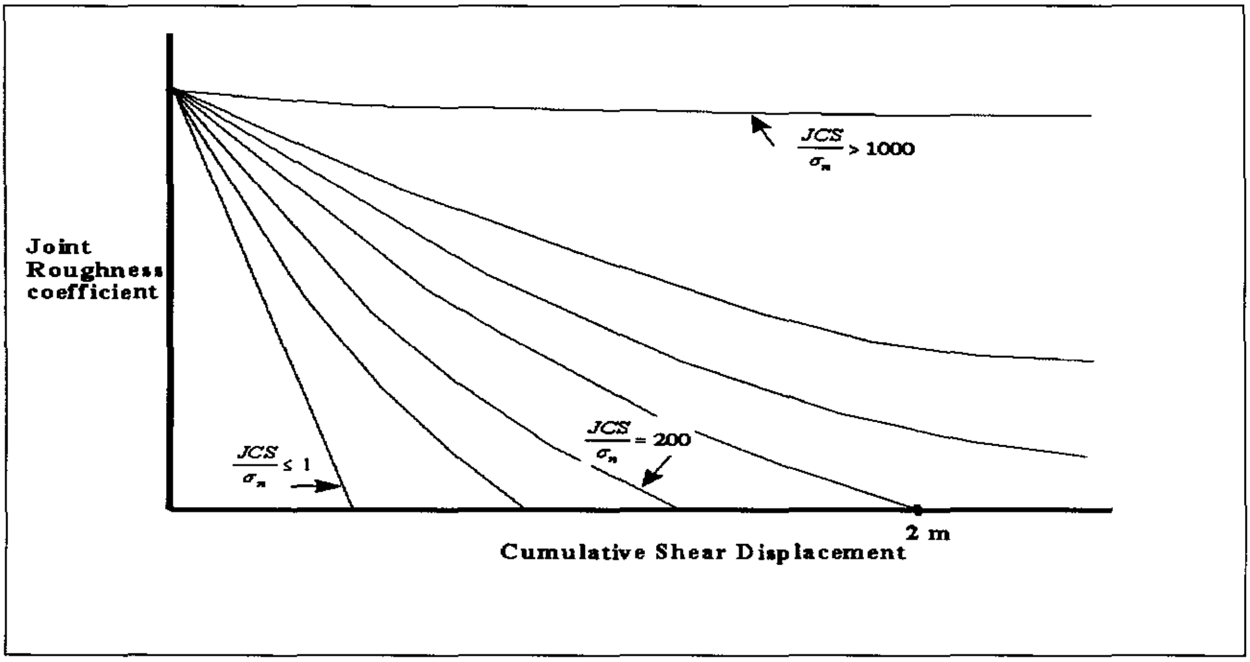


Figure 4.16 **The theoretical relationship between joint roughness coefficients and shear displacement.**

Under high normal stresses (σ_n) shear will normally take place through intact rock material (asperity), whereas for low normal stresses (σ_n) asperities will be overridden and not be damaged or be slightly damaged.

The relationship between joint roughness (in this case JRC was used) and shear displacement was investigated during this study. The influence of high normal stresses were not taken into consideration as testing was limited to normal stresses of maximum 1 MPa.

Figure 4.17 is a representation of Joint Roughness Coefficient (JRC) vs. cumulative shear displacement as determined for the three granite samples tested.

The JRC for each consecutive shear was determined by visually comparing the joint roughness profile as determined with the laser apparatus (as described in chapter 3) with Barton's (1971) joint roughness profiles and assigning a JRC value to each profile. A copy of each profile created by laser measurements was produced on an transparency and put on top of profiles prepared by Barton (1977) and compared visually. The measured JRC valves for Granite 1A, 1B and 1C deteriorated form 8 to 6, 6 to 4 and 12 to 10 respectively.

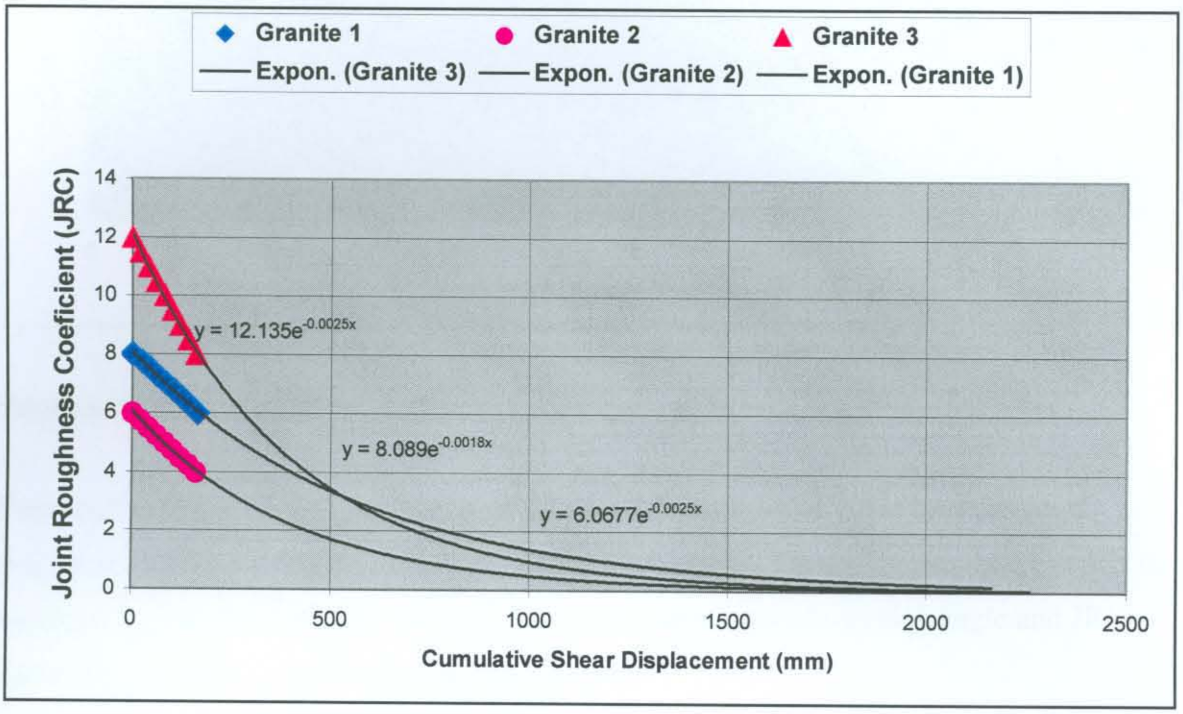


Figure 4.17 **Relationship between JRC and cumulative shear displacement.**

The deterioration of joint roughness of each of the three granite samples were measured visually, with an overlay on Barton's roughness profiles and the JRC value for each consecutive shear determined. The JRC values of each granite sample was the plotted vs. the cumulative shear displacement. An exponential regression was fitted to the points plotted on Figure 4.17. From this figure it can be seen that at the applied normal stress levels a cumulative shear displacement of more than 2,0 meter will be required to make the joint surface smooth as a result of friction. Only then will the friction angle be equal to the true residual or basic friction angle.

Conclusion: From the JRC / Cumulative shear displacement graphs it should be possible to predict the deterioration in joint roughness for different distances of shear displacement at specified levels of normal stress.

4.7.2 The relationship between friction angle and joint roughness.

From a theoretical point of view there should be a relationship between friction angle and joint roughness. This relationship was investigated for the all rock types tested during this project and included the peak and basic friction angles.

Figure 4.18 is a plot of JRC vs. Friction angle.

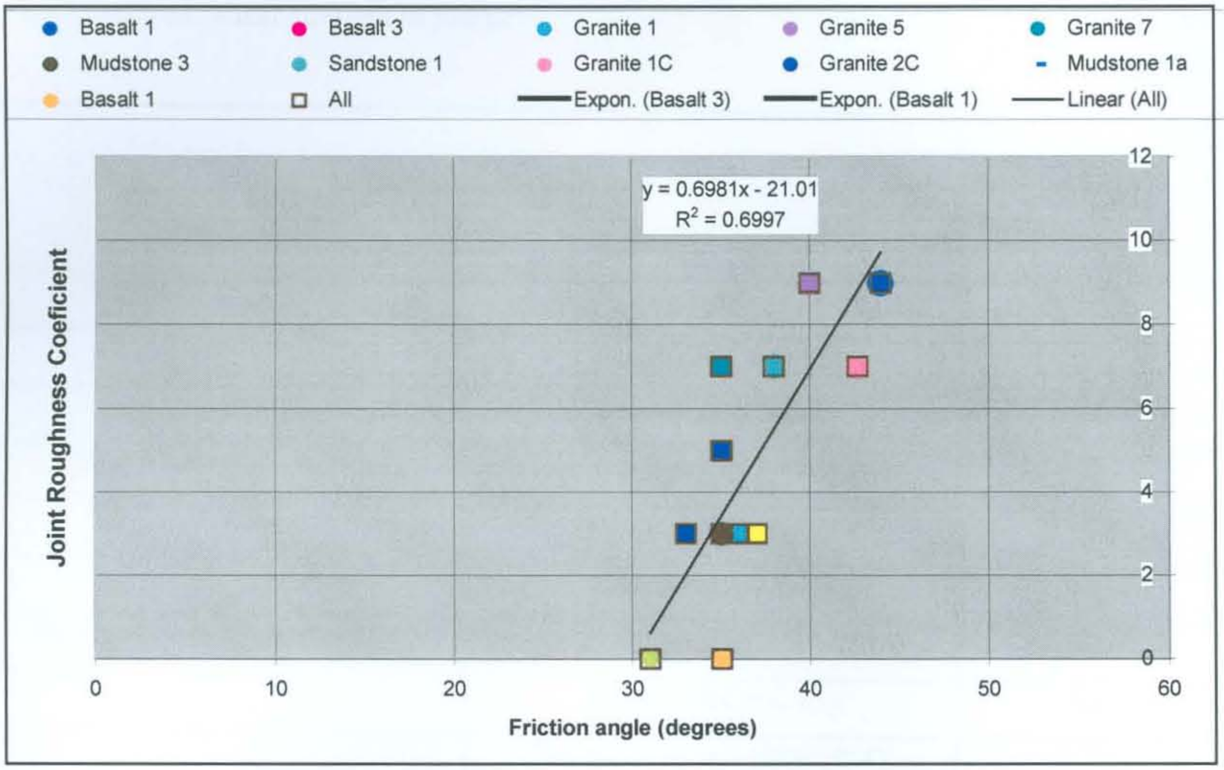


Figure 4.18 **Graph of JRC vs. friction angle**

Conclusion: A reasonable correlation (with a confidence limit of 70%) between joint roughness and friction angle exists for the rock types tested. The rock types tested varied in hardness, origin, structure and strength. The relationship between friction angle and JRC under dry conditions can be expressed as follows:

$$\phi = \phi_b + f(JRC) \qquad \text{where } \phi_b = 30° \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.1)$$

f = is the slope of the line = 1,43

The graph can be used to estimate the friction angle (dry) when the joint roughness coefficient (JRC) is known. In practice this means that a rock mechanics practitioner can measure joint surface roughness on site with a carpenters comb, determine the joint roughness coefficient (JRC) with Barton's (1977) joint roughness profiles and use equation 4.1 to estimate the friction angle of the joint surfaces.

4.7.3 Field estimation of shear strength of joint surfaces in rock

An experienced engineering geologist or rock mechanics practitioner should be able to estimate the hardness (according to Table 5.1) and roughness (Figure 2.9) of a joint surface in the field. He or she would also be able to measure waviness of continuous joints. From these parameters together with the basic friction angle the peak friction angle can be estimated.

The shear strength of Patton's saw-tooth specimens is represented by:

$$\tau = \sigma_n \tan (\phi_b + i) \quad \text{.........................} \quad (2.10)$$

where ϕ_b is the basic friction angle of the surface and i is the angle of the saw-tooth face.

The basic friction angle for any rock material can be determined from Table 2.2 or Table 4.1. The angle of friction of the saw tooth face is determined by the hardness and roughness of the surface. From work done during this research the following guidelines (rule of thumb) can be used to estimate shear strength of joints:

Surface characterization		*i* value
Hardness	Roughness	
Very hard (> 200 MPa)	Very rough (JRC= 14-20)	8°-13°
	Rough (JRC= 6-12)	0°-9°
	Smooth (JRC=0-4)	5°
Hard (100-200 MPa)	Very rough (JRC= 14-20)	Na
	Rough (JRC= 6-12)	2°-16°
	Smooth (JRC=0-4)	Na
Moderately hard (50-75MPa)	Very rough (JRC= 14-20)	Na
	Rough (JRC= 6-12)	Na
	Smooth (planar) (JRC=0-4)	4-7°

*Na – not available

Table 4.22 **Estimation of *i* value contribution to angle of friction**

When this calculated data of the rock types tested in the laboratory are used to plot angle of friction due to surface characteristics (i.e. hardness and roughness) vs. JRC, the result is Figure 4.1.

The results of the laboratory shear testing does not appear to give satisfactory results. For that reason it was decided to use Barton's (1977) empirical formula (2.11).

$$\tau = \sigma_n \tan [JRC \log_{10} (JCS/\sigma_n) + \phi_b] \;\ldots\ldots\ldots\ldots (2.11)$$

Where τ = peak shear strength; σ_n = effective normal stress

JRC = joint roughness coefficient; JCS = joint wall compressive strength

ϕ_b = basic friction angle (obtained from residual shear tests on flat unweathered rock surfaces)

The contribution of roughness and hardness are presented in the following part of the formula: $JRC \log_{10} (JCS/\sigma_n)$ .... (4.2)

This formula was used to calculate the contribution of the hardness (JCS) in terms of Uniaxial Compressive Strength (UCS) vs. the roughness (JRC). The roughness (JRC) was use as values between 1 and 20 and the UCS values from 50 to 350 MPa in multiples of 50. If it is accepted that σ_n = 1 MPa (equal to the stresses normally associated in the foundations of dams and other civil engineering structures) then the value of *i* can be calculated for different JRC vs. JCS values and a graph be drawn as shown in Figure 4.19

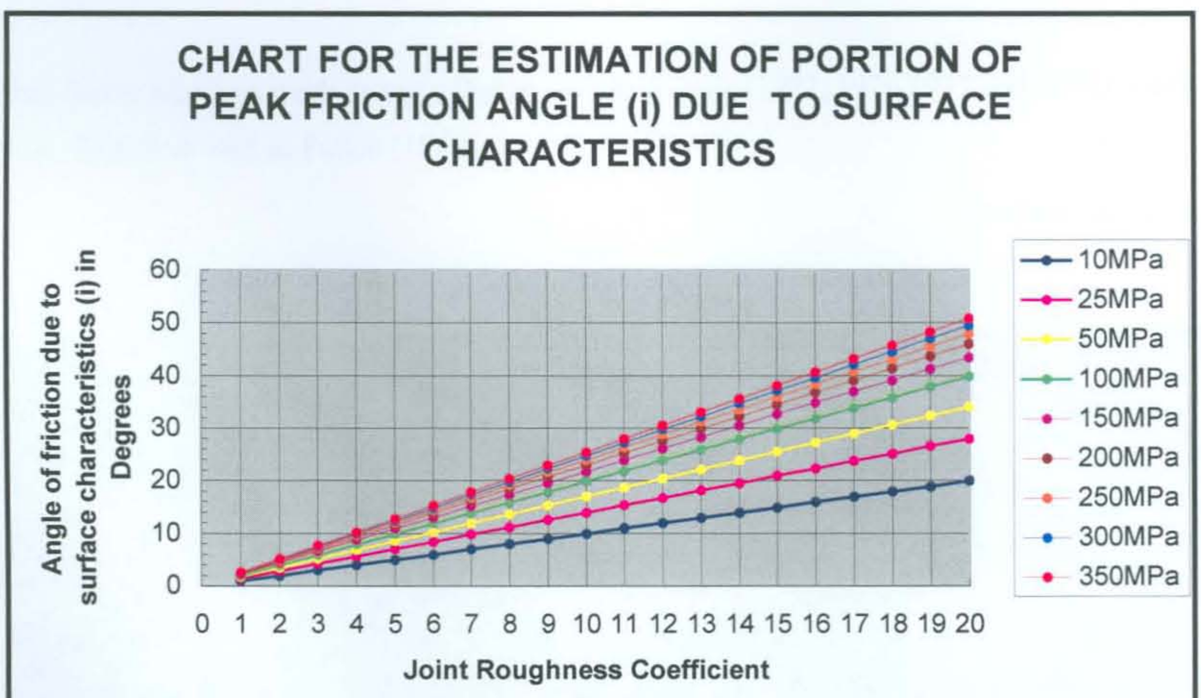


Figure 4.19 **Chart for the estimation of peak friction angle (*i*) due to surface characteristics, for σ_n = 1 MPa**

Any experienced engineering geologist or rock mechanics engineer can now estimate [by estimating (or measuring) in the field] the JRC and the JCS (in terms of UCS) of a joint surface and by using this chart, determine the contribution of the surface characteristics (medium scale roughness) to the angle of friction.

The contribution of waviness could contribute further to the value of *i*. The contribution of this component could be determined by using Hack, et. al.'s (2002) large scale roughness (waviness) profiles. It is especially applicable to large-scale foundations as for dams. Table 4.23 could be used to determine the contribution of waviness to the shear strength of large surfaces.

Large scale roughness (waviness)	Amplitude	Shear strength contribution in degrees
Straight	0 cm	0°
Slightly curved	1,5 – 3,5 cm	2° – 4°
Curved	3,5 – 7 cm	4° – 8°
Slightly wavy – wave length ±1 m	5 – 9 cm	9° - 14°
Wavy – wave length ± 0,5m	5 – 9 cm	14° - 20°

<u>Table 4.23</u> Shear strength contribution due to large-scale roughness (waviness) – (After Hack et. al. , 2002)

By adding the basic friction angle (from Fable 4.1) to this value, the total friction angle, is obtained.

$$\phi_t = \phi_b + i_a + i_w \quad \text{.................} 4.3$$

where ϕ_t = total friction angle and ϕ_b = basic friction angle,

i_a = the angle of the asperity (saw-tooth face, Patton, 1966) and

i_w = is the angle of the waviness (Hack et. al., 2002)

The research has shown that this simple tool will be of use to engineering geologists and rock mechanics practitioners who require a rapid method to determine the angle of friction of a joint surface in the field.

This tool is based on work done by Barton and co-authors (1972, 1976,1977 and 1991), Hack et. al. (2002) as well as Patton (1966).

4.7.4 The influence of true cohesion, rock bridging and waviness on shear strength

Barton and Choubey (1977) does not take into account:

(i) the presence of discontinuity filling with true cohesion (c_t)

(ii) rock bridging (c_b)

(iii) the effect of waviness resulting in change of direction (i)

Van Schalkwyk (1999) therefore suggested that the equation be written as follows:

$$\tau = c_t + c_b + \sigma_n \tan [JRC \,.\, \mathrm{JMC} \,.\, \log_{10}(\mathrm{JCS}/\sigma_n) + \phi_b + i]$$

Where: τ	= peak shear strength	σ_n	= effective normal stress
JRC	= joint roughness coefficient	*JCS*	= joint wall compressive strength
ϕ_b	= basic friction angle	JMC	= joint matching coefficient
c_t	= true cohesion (fill)	c_b	= bridging strength
i	= effect of waviness resulting in change of direction		

Where fill is present on a joint surface, the fill thickness is of great importance. It is postulated that there is a relationship (FTC) between fill thickness JRC which has a value between 0 – 1.

For filled joints the modified Barton & Choubey equation becomes:

$$\tau = c_t + c_b + \sigma_n \tan [JRC \,.\, \mathrm{JMC} \,.(1\text{-}\mathrm{FTC}) \log_{10}(\mathrm{JCS}/\sigma_n) + (1+\mathrm{FTC})\, \phi_b + (\mathrm{FTC} \,.\, \phi_f) + i]$$

Where: τ	= peak shear strength	σ_n	= effective normal stress
JRC	= joint roughness coefficient	*JCS*	= joint wall compressive strength
ϕ_f	= friction angle of fill	JMC	= joint matching coefficient
c_t	= true cohesion (fill)	c_b	= bridging strength
i	= effect of waviness resulting in change of direction		
FT	= Fill thickness in mm	FTC	= -0,07 ln (JRC+1/FT+1) + 0,5
ϕ_b	= basic friction angle of rock		

4.8 Further research and conclusion

This research has provided the framework within further research can be undertaken. The infrastructure is now available in South Africa to investigate the following:

The relationship between shear displacement and joint roughness should be investigated further. Testing should be carried out with low (1 MPa) to High (10 MPa) normal stresses. This could provide a graph the relationship of joint roughness (JRC) vs. shear displacement.

The relationship between fill thickness, joint roughness and shear strength should be investigated further.

This study contributes to the knowledge of shear strength on southern African rock types, in particular on the sampling of specimens, preparation of specimens for testing in the large shear apparatus, the measurement of the roughness and hardness of the joint surface, the testing procedure and the interpretation and application of the results. To a lesser extent the study provides typical values of the shear strength characteristics of the rock joints.