BTA/GE/10-11 **Shear strength of the Bremanger Sandstone**

"Determining the basic friction angle using a Golder Direct Shear Box"

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Title	:	Shear strength of the Bremanger Sandstone "Determining the basic friction angle using a Golder Direct Shear Box"
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Summary

This project focuses on the shear strength of Devonian sandstone cobbles that will protect the area between the sea-water breaker and the beach and will be used to construct a runway for a large crane for the new Maasvlakte 2.

In rock slope design the shear strength of sliding interfaces is often based on Coulomb's model in which shear strength (τ) is expressed as a function of cohesion (c), normal load (σ) and the friction angle (Φ).
A specific model on shear strength behaviour of rockfill is proposed by Barton (Barton, 2008). Barton's model can be used to predict shear strength of rock joints and rock fill when basic rock properties are known. One main factor of influence on shear strength of rockjoints and rock fill is the basic friction angle.

A Golder direct shear box was used to obtain the basic friction angle of the Bremanger sandstone. First the basic friction angle was determined (using flat saw-cut surfaces). In the next phase fresh tensile cracked rock discontinuities were tested. Measured stresses were corrected using measured dilatancy to estimate the basic friction angle. The influence of different rock properties such as roughness, rock strength and visible layering was studied. Finally natural non-matching surfaces were researched to see how the shear strength changes due to the weathering and smoothening of the rock.

The following main results and conclusions were drawn from the research project:

Flat saw-cut surfaces:
- The basic friction angle of the Bremanger (flat saw-cut surfaces) was not measured correctly. Since the sample halves were polished in order to make them match, the measured friction angle is rather an indication of the polishing process than the rock properties.

Tensile-cracked surfaces:
- For the tensile cracked samples, the average residual friction angle is [redacted] degrees. The residual friction angle was used as the basic friction angle rather than the peak friction angle since high peak shear stress values are caused by asperities at the edges of the tested samples. The shear strength dropped massively as soon as these asperities broke off.

- Residual friction angles do not depend on wet or dry test conditions.

- There is a direct link between UCS and shear strength. The higher the UCS value, the higher the residual stress value.

- The Bremanger sandstone is a Metasandstone. Layering is still macroscopically visible but cleavage does not occur along this layering.

Natural non-matching surfaces:
- These surfaces were weathered and smoothened. This caused the residual friction angle to drop to [redacted] degrees. 3D Leica pictures confirmed that the surface of this tested sample was smoother than the fresh tensile-cracked ones.

Contents

I. Introduction

Rotterdam harbor is one of the biggest harbors in the world. The current harbor and its associated industrial area are expected to reach their growth limit within a few years. Therefore the reclamation of an area west of the Maasvlakte was planned to accommodate a new container terminal providing access for the biggest ships.
Construction of the new Maasvlakte 2 started in September 2008 by Koninklijke Boskalis Westminster and Van Oord (PUMA).

In order to protect the land that is reclaimed from the sea it is necessary to build a strong seawall. The build-up of the seawall for the Maasvlakte 2 is schematically presented in Figure I.1. Concrete armourstones of the Maasvlakte 1 will be re-used to build a sea-water breaker. Between the sea-water breaker and the beach, the ground will be protected by Devonian sandstone cobbles (Bremanger). A runway for a large crane used to place the armourstones will be constructed. It will be made of Devonian sandstone cobbles. This research project focuses on the shear strength of these cobbles.

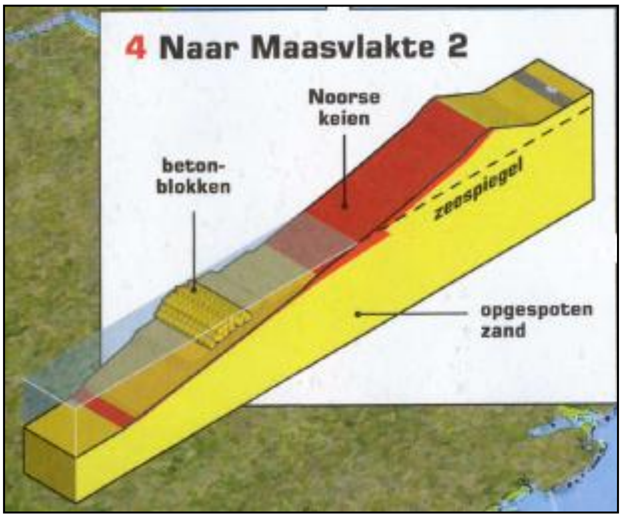


Figure I.1: Seawall build-up for Maasvlakte 2 (MV2 magazine, 2009)

To design a runway that is capable to carry a large crane, it is important to have good estimates of the shear strength properties of the used cobbles. In rock slope design the shear strength of sliding interfaces is often based on Coulomb's model in which shear strength (τ) is expressed as a function of cohesion (c), normal load (σ) and the friction angle (Φ).
A more specific model on shear strength behaviour of rockfill is proposed by Barton (Barton, 2008). It has been derived by analogy between the behaviour of rough rockjoints and rock fills. Barton's model can be used to predict shear strength of rock joints and rock fill when basic rock properties are known. One main factor of influence on shear strength of rockjoints and rock fill is the basic friction angle.
In this research project a Golder shear box was used to obtain the basic friction angle of the Bremanger sandstone. First the basic friction angle was determined (using flat saw-cut surfaces). In the next phase fresh tensile cracked rock discontinuities were tested. Measured stresses were corrected using measured dilatancy to estimate the basic friction angle. This angle was determined using Hencher and Richard's approach (Hencher & Richards, 1982). The influence of different rock properties such as roughness, rock strength and visible layering was studied. Finally natural non-matching surfaces were researched to see how the shear strength changes due to the weathering and smoothening of the rock.

Chapter 1: Theory

1.1 (Mohr-)Coulomb
In order to to carry out stability analyses on rock discontinuities it is necessary to determine the friction angle of the sliding surface. One should also collect information on the sliding interface such as surface roughness and possible infillings (such as cementing material).
In rock slope design, discontinuities are assumed to behave as a Coulomb material that fulfills the shear strength criteria proposed by Coulomb in 1773:

$$\tau = c + \sigma \tan\Phi$$

In which shear strength of the sliding interface (*τ)* is expressed as a function of cohesion (*c*), normal load (*σ*) and the friction angle (*Φ*).

Figure 1.1.1 shows the process to determine the peak and residual friction angle graphically.
Figure 1.1.1(a) shows the sliding interface (or discontinuity). A normal load is applied perpendicular to the sliding interface. As shear stress is monitored as a function of horizontal displacement a typical graph is shown in figure 1.1.1(b). First the shear stress increases linearly with the horizontal displacement. Then non-linearly until a peak value is reached that corresponds with the peak shear strength of the material. After the peak value is reached, the required stress for displacement decreases until a constant value is reached. This is the residual shear strength.

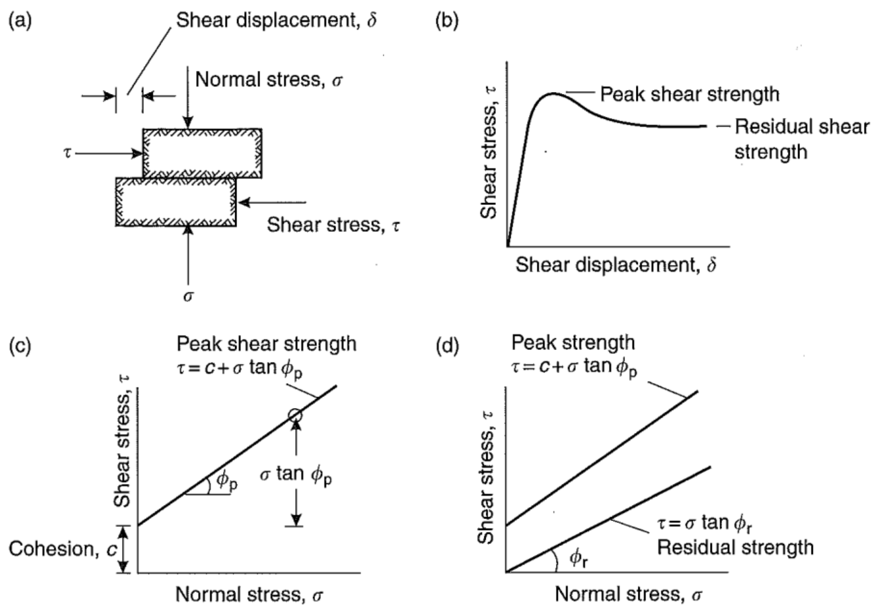


Figure 1.1.1: Mohr(-Coulomb) criteria on rock strength. (Wyllie & Mah, 2004)

When these tests are performed using different normal loads and peak shear strength is plotted against the corresponding normal load (corrected for displacement), and a linear trend line is drawn through these values, figure 1.1.1(c) is obtained. The slope of the line is equal to the tangent of the peak friction angle. It's intercept is the cohesion (c) (if present). The same process can be followed in order to obtain the residual friction angle. The result of this process is shown in figure 1.1.1(d). In this

ϕ_b

case residual stress is expressed as a function of normal load and the residual friction angle only. This is caused by the fact that the cementing material is no longer contributing to the shear strength since it's broken due to displacement. The residual friction angle is lower than the peak friction angle because the rock asperities are grinded off leading to a smoothened shearing interface.

1.2 Barton's model

In order to predict shear strength behaviour of rock joints and rock fill, Barton proposed two models in which he incorporated certain rock properties such as surface roughness, the strength of rock or rock particles and the basic friction angle. Both the model for rock joints and the model for rock fill are explained below.

1.2.1: Barton's model on the shear strength of rock joints

Barton described an empirical relationship to describe shear strength of rock joints. It can be used to predict shear strength data by performing just a few simple tests. The empirical relation is given as:

$$\tau = \sigma_n \tan\left[JRC \log_{10}\left(\frac{JCS}{\sigma_n}\right) + \phi_b \right]$$

Where

τ = Peak Shear Strength

σ_n = Effective normal stress (corresponding to the peak shear strength)

JRC = Joint Roughness Coefficient

JCS = Joint wall Compressive Strength

ϕ_b = Basic Friction Angle (=residual friction angle obtained from residual shear stress tests on flat unweathered rock surfaces)

JRC

There are two ways to define the JRC value. The first is by backwards calculation when all other parameters are known. Thus;

$$JRC = \frac{\arctan\left(\frac{\tau}{\sigma_n}\right) - \phi_b}{\log_{10}\left(\frac{JCS}{\sigma_n}\right)}$$

The other way is by comparing the joint's surface to the typical roughness profiles for JRC proposed by Barton (1977)(Appendix 4).

JCS

The Joint Wall Compressive strength of the unweathered joint wall, or JCS, is equal to the unconfined compressive strength(UCS) of the unweathered rock. It can be estimated by performing a UCS test on a sample from the specific rock. Most rock joint surfaces in the field are weathered to a certain extend and therefore the JCS will not be the same as the UCS. In order to find the right JCS value, one should use a Schmidt Hammer.

ϕ_b

The basic friction angle can be determined by performing a tilt- or shear box test on diamond saw prepared fresh-cut rock samples (Barton & Choubey, 1977). One has to take in care that the specimen's granular texture is exposed at the sliding interface although no macroscopic interlocking of the two surfaces should occur. This can be achieved by sandblasting the saw-cut surfaces (Barton, 1971).

It turns out that the basic friction angle of unweathered rocks is mostly between 25 and 35 degrees depending on the rocktype (Barton & Choubey, 1977). It can therefore be quite accurately estimated without performing a shear box test.

1.2.2: Barton's model on the shear strength of rock fill

The model for estimating the shear strength of rock fill is very similar to the model for rock joints. Factors that are mostly of influence are porosity and the degree of compaction. The particle roughness is also very important (Barton, 2008).

$$\tau = \sigma_n \tan[R log(\frac{S}{\sigma_n}) + \Phi_r]$$

Where

τ	= Peak Shear Strength
σ_n	= Effective normal stress (corresponding to the peak shear strength)
R	= Effective roughness
S	= Particle crushing strength
Φ_r	= Residual friction angle

R

R, the equivalent roughness of the rock fill, replaces the JRC in the Rock Joint model. It can be determined by performing a large scale tilt-test on the rock fill as shown in figure 1.2.2.1. The effective roughness can then be calculated using Barton's equation for the tilt test as:

$$R = \frac{\alpha^0 - \phi_b^0}{\log(S/\sigma_{no})}$$

Provided that the basic friction angle and the particle crushing strength of the material is known.

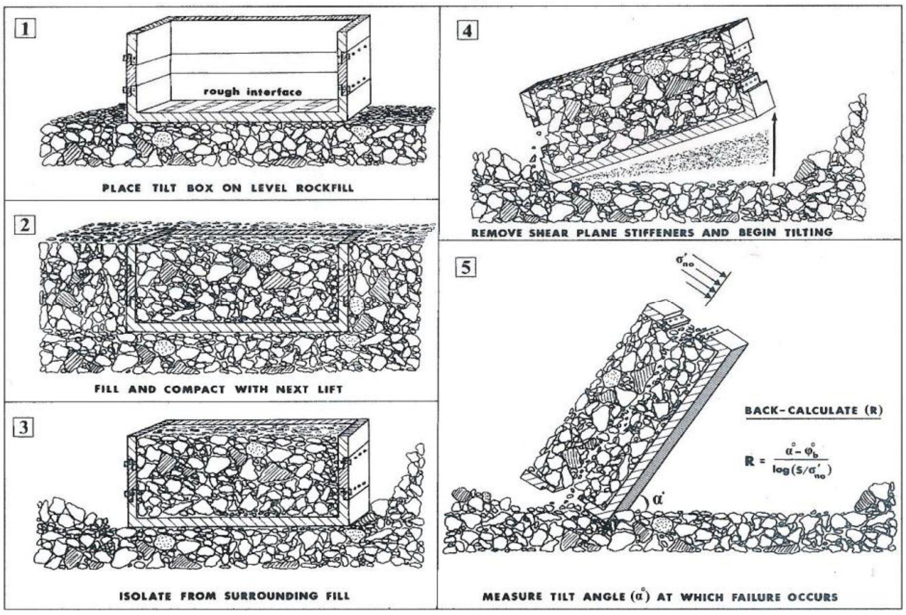


Figure 1.2.2.1: Determination of R (Barton, 2008).

The other way of determining R is by using an empirical graph as shown in Figure 1.2.2.2. It clearly shows the importance of compaction and porosity as well as the shape of the rocks.

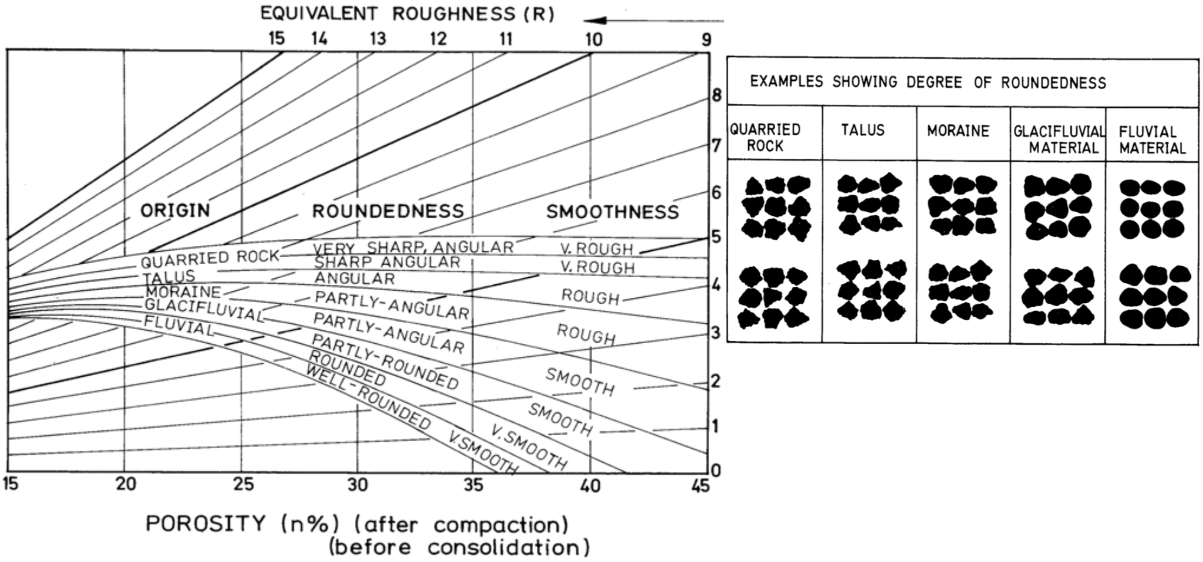


Figure 1.2.2.2: Estimation graph to predict R without performing tilt tests (Barton, 2008).

S

The particle crushing strength is determined by using a strength factoring graph for estimating S as a function of UCS (σ_c) developed by Barton and Kjaernsli, 1981. If the UCS value and the d_{50} of the particles are known, the scheme easily gives S, the particle crushing strength.

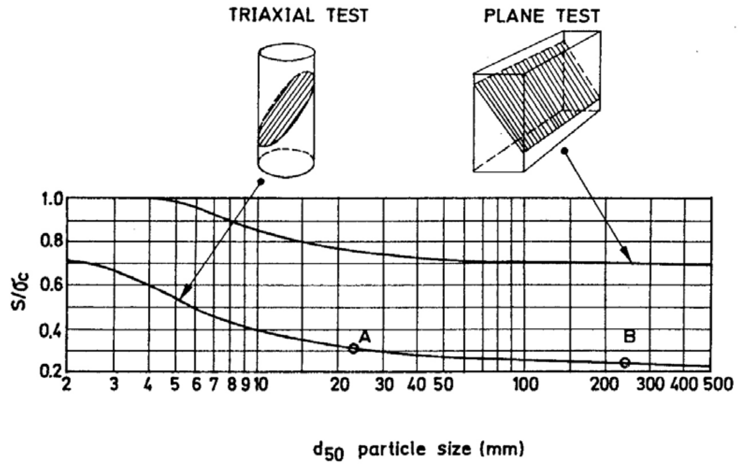


Figure 1.2.2.3: Conversion of the rock's UCS strength to rock fill's particle crushing strength.

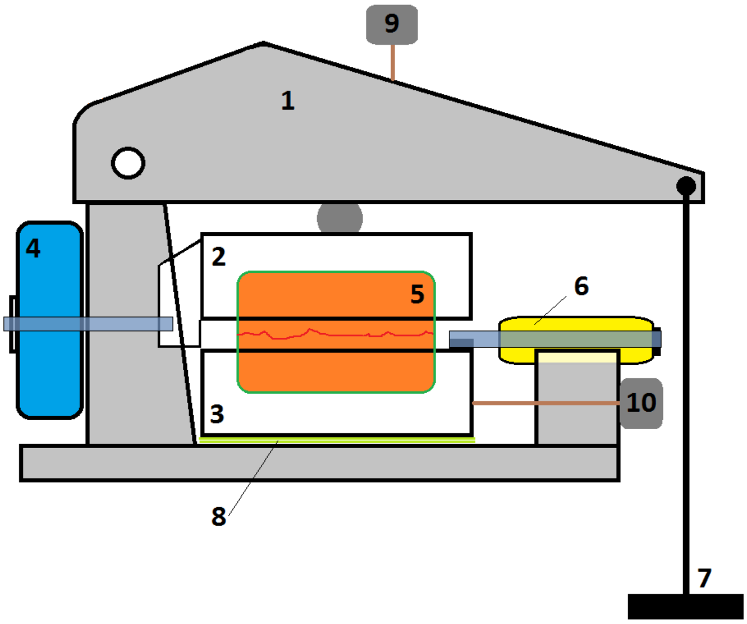
Φ_r

The residual friction angle can be calculated by performing shear box tests. In this research project the residual friction angle is calculated by plotting the residual strength of each loading stage (50, 100, 250, 500, 1000 KPa) in a graph. By the use of a trend line the residual friction angle was calculated.

Chapter 2: Test Description

2.1 The Golder shear box apparatus

To measure the shear strength of rock joints we made use of a Golder Shear box.
The Golder Shear box setup is designed to measure shear strength of rock discontinuities under different normal stresses perpendicular to the sheared plane. The setup is illustrated in figure 2.1.1.



1. Lever arm
2. Upper box
3. Lower box
4. Force Transducer
5. Specimen
6. Hydraulic jack
7. Weight
8. Teflon layer
9. Dial gauge(vertical displacement)
10. Dial gauge(horizontal displacement)

Figure 2.1.1: The Golder shear box as used in the experiments

The machine consists of an upper and lower box that are holding both halves of the specimen. Both halves of the specimen are fixed in the boxes by dental plaster such that the discontinuity between them is in line with the direction of shearing.
The lower box is able to move in horizontal direction and friction between the lower box and the bottom of the apparatus is minimized by the use of a Teflon layer lubricated with Teflonspray. The upper box is fixed in place and connected to a force transducer that measures the shear force on the specimen's discontinuity. For low normal loads (less than 500KPa) a 5KN force transducer was used while for the 500 and 1000 KPa loads a 50KN force transducer was necessary.
To move the lower box, one has to increase the shear force on the box by the use of a hand pump driving a 5 ton hydraulic jack attached to a yoke which moves the lower box.
Since we want to measure shear stress at different normal loads, the normal force is applied by the use of a lever arm acting on the upper box. The more weights added to the arm, the higher the normal load.
Finally, horizontal and vertical displacement of the specimen is measured by using digital dial gauges. Vertical movement was only measured as an average at the center of the upper box although rotations of the upper box were sometimes observed. Both the digital dial gauges and the force transducer are connected to a computer which automatically records the raw data every 2 seconds. Measurements are continuously plotted as shear stress vs. horizontal displacement in order to keep track of the experiment's progress.

2.2 Calibration of the Golder Shear Box setup

Both the dial gauges and force transducers were calibrated before testing started. Also the amplification factor of the lever arm for applying the normal load was determined. This was done by placing a calibrated force transducer in the same horizontal position and at the same (initial) height as the upper box would be during a shear test. By increasing the deadweight on the lever arm the force transducer will show the amplified normal load. One can calculate this amplification factor for each amount of weight by doing a series of measurements (Appendix 1).

It turns out that the amplification varies with applied weight. This can be explained by the fact that the axle to which the lever arm is connected starts to deform when a lot of weight is added to the arm.

Due to the deformation of the axle at high loads no average amplification factor was used to determine the weight that needs to be added in order to get the right initial normal stress conditions. Instead amplification factors were interpolated to the right values for each test (**50, 100, 250, 500, 1000KPa**). Once the exact amount of weight to be added was known, the closest possible combination of standard weights was selected. An example of this calculation is shown in Appendix 1. Since most of the samples were prepared at the same size (length x width), these calculations only had to be done once. However; if an initial load differed too much from the preferred value, the right amount of weight was recalculated.

2.3 Test Procedures

2.3.1: Shear Box tests

All shear box tests were performed following the ISRM recommendations (ISRM, 2006). After the preparation of the sample the first normal load was applied and a shear box test performed. Shearing was performed at a rate of about 1mm/minute.

Since preparing the samples takes a lot of time (sawing, creating a fracture and putting the sample in the boxes) multiple tests were performed on the same sample. Both multistage tests with increasing and decreasing normal load were performed to compensate for possible decreasing true peak strength during subsequent test runs. To keep track on the sample damage, photographs were taken after each loading stage and the sample was cleaned before performing the next loading stage with matching discontinuities. These photographs can be found in Appendix 5.

Since the rock fill will be used along the seaside in a possibly wet environment, shear box tests were also conducted on wet, saturated samples. In order to completely saturate the sample it was placed under vacuum for at least 12 hours.

2.3.2: UCS, PLT and BTS tests

UCS, PLT and, respectively, BTS tests were conducted following ASTM D2938-95/D3148-96, ASTM D5731-95 and, respectively, ASTM D3967-95A standards. All tests were performed in dry conditions.

2.3.3: Damage observations using 3D pictures

To keep track of the grinding and smoothening of the sample surfaces 3D Leica pictures were taken before and after each loading sequence (that is; a 3D image was taken before and after the test sequence for samples S7 and S8). From these 3D images a ratio of true area against projected area was calculated which gives an idea about the damaging of the sample due to shearing. The photographed area is 2 cm x 2 cm. Two more images were taken after the shearing of a smooth natural surface to compare this sample with the fresh tensile cracked ones.

2.4 Tested material

All tests were performed on Bremanger Sandstone sent by Boskalis in both 2007 (S1, S2) and 2010 (S3-S10). The Bremanger is a Devonian Sandstone from Norway. It's a quarried rock that lost many of its sharp angles due to its processing. Many of the provided cobbles show flat surfaces that seem to coincide with the layering of the rock though this was not always the case.
Especially when we attempted to create man-made fractures along the visible layering in samples, the rock had no preferred direction of cleavage. In order to test the rock in all possible conditions, samples were prepared parallel to the visible layering and perpendicular to the layering. A rock sample with no visible layering was tested as well.

2.4.1: Mineralogy

To understand why the rock doesn't prefer to crack along this visible layering a full mineralogical description was made with the help of M.M. van Tooren and added in appendix 2.
It turns out that the original sedimentary structure of the sandstone is still macroscopically visible. It can be concluded that layering is still observable but since the rock has undergone some metamorphism, the individual grains are compressed to and into each other. This is the reason why the sandstone does not crack along the macroscopically visible layers.

2.4.2: Sample preparation

In this research project the samples were prepared in three different ways. As described earlier in the theory, the basic friction angle should be determined by shear box tests on fresh diamond saw cut samples (S1&S2). After that, experiments were performed on fresh tensile cracked surfaces (S3-S8) in order to obtain the residual friction angle of the Bremanger sandstone. Finally; two multistage tests were performed on natural non matching 'smooth' surfaces in order to get an idea about the reducing of the friction angles due to weathering.
In order to get good results from our Golder shear box setup, Golder Associates added a list of physical constraints that a tested sample should satisfy. They are listed in table 2.6.1.

1. The sample length should be such that the spacing between the boxes with the samples in position will be approximately 5mm. 2. The roughness of the surface should be such that asperities do not deviate from the mean surface plane by more than 2.5 mm. 3. The area of shear surface should probably be at least 40cm2. 4. Ideally the shear surface should have a shape elongated in the shearing direction but this is not critical.

Table 2.6.1: Physical constraints that tested samples should satisfy. (After Golder Associates, 1984)

While taking into account these constraints, the different preparation methods are explained now.

Preparation of S1&S2

To prepare these samples a diamond saw was used at the TUDelft's cutting lab. Since the Bremanger sandstone is a very strong rock, it turned out to be impossible to create two matching smooth surfaces due to the oscillation of the saw. In order to get flat surfaces, the samples were polished with a 175mu polishing paste.

Preparation of S3-S8

To create fresh man-made fractures in the rock samples, a 75mm core was first drilled. Then two slots were driven over the length of the core directly towards each other. By placing the core between splitting plates a fresh fracture was created while the slots functioned as crack inducers (Figure 2.4.2.1).

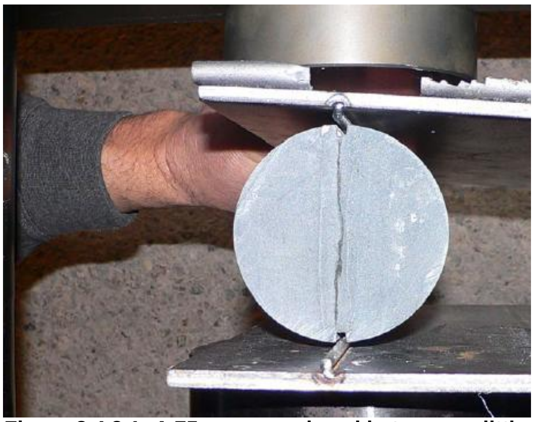


Figure 2.4.2.1: A 75mm core placed between splitting plates

Preparation of S9&S10

Sample 9 and 10 were prepared as natural non-matching surfaces. Cobbles with flat surfaces were chosen from the provided rocks to ensure that the contact surface area approximates the area of the sample. This was done because in this research, true contact area isn't taken into account. Both halves of Sample S9 were prepared from the same rock. Many of the received Bremanger cobbles have at least one or two flat surface(s) and therefore it was interesting to gather data on shear stress behavior of these natural surfaces. The two sample halves of S10 had a calcite layer on top and were therefore tested in order to see if this layer modified the rock's shear stress behavior.

2.5 Performed tests

Sample	direct Shear box tests						UCS	BTS	PLT
	Smooth polished discontinuities		*Fresh tensile crack*		*Non matching Smooth natural*				
S1	⊥	dry 50, 100, 250, 500, 1000							
S2	//	dry 50, 100, 250, 500, 1000							
S3			//	dry 50, 100, 250, 500, 1000					
				wet 1000					
S4							2 // 2 ⊥	4 ⊥ //	
S6			//	dry 100, 250, 500,1000			2 // 2 ⊥	6 ⊥ // 4 // ⊥	
				wet 100, 250, 500, 1000					
S7			⊥	wet 50, 100 250, 500, 1000			1 // 1 ⊥	2 // ⊥ 2 // //	
				dry 50, 100, 250, 500, 1000, 500					
S8			NV	wet 1000, 500, 250, 100, 50, 1000			1 NV	3 NV	
S9					//	dry, 50,100, 250, 500, 1000			
S10*					//	dry, 50,100, 250, 500, 1000			

S10*: Non matching smooth natural surfaces with a top layer of calcite.

Chapter 3: Results

Methodology

The recorded direct shear box data is presented in Appendix 3. The recorded data was corrected for horizontal and vertical displacement. Since all the tested samples are rectangular horizontal correction is straightforward as horizontal displacement is measured. Corrections for dilatancy are also taken into account using the following correction equations proposed by Golder Associates (1984).

$$\tau_i = (\tau \cos i - \sigma \sin i) \cos i$$

$$\sigma_i = (\sigma \cos i + \tau \sin i) \cos i$$

In which i is the angle between the sample failure plane and the horizontal shear plane. It is calculated from the vertical displacement vs. horizontal displacement graphs (Appendix 3).

3.1 Determination of the basic friction angle on saw-cut surfaces

The basic friction angle of the Bremanger rock was determined by performing direct shear box tests on flat diamond saw-cut surfaces (Barton & Choubey, 1977). The shear stress vs. horizontal displacement curve never reaches a constant residual shear stress value for S2. Instead, shear stress values keep increasing over the complete length of horizontal displacement (see Appendix 3.1). Therefore, the residual stress value is chosen arbitrarily at 6 - 8 mm of displacement. The shear stress data of sample S1 does tend to go to a relatively stable residual strength value. Residual shear stress values were plotted against different normal load steps and a trendline was fitted to the data to calculate the basic friction angle.

Figure 3.1.1: determination of basic friction angle on saw-cut surfaces.

The results of the shear box test result in a basic friction angle of [redacted] degrees for sample S1 and [redacted] degrees for sample S2. The higher angle for sample S2 has to do with the fact that during the testing of sample S2 shear stress data kept raising extremely strong compared to sample S1 and never reached a residual stress level (strain hardening). It is therefore not likely that this is a good estimate of the basic friction angle. As described by Barton & Choubey (1977) basic friction angles for sandstones are almost always between 25 and 35 degrees. In this experiment it is believed that the friction angle is more an indication of the polishing process rather than a good estimate of the rock itself.

3.2 Determination of the residual friction angle of fresh tensile cracked samples

To determine the residual friction angle of the Bremanger Sandstone multiple tests have been performed on fresh tensile cracks. The residual friction angle is used to describe the rock's shear strength behavior since the results indicate that the peak friction angle seems to be non-representative. Multiple experiments lead to exceptionally high peak shear strength values (for example S8-sat-1000KPa and S7-dry-1000KPa, Figure 3.2.1). This can be explained by the fact an asperity at the edge of one of the sample halves makes horizontal displacement impossible and induces a high shear stress build-up. As soon as a chip of rock broke off; stress levels 'normalize' to a residual value. Therefore the residual shear-stress levels and the resulting residual friction angle are thought to be more representative for the Bremanger Sandstone. As dilatancy did not cancel out for the range of horizontal displacement applied, the stresses were corrected for dilatancy.

Figure 3.2.1: Multiple loading stages for different samples.

Individual graphs for the different samples can be found in Appendix 3. One can conclude from these graphs that even the residual stress values not always stay constant. In order to compare results for different samples, residual stress values were chosen at 8mm. In cases where testing was discontinued before 8mm of horizontal displacement was reached, the last relevant measurement was used as the residual stress value (for example S3-dry-50KPa, Appendix 3.2 residual shear stress was measured at 5,918mm).

Figure 3.2.2 shows a graphical summary of the residual shear stress values corrected for dilatancy. All the shear stress data is combined and a 'best fit' trend line was plotted assuming zero cohesion. This leads to an average residual friction angle of [redacted] degrees. A summary of individual residual friction angles of each sample is given in Appendix 3.4. They vary from [redacted] to [redacted] degrees.

[redacted]

Royal Boskalis Westminster nv

Figure 3.2.2: All shear stress vs. normal load data of samples S3, S6, S7 and S8.

3.2.1: Influence of rock strength (UCS)

Figure 3.2.1.1 shows the shear stress vs. horizontal displacement for different samples at multiple normal load stages. Figure 3.2.1.2 shows the UCS data for the same samples. From the graphs one can immediately see that the UCS values of the rock are directly related to the shear stress data. The higher the UCS value, the higher the shear stress values. In the graph it's also visible that sample S8 has one extremely high peak shear stress value during the 1000KPa loading stage. This was caused by the sample being stuck until a piece of rock broke off resulting in a sudden horizontal displacement of about 4mm.

Figure 3.2.1.1: Shear stress behavior of samples S6, S7 and S8.

Figure 3.2.1.2: UCS values corresponding with the samples as shown in figure xxx.

3.2.2: Influence of rock strength (Graphically)

After each loading stage (50, 100, 250, 500, 1000KPa) a picture was taken of both sample halves. These photographs are used to compare damage caused by the grinding of the sample to the shear stress behavior of the rock. All pictures are collected in Appendix 5.

As expected the rock is smoothened due to shearing at high normal loads. The grinding of the joint interface increases as normal load increases. When the pictures of sample S7 are compared to the 3D Leica images and data, we can see that the surface roughness (proposed as a ratio between true surface area and projected surface area) decreases after a series of tests (Appendix 5 and 6). Furthermore, figure 3.2.2.1 shows that grinding of the rock does not occur along the complete surface of the sample. Certain true contact areas exist and the grinding of these contact areas increases as normal load is increased.

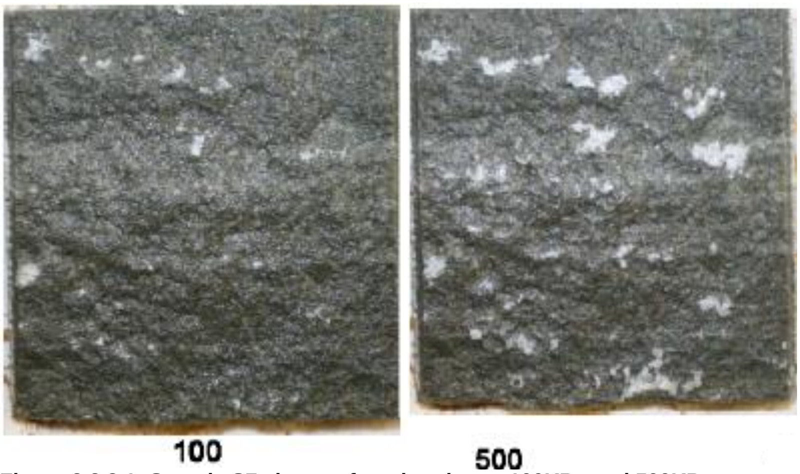


Figure 3.2.2.1: Sample S7 shown after shearing at 100KPa and 500KPa.
As normal load increases, the true contact areas show more grinding of the rock.

When the pictures of sample S6 and S8 are compared to their UCS values, one can observe that sample S8 shows more damage than S6. S8 is also weaker than sample S6 in UCS test conditions. From the few results a relation between UCS and sample damaging is assumed. The weaker the rock, the easier asperities are grinded off.

3.2.3: Influence of multiple loading stages

Sample preparation for the Golder Shear Box is a very much time consuming process. Therefore multiple loading stages were performed at the same sample. In order to keep track of possible errors in the measurements sample S7 was tested in saturated conditions first. After that the sample was tested in dry conditions from 50 to 1000KPa and finally at 500KPa again. Sample S8 was tested in saturated conditions only. First it was tested from 1000 to 50 KPa and then at 1000KPa again. Some of the results are plotted in figure 3.2.3.1 (For detailed test data, see Appendix 3).

Figure 3.2.3.1: Multiple loading of samples S7 and S8.

The graph shows that peak shear stress values differ when a sample is re-loaded at a certain normal load. Meanwhile the residual stress stays about the same after multiple loading stages. When these results are compared to the pictures of the damage study it is concluded that the damaging of the sample takes place before the peak shear strength is reached and that the residual shear stress level is based on the sample surfaces sliding along each other.
Due to the fact that peak shear stress values differ in multiple loading stage tests, it is only fair to use the residual stress levels.

3.2.4: Influence of water

Figure 3.2.4.1 shows the relation between dry and saturated samples S6 and S7. As can be seen in the graph, the shear strength of the rock is not influenced by the presence of water. Sample S6 was first tested in dry conditions while sample S7 was first tested in saturated conditions before repeating the loading stages in dry conditions. One can observe some differences in peak shear stress values between dry and wet conditions for the same sample. This can be explained by the fact that when multiple tests are taken on the same sample, the rock asperities are grinded off and the overall joint surface is smoothened. For example during the S7-dry-1000KPa test, a chip of rock broke off resulting in a lower peak shear stress during the S7-sat-1000KPa test. Residual shear strength values tend to go to the same level in both dry and saturated conditions.

Figure 3.2.4.1: Influence of water saturation on shear stress behavior of samples S6 and S7.

3.3 Determination of the residual friction angle of natural non-matching smooth surfaces

3.3.1: Natural non-matching smooth surfaces

Sample S9 was prepared as two non-matching smooth natural surfaces. The corrected shear stress vs. horizontal displacement curves show no residual stress levels (continuous strain hardening, Figure A3.3.3). To compare it with the fresh tensile cracks the 'residual' stress value was measured at 8mm displacement. This leads to a residual friction angle of [redacted] degrees (Figure 3.3.1.1).

Figure 3.3.1.1: Residual friction angle of sample S9.

This corresponds to the expectation that the friction angle decreases when a sample becomes smoother and the number of asperities decreases. This expectation is proved by the use of the 3D Leica images that return a Ratio of true area to projected area of 1.091 compared to a ratio of 1.235 for sample S7 and 1.163 for sample S8 (Figure 3.3.1.2).

Figure 3.3.1.2: Residual friction angle vs. Area ratio. When the ratio decreases towards 1, the residual friction angle decreases as well.

3.3.2: Natural non-matching smooth surfaces with calcite layer on top

While selecting the Bremanger cobbles it was noticed that some of the rocks had a calcite layer of a few millimeters on the outer surface of the flat surface. In order to check whether this calcite layer is of influence on the rock's shear stress behavior a direct shear box test series was performed on a sample of this kind. The result of this test is presented in figure 3.3.2.1 .

When the same procedure as for the other samples is applied one can see that the linear trendline (assuming 0 cohesion) does not fit at all (blue line). The resulting residual friction angle in this case is [redacted] degrees.

If we assume that the 1000KPa test on this sample went wrong, a linear fit of the remaining is clearly possible (black line). This leads to an even higher residual friction angle of [redacted] degrees.

Another possibility is that below a normal load of about 500KPa, there is some other process which is controlling the shear stress behavior. In this case we assume that the green line gives the right relation which leads to a residual friction angle of [redacted] degrees. This is a risky assumption since no test data is available for normal loads higher than 1000KPa. More tests would be necessary to draw final conclusions.

The fourth possibility is that a material properties of calcite lead to a non-linear shear stress vs. normal load behavior. A non-linear fit is proposed in red.

Figure 3.3.2.1: Multiple fitting options for sample S10 with a calcite layer at the shearing interface.

Chapter 4: Conclusions & Recommendations

Mineralogy
The Bremanger sandstone is a Metasandstone which is a sandstone that has undergone some metamorphism. Due to the metamorphism the mineralogy of the matrix and cement has changed. Macroscopically the texture of the sandstone hasn't changed, the layering is still visible but cleavage during sample preparation does not occur along this visible layering.

Basic friction angle
Determination of the basic friction angle did not work out as supposed to. Due to the high rock strength of the Bremanger it was impossible to saw-cut smooth matching surfaces. Therefore the sample halves had to be polished in order to make them match. This leads to a basic friction angle that rather reflects the polishing process than the rock properties in shear box testing. It would be interesting to sandblast the samples as proposed by Barton (1971) but one has to take care that the rock's true granular texture is exposed and that micro-cracking susceptible to weaken grains, are not present below the sand blasted surface.

Residual friction angles: Fresh tensile cracked surfaces
The residual friction angles of fresh tensile cracked samples were obtained by using a Golder shear box. Multiple tests were performed on the same sample; 50, 100, 250, 500 and 1000KPa. For all samples together this leads to an average residual friction angle of [redacted] degrees with individual friction angles varying between [redacted] (S8-saturated) and [redacted] degrees (S6-dry).

The following conclusions can be drawn from the shear box tests on fresh tensile cracked samples:

- Peak shear strength values do not represent the true shear strength of the tested rock samples. High peaks are caused by asperities at the edges of the tested samples. As soon as the asperity broke off, the shear strength dropped massively.
- The Golder shear box is of good use in obtaining residual shear stress values of rock samples in many cases. Sometimes during a direct shear test, no residual stress level is observed within the limited displacement range of ~10mm. Therefore the residual stress level is always measured at 8mm of horizontal displacement. Even if no residual stress level was obtained. It would be interesting to do some research on how the used experiment setup can be scaled-up. In that case residual stress values can be measured more accurately.
- Multiple shear box tests can be performed on the same rock sample to limit the time consuming sample preparation process. Although peak shear stress values started to differ when multiple tests were performed on the same sample, the residual values stayed nearly the same during the complete 50-1000KPa test series.
- The UCS values of individual rock samples are directly related to their shear stress behavior. The higher the UCS value the higher the residual stress value. It is also graphically observed that softer rock samples in UCS conditions show more grinding and larger damage zones in the pictures taken after each normal load stage.
- The 3D Leica images show that the discontinuity surface is smoothened and asperities are grinded off due to shear box testing. They also show that there are high damage zones and low damage zones. It is concluded that there are only a few contact points

during shearing. To get more insight into this, one should calculate the area size of the damage zones after each test.

- Because the Bremanger is going to be used as a seawall protection layer and along the seaside in wet climatic conditions, the rock was also tested in saturated conditions. It is concluded that the saturation of the rock does not influence the residual shear stress values because in dry and saturated conditions the residual stress values tend to go to the same level.

Residual friction angles: Non matching smooth natural surfaces
A natural non-matching smooth surface was tested as well to get an insight in shear stress behavior of the Bremanger after weathering and smoothening. As expected the residual friction angle drops and comes out at [redacted] degrees. When sample S9 is compared to samples S7 and S8 in 3D Leica pictures it is clear that sample S9 is smoother than the other two.

Finally a natural smooth non-matching surface with a calcite layer on top was tested. The results of the shear box tests show strange behavior since the highest load (1000KPa) is out of line with the other shear strength values. Residual friction angles vary from [redacted] and [redacted] to [redacted] for different interpretations. Another series of test on a sample with calcite layer on top is preferable to draw final conclusions.

Appendices

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