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# Interface Strength of Rock Discontinuities

## Based on Experiments Conducted Using the Direct Shear Box

TU Delft

# Interface Strength of Rock Discontinuities

## Based on Experiments Conducted Using the Direct Shear Box


By

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TU Delft

# Preface

This report serves the purpose of outlining and focusing on the research done by a student from Delft University of Technology. The research topic focuses on the concept of interface strength of rock discontinuities through shearing experiments. These experiments were conducted as a part of clarification for certain parts to a more elaborate project concerning rock fracturing in the Applied Geophysics and Petrophysics section in Delft University of Technology.

Readers interested in obtaining more insight to direct shear experiments and the basic concepts of rock interfaces and discontinuities can refer to the sections to come in this progress report. The equipment used throughout these experiments were utilized in a somewhat unconventional manner which have proven to provide elaborate and relatively precise results.

*Delft, October 2017*

# Abstract

The aim of this project is to focus on the effect of mechanical contrast and surface roughness as factors influencing the shear strength of the interface of different rock samples. The shear strength of an interface is significant in experimental projects that for instance address the containment and propagation analysis of hydraulic fractures.

A discontinuity can be defined as any type of interruption in mechanical and structural properties of a rock layer. The samples used in this project are mechanically discontinuous at the interface. These samples consist of 3 different sandstones, one granite and one monzodiorite samples. These samples were prepared to fit a certain casket that was specially designed for this project. The mechanical contrast between pairings of these samples were obtained through calculations for difference in unconfined compressive strength between the rock types. The samples were then placed in a direct shear box and sheared against each other to obtain shear force and vertical displacement profiles while under a specific normal load.

In three different sets of experiments, specific pairings of samples were analysed and processed. Each pairing showed a unique set of results which were then compared with one another. Each experiment set focused on a certain aspect. The first set of experiments focused on the effect of mechanical contrast. The second experiment set focused on the change in surface roughness caused by shearing at higher loads. The third set focused on the effect of predetermined changes on surface roughnesses and how this would affect the shear stress profiles.

The values obtained through these experiments were then mathematically processed and shear stresses and normal stresses were plotted against each other. From these plots the friction coefficients and angles of friction were calculated.

The results show that mechanical contrast has a direct effect on the shear stress profiles. A constant mechanical contrast of two different pairings of samples results in the same trend no matter what rock types were used. In other words, if two different pairs are sheared against each other with each pair having the same mechanical contrast, the shear stress profiles will have the same friction coefficient. The surface roughness also directly effects the shear stress profiles. The results showed that the higher the measure of surface roughness, the higher the shear stress will be. The predetermined surface roughnesses of the samples were 125 and 75 μm.

# Acknowledgements

First and foremost, I would like to thank Dr. A. Barnhoorn for his constructive assistance and patient guidance throughout this project. The time spent by Dr. Barnhoorn on advising and guiding me through this project is sincerely appreciated.
I would also like to thank Dr. Ir. D. J. M. Ngan-Tillard for accepting to be my second supervisor and for contributing this project.
I would like to thank Ing. W. Verwaal, the lab technician involved in this project, who has not only helped me with the experiments but has also given me much insight to the basic concepts behind these experiments. It goes without mentioning that other lab technicians such as J.J. van den Berg, J.G. van Meel and A. Mulder, who have helped in this project are equally appreciated.
I would lastly like to thank L.A.N.R. Douma, without whom this project would have not been possible. Her constant presence and assistance, patience and constructive guidance is sincerely appreciated.

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# Introduction

In modern applied geophysics and petrophysics, multiple experimental studies focus on the interface strength of rock discontinuities (Simonsom et al, 1978). For example, experimental studies in fracture containment and simulations of hydraulic fracturing in low permeability reservoirs. Shear strength or interface strength of rock discontinuities is an important factor in such experimental studies as it has direct effect on the propagation of fractures once reaching different interfaces. A discontinuity can be defined as an interruption of structural or mechanical properties of rock layers. An example of a discontinuity is a fracture. To simulate the shearing of different rock interfaces in order to have an understanding of the growth and containment of these fractures is of great significance in the mentioned experimental studies. The propagation of hydraulic fractures from a low-modulus to a high-modulus material would be interrupted at the interface of the two different materials due to the fact that the intensity of the stress approaches a measure of zero near the interface (Simonsom et al, 1978).

The objective of this report is to analyse and understand the effect of mechanical contrast and surface roughness on the shear strength of an interface. Due to the fact that a discontinuity is an interruption in mechanical properties, it is important to observe how mechanical contrast affects the shear strength of the interface at that discontinuity. The surface roughness of interfaces can also have direct effect on the shear strength of an interface and is therefore important to analyse (Teufel and Clark, 1981).

Interface strength is a significant subject to be analysed in projects that focus on hydraulic fracture growth and containment. In such projects the factors influencing the interface strength are therefore of great significance (Teufel and Clark, 1981). These factors may affect the propagation of fractures and ultimately the containment methods.

Chapter 1 of this report focuses on the theoretical approach behind the concept of shearing and the mathematical approach behind the analysis of the results obtained through the previously mentioned experiments. Chapter 2 addresses the material preparation and equipments used throughout the experiments. This chapter also discusses the different types of experiments done throughout this project and the methodology behind them. Chapter 3 shows the results obtained through the previously mentioned reports. Chapter 4 of this report discusses the results and analyses the dependability of the results on the factors in question. Chapter 5 concludes the report and offers recommendations for further analysis of the subject in question.

# 1. Theory

*This chapter focuses on the theoretical approach and the general methodology behind the experiments done throughout this project. The first subchapter addresses the main theory behind discontinuities and shear strength of rock interfaces. The second subchapter addresses the applicable side of shear experiments such as the mathematical approach behind calculations and how and where the results would be applicable.*

## 1.1. Theory and Definitions

The term discontinuity can be defined in numerous ways and has been through various research papers (Hencher and Richards, 2014). In this report, the term discontinuity is defined as any sort of interruption or change in a rock's structural and mechanical properties. Examples of these properties are stiffness, density and strength (ATSM, 2008a).

The degree of incipiency of a discontinuity is defined as the measure of how mechanically uniform a boundary between two rocks is (Sheng et al, 2015). A full mechanical discontinuity is defined as a complete interruption of mechanical properties between samples. The degree of incipiency is an important factor as it has a direct effect on cohesion and tensile strength. The samples used throughout this project can be described as mechanically discontinuous at the interface which means that they have no true cohesion.

A shear test consists of several predefined concepts that need to be discussed before the results of a shear experiment can be analyzed. The first concept is the application of shear stresses and normal stresses in shear experiments. As it will be elaborated upon later, in the experiments done throughout this project two frames containing samples will be sheared against each other with a certain normal load applied on top of the frames. A certain shear displacement also known as horizontal displacement will then be recorded. Theoretically, an experiment will result in the obtainment of a shear strength versus horizontal displacement graph (Fig. 1). This graph has a peak strength and will continue to plateau out as residual strength. It is also expected in theory that once the shear stress is plotted against the normal strength a certain linear trend must be observed at a certain slope which is defined as the angle of friction (Hencher and Richards, 2014).

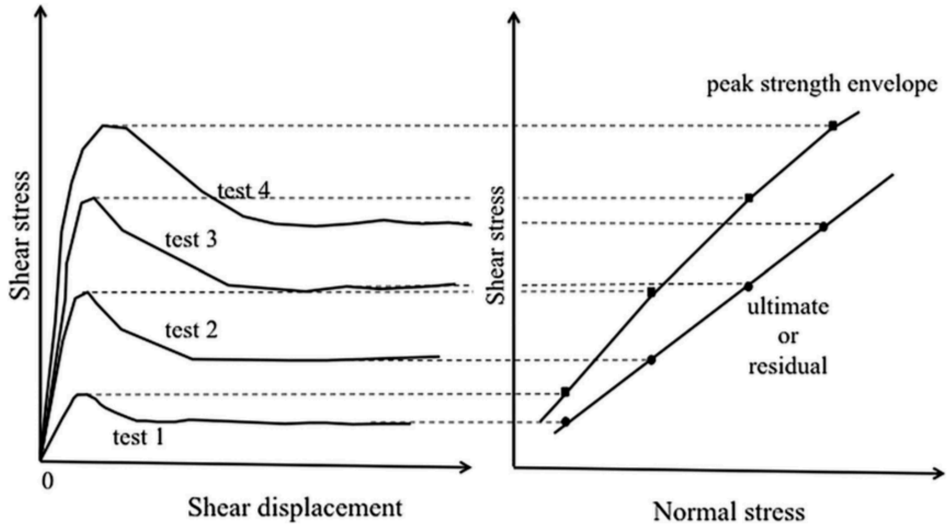


Figure 1: Example of 4 different shear tests and the obtained results
Adapted from *Assesing the Shear Strength of Rock Discontinuities at Lboratory and Field Scales* (p. 888), by S. R. Hencher and L. R. Richards, 2014.

Certain factors are of significance when it comes to contributing to the shear strength of a specific rock type (Hencher and Richards, 2014). Examples of these factors are the roughness of the interface and textural friction. The concept of textural friction addresses the adhesion at the contact areas between the two or more interfaces being tested. This concept contributes to the frictional resistances once the samples are being sheared against each other. This resistance leads to the deformation of the contact area in question. The deformation can consist of changes in roughness of the interface. This deformation can result in a change in the direct results of a shear test such as shear strength of the interface and the vertical displacement that the samples may experience.

Due to the fact that surface roughness acts as a significant factor in the determination of shear strength, it is important to note that with increasing surface roughness, the coefficient of friction increases (Teufel and Clark, 1981). The effect that change in surface roughness can have on the outcome of shear experiments is shown in Fig. 2. As it can be seen, with increasing roughness the measure of shear stress increases within periods of constant normal stresses.

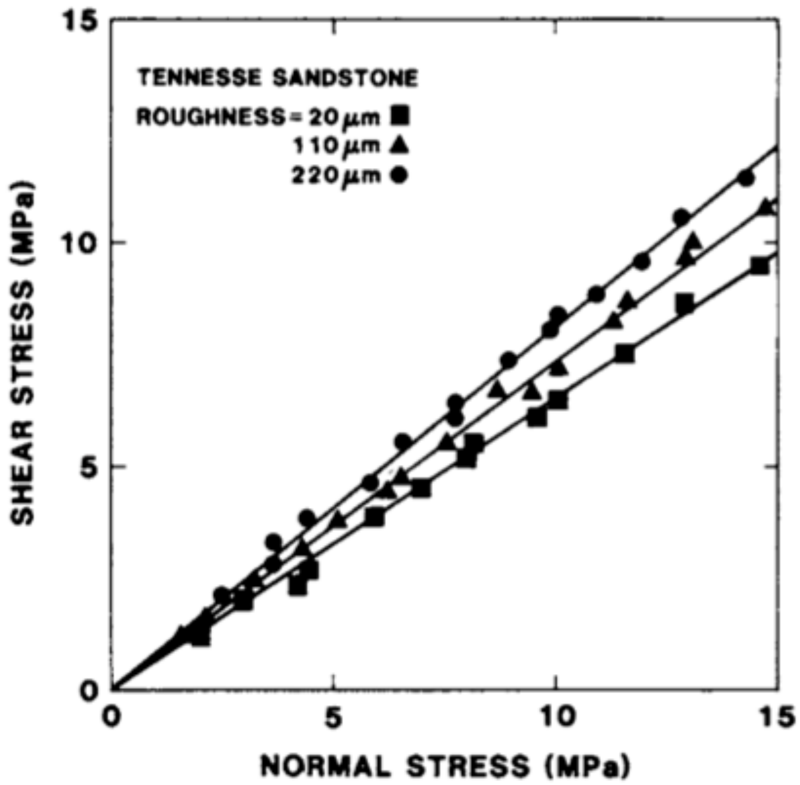


Figure 2: The effect of change in surface roughness on shear stress
Adapted from *Hydraulic Fracture Propagation in Layered Rock: Experimental Studies of Fracture Containment* (p. 24) by L. W. Teufel and J. A. Clarck. 1981.

Despite the fact that shear tests in laboratories usually have expected outcomes such as a unique friction angle and shear strengths for a certain rock type, one must realize that these results need to be adjusted before direct comparison to a real-life geological situation. Discontinuities in real time field experiments such as fault planes or landslides are far more complex compared to the interfaces of two saw cut core samples tested with predetermined and uniform mechanical properties. This has to do with the concept of degree of incipiency. To elaborate, one must realize that a landslide or a fault plane has a much higher degree of incipiency compared to samples used in the laboratory as they are not fully discontinuous in a mechanical sense.

## 1.2. Mathematical Approach

The shear stress across an interface is highly dependent on cohesion and frictional properties of the interface. The shear strength of a certain rock type can be defined following Eqn. 1.

$$\tau = c + \sigma_n \tan(\phi) \qquad (1)$$

In equation 1 the parameters $\tau$, $c$, $\sigma_n$ and $\phi$ are shear strength, cohesion, normal stress and angle of friction respectively (Hencher and Richards, 2014). The tangent of $\phi$ as one parameter is also known as the friction coefficient. Therefore, the same formula can be written in a second manner where $\mu$ is the coefficient of friction as illustrated in Eqn (2) (Teufel and Clark, 1981).

$$\tau = c + \sigma_n \mu \qquad (2)$$

Throughout this project, the calculation of the shear and normal stresses was done through the following equations;

$$\tau = \frac{F_s}{\mathrm{A}} \qquad \text{and} \qquad \sigma_n = \frac{F_n}{A} \qquad (3)$$

where $F_s$, $F_n$ and $A$ are shear force, normal force and contact area respectively.

The samples used in this project have no apparent cohesion as far as the interfaces between the samples is concerned. This means that the shear strength is purely dependent on the angle of friction. The angle of friction can be determined by obtaining the slope of the linear fit that would run through the recorded shear stress vs normal stress gathers. This will be discussed in more detail in chapter 3.

In summary, the application of the theoretical concepts featured in this chapter to the results that are to be presented in this report is quite evident. The influence of surface roughness on interface strength and the expectation of linear trends in shear stress versus normal stress are examples of concepts that have continuously and crucially affected the decision-making process throughout this project. Such details will be discussed further in chapter 3.

# 2. Materials and Methodology

*This chapter addresses the materials used in the shear-box experiments done throughout this project. Further on, the description of the experiments is elaborated. The first subchapter addresses the different samples and the pairing of samples for experiments. The second subchapter addresses the setup description and objectives of the different experiment sets.*

## 2.1. Sample Material and Preperation

The samples used throughout this project consist of five different rock types. These rock types each have their unique properties. Three different sandstone samples, one Benin granite and one monzodiorite sample were used. The sandstone samples consist of Red Felser, Bentheim Sandstone and Ainsa which is believed to be a metamorphosed sandstone.

The mineralogy and composition of the samples were not studied in great detail. However, as it can be seen in Figure 3, the Red Felser (RF) and Bentheim (BH) samples both show an abundance of Quartz grains. The granite (GR) sample consists of minerals such as Quartz and other minerals of the Plagioclase and Alkali Feldspar groups. The Ainsa (AI) sample consists of Quartz grains and Muscovite. The last sample was characterized to be a monzodiorite due to the abundance of plagioclases and the lack of quartz. The mafic mineral existing in this sample is Hornblende. The minerals were characterized with the usage of microscopic images and a magnifying glass.

The samples were cored in cylindrical formats and were then cut on the top and bottom faces in order to fit properly in the designed casket. The polishing of each sample is described in the next section since it was polished differently per stage. Examples of these samples and the way they were cut are shown in Figure 4.

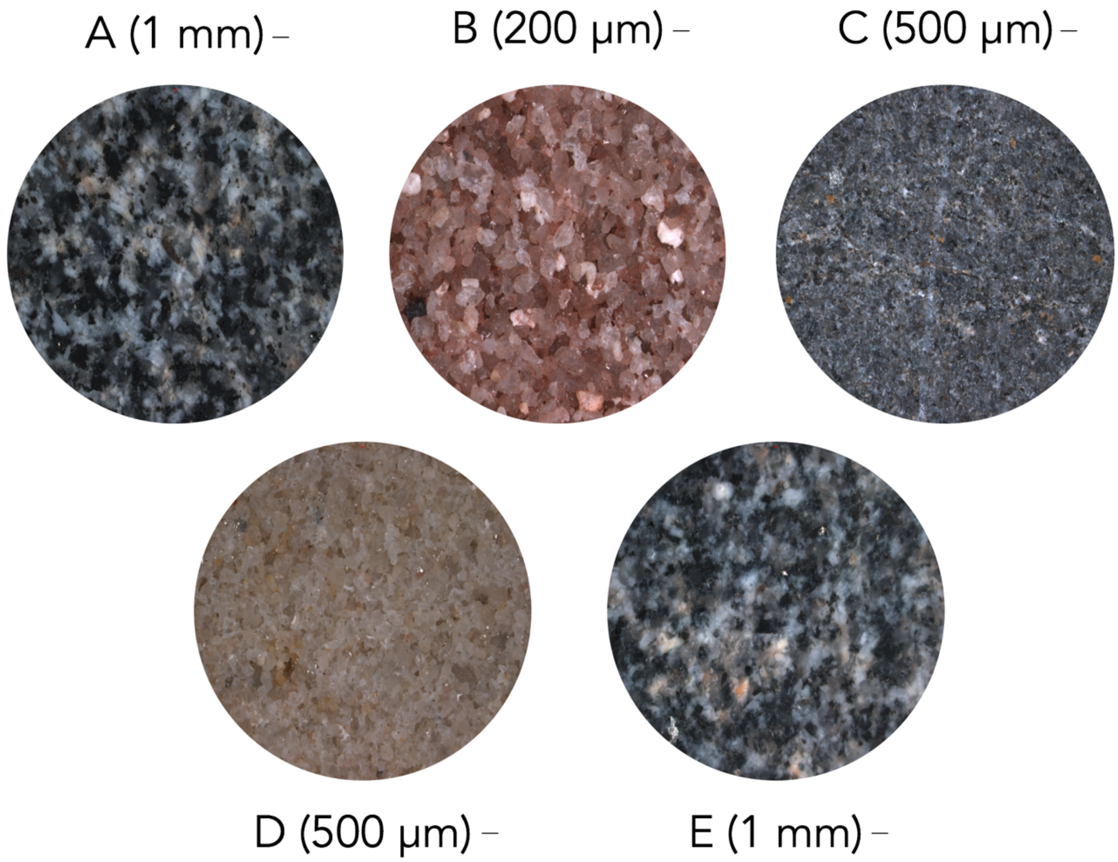


Figure 3: Microscopic images of all samples and scale of the images. A: GR, B: RF, C: AI, D: BH, E: MD

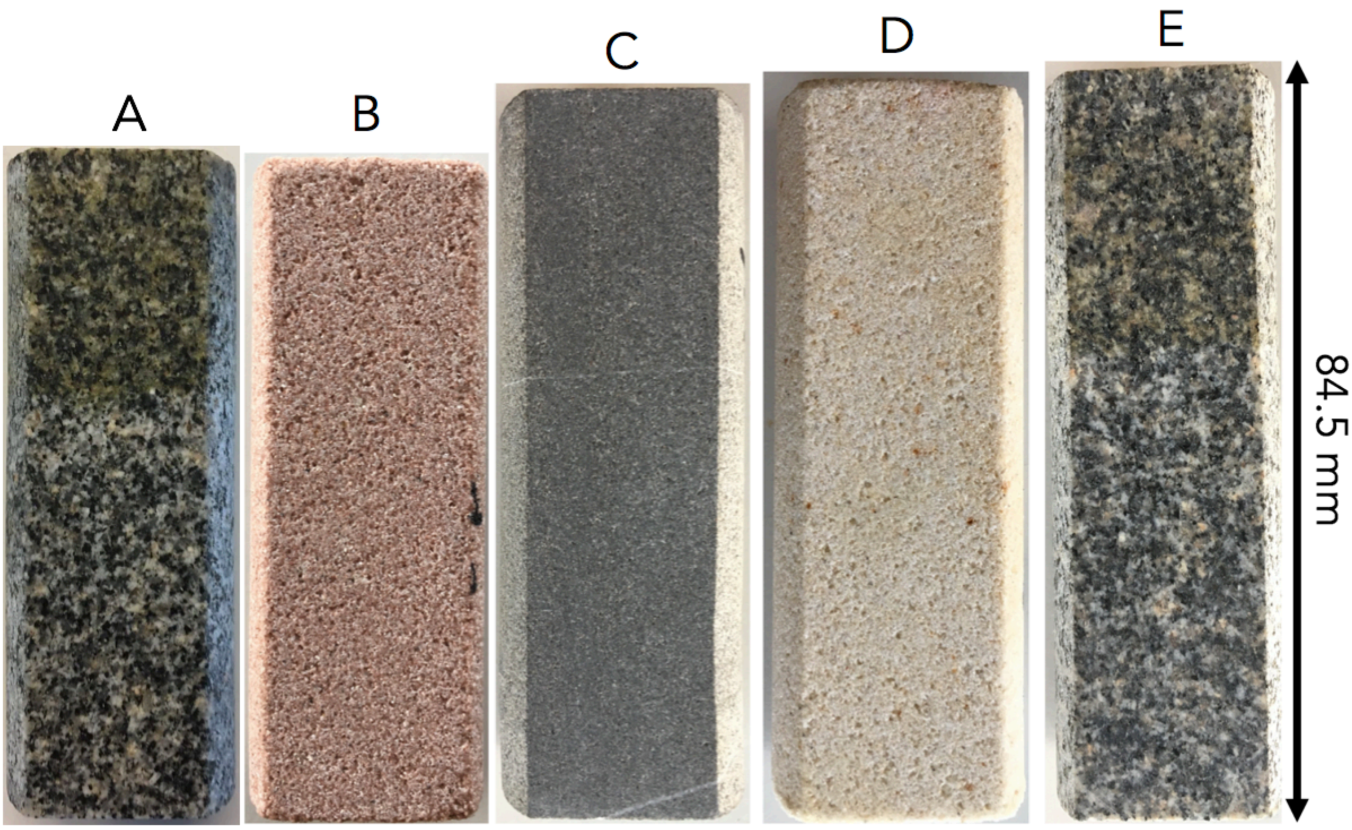


Figure 4: All samples and scale. A: GR, B: RF, C: AI, D: BH, E: MD

The samples were tested in several manners namely in pairs of two different rock types to analyse the shear strength of two different interfaces. They were also tested in pairs of the same rock type in order to solely focus on the interface properties. The ratios of mechanical contrast between these samples are illustrated in Table 1. These values are based on the difference in unconfined compressive strength between the two rock types. The strength of the monzodiorite is believed to be the same of the granite sample and so it would have a similar mechanical contrast with other samples paird with granite in Table 1.

Table 1: Mechanical Contrast Ratios

| | |
|---|---|
| RF vs BH | 1.3 |
| AI vs BH | 4 |
| AI vs GR | 1.2 |
| GR vs BH | 4.9 |
| GR vs RF | 6.2 |

The weight and dimensions of each sample were measured before each experiment. The dimensions were used to calculate the area of each interface. These values are presented in Appendix 2. The results of these measurements are of great significance to the calculation of stresses in chapter 3.

## 2.2. Experimental procedure and Setup Description

The main objective of the tests is to determine the shear strength of planar discontinuities between different rock types. The results obtained directly from the shear test consists of two profiles. The first profile is the total shear force versus the horizontal or normal displacement. The second profile is the vertical displacement vs the horizontal displacement. The purpose of the shear box tests is to determine the shear strength of these discontinuities as an absolute function of the normal stress applied to the plane of shearing.

The usage of the direct shear-box consists of several parts which are briefly discussed in this paragraph. These first part is the setup which consists of a mould or frame in which the samples are placed. The second part is a system with which a normal load can be applied perpendicular to the plane of shearing. The next part is a system that applies the force to shear the samples against one another. The last part consists of three micrometre dial gauges using which shear, horizontal and vertical displacements can be measured. These parts are illustrated in Fig. 5A. The load applying system consists of two parts. One which directly applies a certain weight and an arm which applies load with momentum with an arm factor of 10.28. This system is illustrated in Fig. 5B.

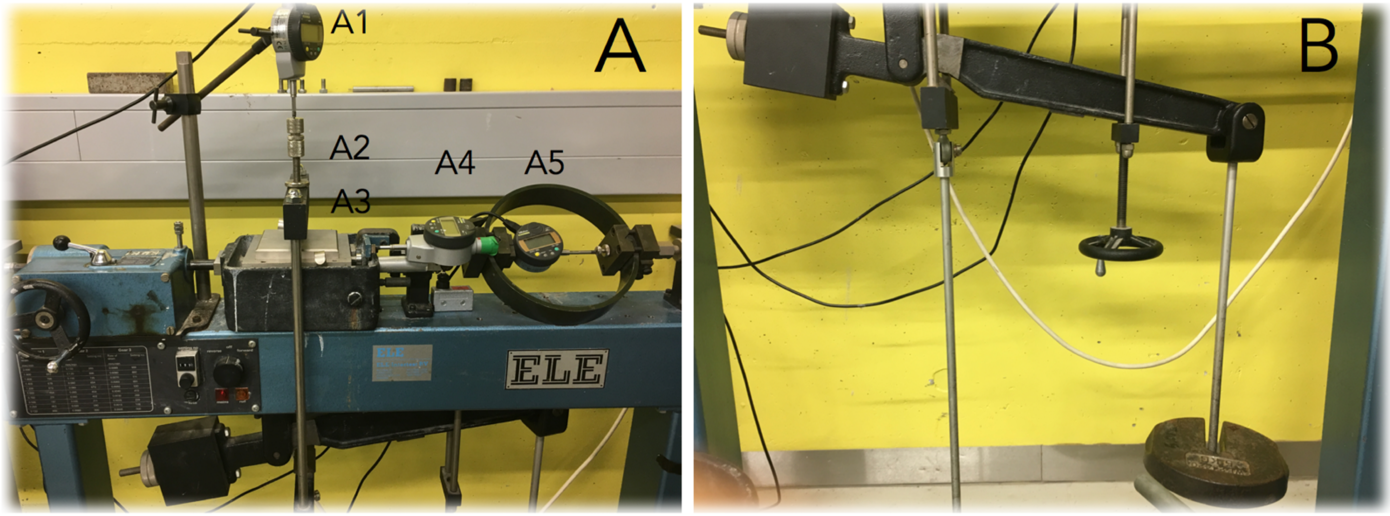


Figure 5: Direct Shear-Box and Normal Load Applying System
5A: A1: Micrometer dial gauge measuring vertical displacement. A2: Weight hanger. A3: Frame and Casket. A4: Micrometer dial gauge measuring horizontal displacement. A5: Micrometer dial gauge measuring shear force.
5B: Load applying arm

The system applying the force to move the frames and shear the samples is adjustable in terms of the rate at which it applies the force and at which speed the frames move against each other. For the experiments conducted throughout this project the same setting was used which is the first gear of the shear box with the setting number set to 197 which has a rate of strain of 0.5 millimetres per minute.

Due to the fact that the direct shear box is commonly used for soil samples rather than rocks, a special casket was designed to hold the rock samples within a frame. The specifics of this casket are further elaborated on in Appendix 1. The casket and the frame can be seen in Figure 6. This casket functions as a mean to stop the samples from moving sideways or in other words wobbling within the frame. As it can be seen, the top casket is mounted on the top frame and with the samples they can be placed in the shear-box.

Once the samples are placed in the caskets and the frames are set in position in the shear-box, the normal load applying system is put in place and the gauges are set in position. The next step is to have a zero reading on the gauges and to manually apply shear using the handle to observe that the shear is indeed being recorded. The frames will then be brought back to the original position with the zero reading and the machine is set in gear to begin the experiment. While shearing the values on the gauges will be recorded by a computer and two graphs will appear. The first graph shows shear force (N) vs horizontal displacement (mm) and the second graph illustrates the vertical displacement (mm) vs horizontal displacement (mm). The machine shears the samples at a constant rate against each other. Disturbances in the rate of shearing is possible due to the stick and slip effect.

As explained in the first chapter the shear will peak to a certain value and begin to approach a residual value that is of less or the same value as the peak. At higher stresses, however, the values after the peak can be of greater value. The results obtained from these experiments will be shown in the mentioned format throughout chapter 3.

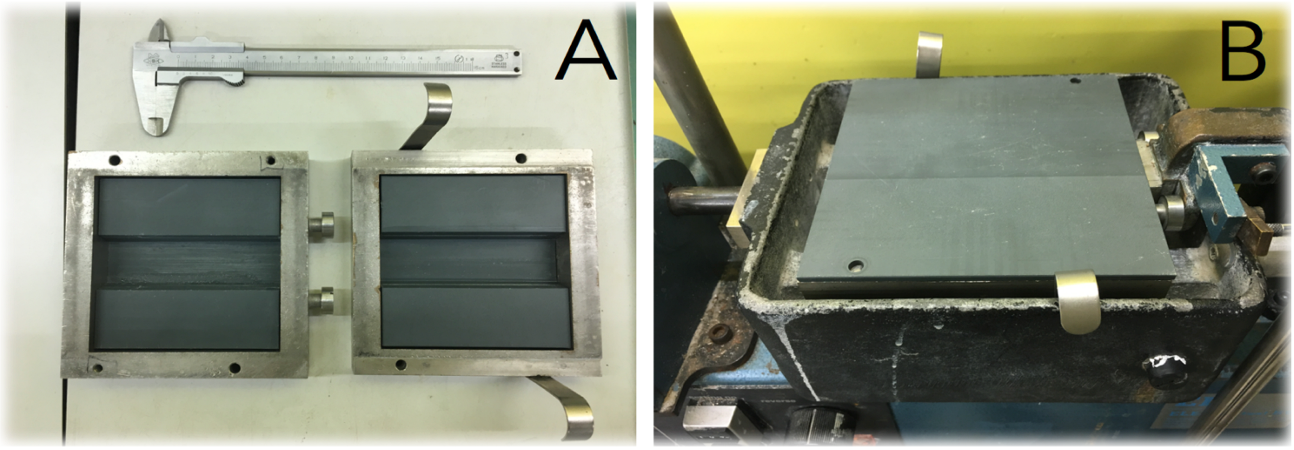


Figure 6: A: Casket inside the frame. B: Casket and frame inside the shear box

## 2.3. Experiment Sets

The conducted experiments consist of three different sets. The first set consists of two stages with different levels of normal loads applied. The second set was conducted as a continuation to the first set. The results obtained from this set of experiments showed patterns of changes in surface roughness. These changes were then further analysed and became the main focus of the second set of experiments. The third set was conducted to focus on the effects of changes in interfaces by polishing of the interfaces. Each set is discussed briefly in this section and the results are further discussed in chapter 3. All experiments were conducted twice for clarification and error mitigation.

The first set of experiments were done using the pairs shown in Table 2. These samples were used in the first stage of this experiment set. In this stage, the normal load profiles are low compared to the normal load profiles of the second stage. These samples sheared against each other with 6 different normal loads applied.

Table 2: Sample pairings, first part of experiment set 1.

| |
|---|
| RF vs BH |
| AI vs BH |
| AI vs MD |
| MD vs BH |
| GR vs RF |

The second stage of this set of experiments was done on three different pairs being Granite versus Ainsa, Monzodiorite vs Bentheim and Bentheim vs Red Felser at relatively high normal stresses in order to observe the behaviour of these samples at higher stresses. The choice of samples was solely based on the difference in mechanical contrasts. The focus of this stage was to compare shear strengths of pairs based on the measure of mechanical contrast at higher normal loads.

The second set of experiments was originally a continuation of the first set with higher normal stresses. Upon repeating the experiments as a mean of error mitigation, the shear force profile showed higher values. This was indicative of a change in the interface. Once the results were observed, the focus then turned to the changes caused by the shear experiments and the effect change in surface roughness on the shear strength of the used samples.

The third set was dedicated to the observation of the difference in shear profiles based on predetermined changes on the interfaces. These changes consisted of polishing the surface with certain roughnesses. The samples were polished before each experiment at measures of 125 and 75 microns in order to have results to compare the effect of this polishing on the shear profiles.

The results of the mentioned experiments are further discussed in chapter 3. The decisions made throughout the experiments and the ideology behind the different sets of experiments will then be clarified based on the obtained results.

# 3. Results

*This chapter focuses on the results of each experiment set discussed in chapter 2 and the main analysis and discussions that follow the obtained results. The first subchapter, consisting of two parts, addresses the first set of experiments, focusing on the comparison between all mentioned samples. The second subchapter focuses on the second set of experiments that puts emphasis on the effects of change in surface roughness caused by shear experiments. The third subchapter addresses the importance of predetermined changes in surface roughness and how they affect the outcome of shear experiments.*

## 3.1. Experiment Set 1: Comparison of All Samples

### *3.1.1. Stage 1*

In this stage of the experiments all the pairs mentioned in Table 2 were sheared against each other. The obtained shear and vertical displacement profiles from all the experiments show similar patterns but have different values. Due to the similarity of the patterns in the obtained results, only one set of profiles is discussed in this section. The data processed to obtain the results for all other experiments done in this stage is referred to in Appendix 2.

The results that are discussed in this section are from experiments done with Red Felser and Bentheim samples. The direct results of all 6 experiments are shown in the next two figures. The shear stress versus horizontal displacement profiles are illustrated in Fig. 7. The vertical displacement versus horizontal displacement profiles are illustrated in Fig. 8. As it can be seen the normal loads applied on the samples are shown in the title of each graph. The normal loads applied throughout this stage of experiments consist of 29.8 N (a), 73.25 N (b), 122.3 N (c), 171.3 N (d), 220.4 N (e) and 269.4 N (f).

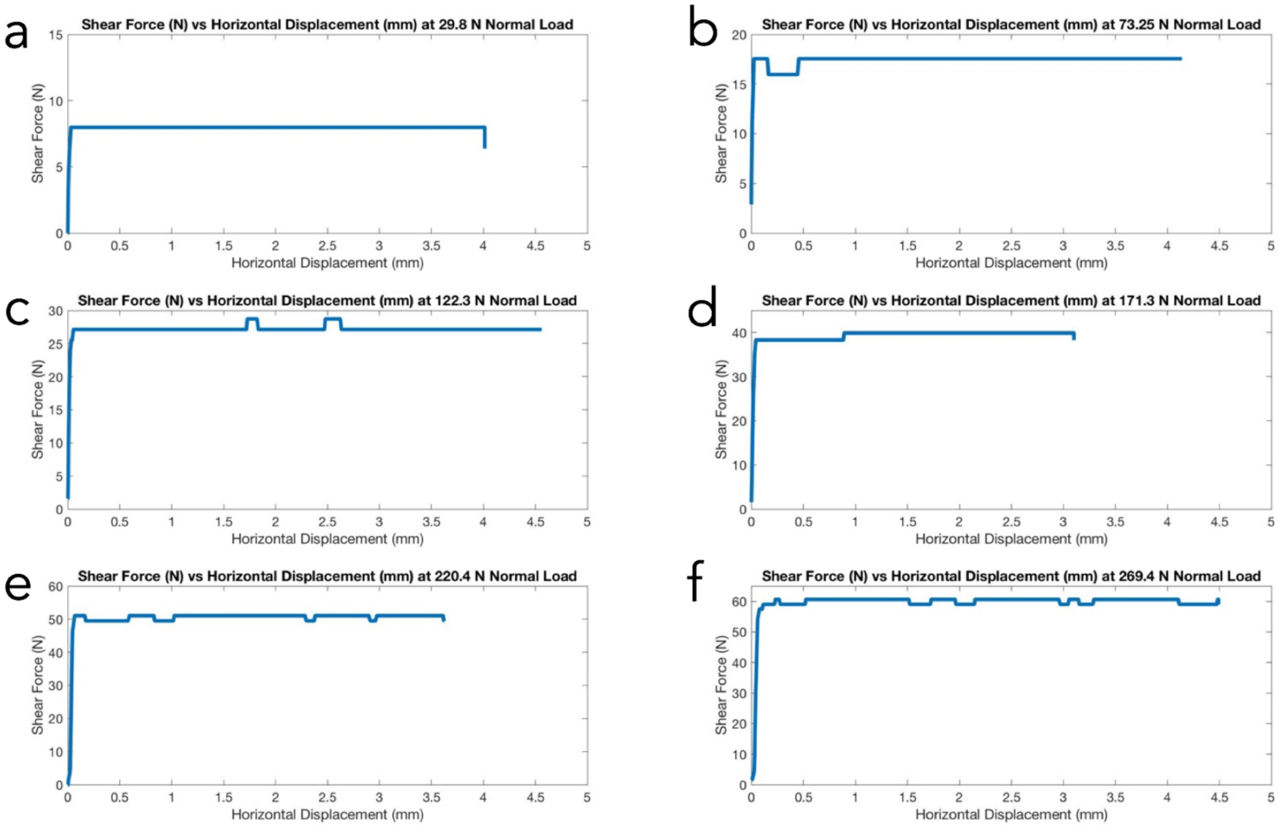


Figure 7: RF vs BH, Stage 1 Experiments. Shear Force (N) vs Horizontal Displacement (mm). The normal loads increase from 29.8 N to 269.4 N from graph a to graph f.

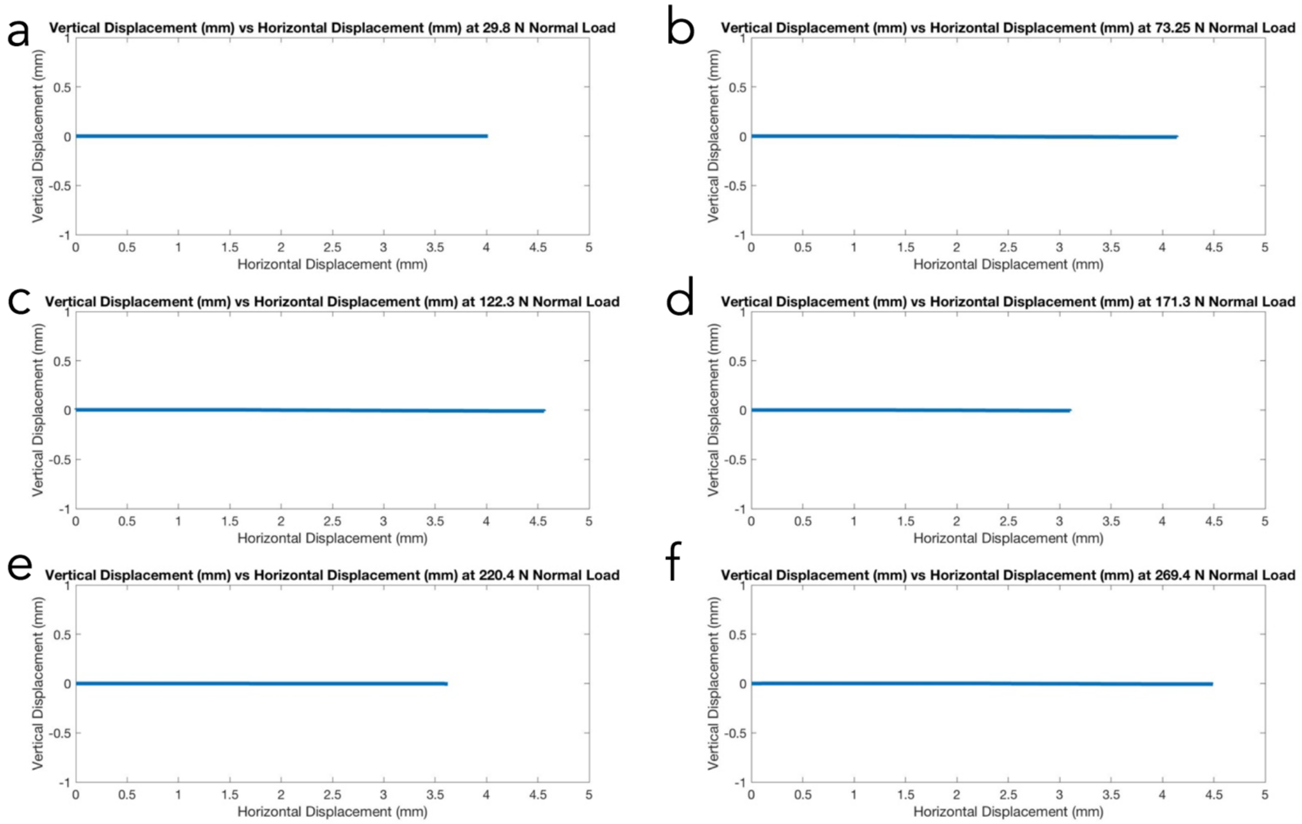


Figure 8: RF vs BH, Stage 1 Experiments. Vertical Displacement (mm) vs Horizontal Displacement (mm). The normal loads increase from 29.8 N to 269.4 N from graph a to graph f.

As it can be seen for the most part of the experiments the value of the shear force plateaus out at a constant rate. The fluctuations in the shear profile are due to possible disturbances in the movement of the samples or the fact that the machine may not record a value in between the fluctuations. In case of the machines inability to record between the two plateaus of the fluctuations, the values are averaged out. However, if the graphs consist of constant values for a majority of the experiment then the most occurring value is taken. Once the shear force is obtained, it is divided by the contact area of the samples to obtain the shear stress as shown in Equation 3. The result is then plotted against the normal stress that was applied in that specific experiment. Fig. 8 shows that the change in vertical displacement throughout the experiment is extremely low.

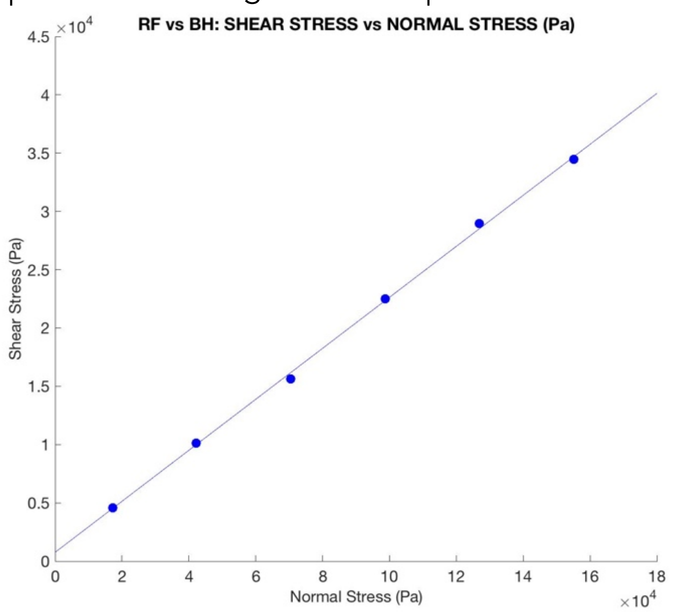


Figure 9: RF vs BH, Stage 1 Experiments. Shear Stress (Pa) vs Normal Stress (Pa)

Fig. 9 shows the shear stress versus the normal stress to obtain the coefficient and the angle of friction. As expected, the trend fitted through the data points behaves linearly. The coefficient of friction ($\mu$) is equal to 0.22 whereas the angle of friction ($\phi$) is 12.33° (Fig. 9). These values define the linear relationship between shear stresses and normal stresses in this specific experiment.

#### *3.1.2. Stage 2*

In this stage of the experiments 3 specific pairs were tested against each other based on the measure of mechanical contrasts. The pairs tested in this stage consist of monzodiorite versus Bentheim (MD vs BH), Ainsa versus Granite (GR vs AI) and Red Felser versus Bentheim (RF vs BH). The choice of the samples was influenced by the fact that the mechanical contrast between the Ainsa and Granite samples and also between the Red Felser and Bentheim samples was low whereas the contrast between the Monzodiorite and Bentheim samples was relatively high. By conducting these experiments at higher loads one can focus more on the effect of mechanical contrast on shear strength of interfaces.

The separation of the two stages is due to a change in focus. The focus in the first stage was to analyse different pairs of samples without considering the mechanical contrasts and the roughnesses. The purpose was to simply observe how the samples behave once shear is applied. The second stage focused more on samples that had a similar or very different mechanical contrast to analyse the effect of these contrasts. For instance, the two sandstones were sheared as "softer" materials against each other whereas the granite and the Ainsa were sheared as "harder" materials. The monzodiorite was then sheared against the Bentheim to analyse the effect of this large mechanical contrast between a hard and a soft material.

Higher loads were applied compared to the first stage in order to have more extreme effects of shearing and to provide a chance to compare the obtained data with literature in a more precise manner. The results shown in other research papers all had data sets with higher normal loads applied on the samples. The normal loads applied throughout this experiment had restrictions set for them and had to be limited within a certain range. The maximum load that could be hung from the system was 70 kilograms. This is further discussed in the conclusion and recommendations section.

In this section, the results that are discussed were obtained through experiments conducted on the Granite and Ainsa samples. The data processed to obtain the results of all other experiments are referred to in Appendix 2. The shear force versus horizontal displacement profiles are shown in Fig. 10. The vertical displacement versus horizontal displacement profiles are shown in Fig. 11. The normal loads applied throughout this set of experiments are 577.4 N (a), 1081.7 N (b), 2090.1 N (c) and 4107.1 N (d).

As it can be seen in Figure 10, the fluctuation of shear forces is much more apparent compared to the experiments with the mentioned normal loads in Fig. 7. This is due to the fact that the normal forces applied in these settings are much higher compared to those of stage 1. The fluctuations are due to the slip-stick phenomena at such high normal loads. The jerking motion when the samples are sheared against each other causes the back and forth fluctuation of the shear force measured by the system. This however causes no ambiguity in readings. The peak shear force was read off of each first reading and later on the values were computed through Equation 3 so that shear stresses would be obtained. The values were then plotted against the normal stresses applied to realize the possibility of obtaining the friction coefficient. It can also be observed in Figure 11 that the changes in vertical displacement are insignificant just as they were in stage 1.

The insignificance of this change in vertical displacement is due to the fact that the samples are saw cut and polished in a parallel manner on both sides, causing geometrically smooth surfaces that slip against each other without any interruptions.

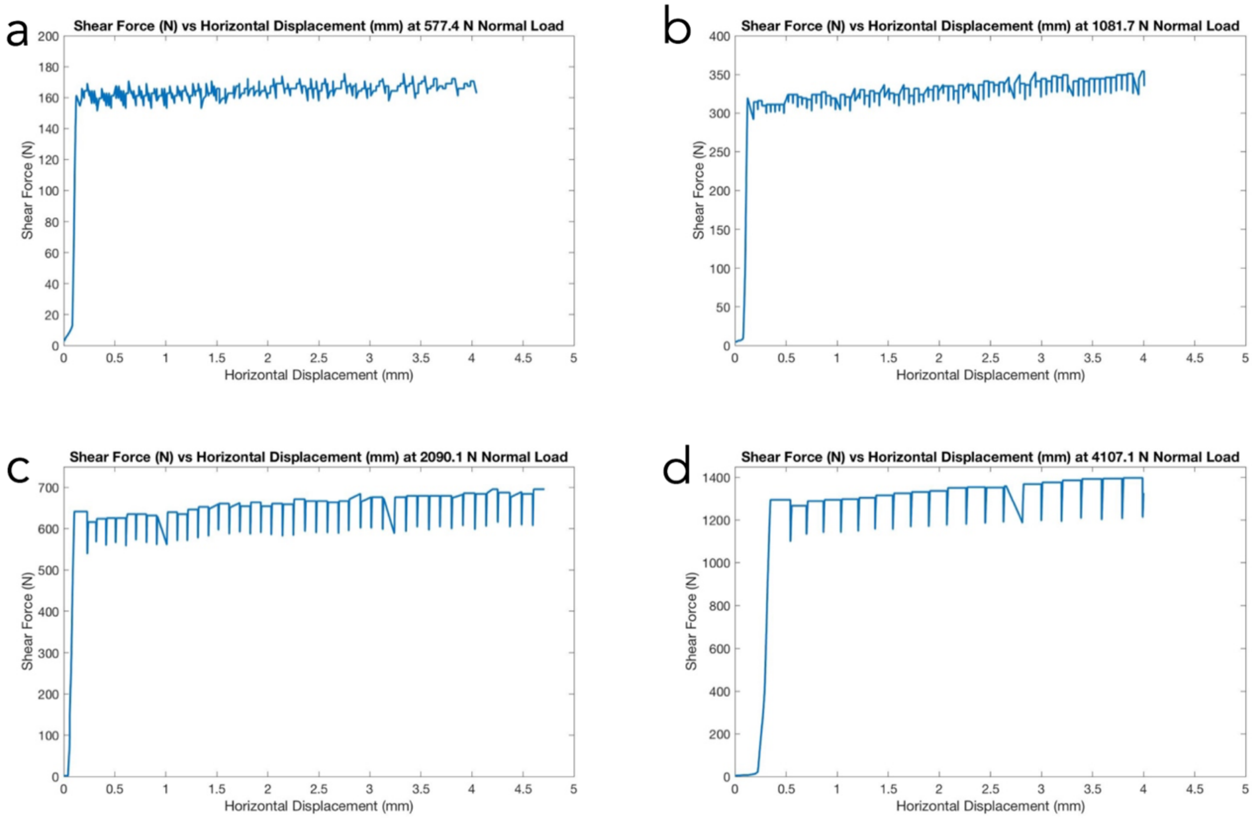


Figure 10: GR vs Al, Stage 2 Experiments. Shear Force (N) vs Horizontal Displacement (mm)

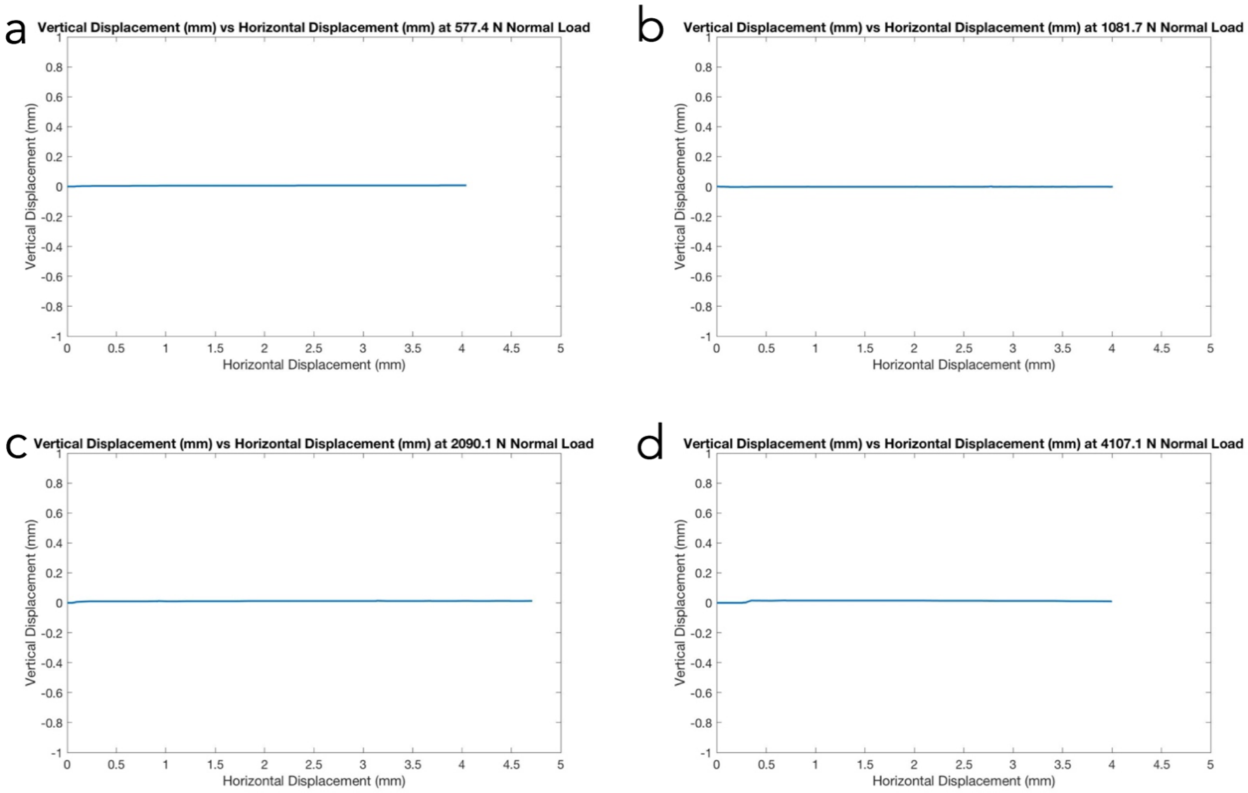


Figure 11: GR vs Al, Stage 2 Experiments. Vertical Displacement (mm) vs Horizontal Displacement (mm)

Upon obtaining the shear stress values and plotting them against the normal stresses, a slope of 0.32 was obtained for the best fitted line through the scattered data points. This results in a friction coefficient of 0.32 and an angle of friction of 17.74°. This is illustrated in Figure 12.

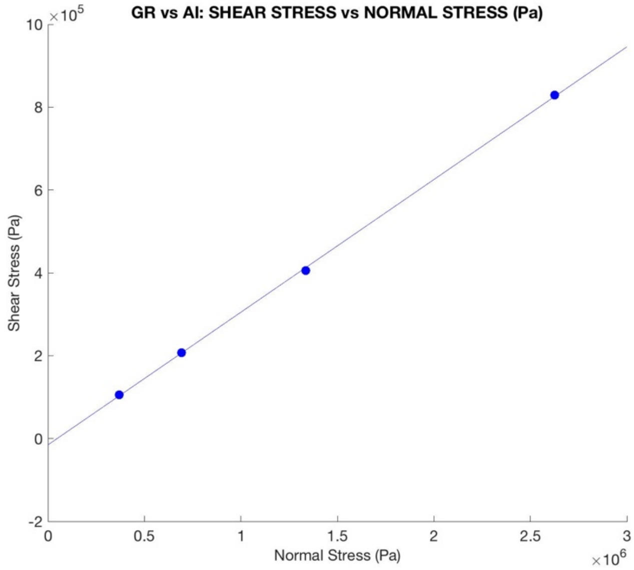


Figure 12: GR vs AI, Stage 2 Experiments. Shear Stress (Pa) vs Normal Stress (Pa)

Figure 13 illustrates the different trends of all experiments done in stage 1. Despite the fact that the expected linearity is clearly existent, one can notice that the concept of mechanical contrast between the tested pairs has quite a significant effect. For instance, the pairing of Ainsa and Bentheim samples lies close to the pairing of Granite and Bentheim samples. Both of the mentioned pairings have high mechanical contrasts and so this raises the question to compare the results of stage 2 with stage 1.

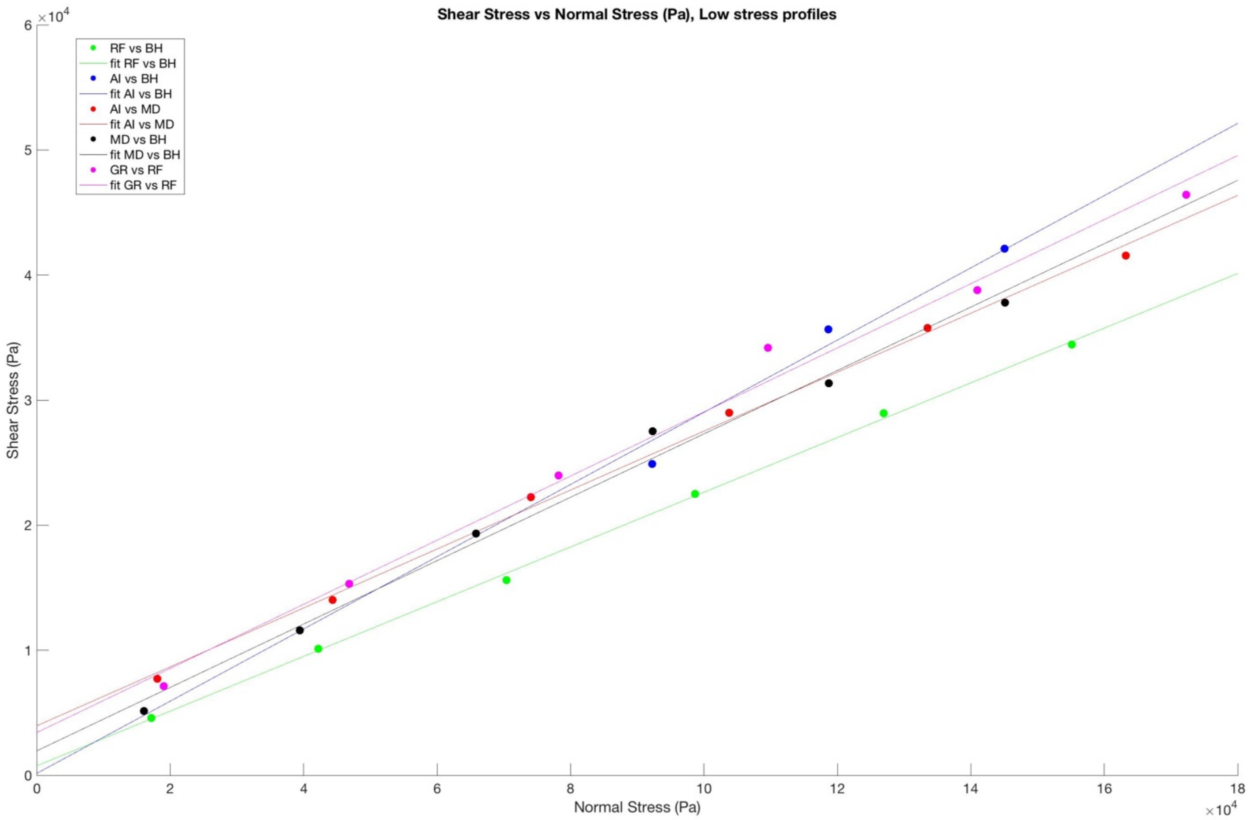


Figure 13: All Results from Stage 1. Data and fitted lines illustrated in legend.

The results of stage 2 were then compiled and graphed all together to observe the effect of mechanical contrasts on the mentioned pairings. As it can be seen in Figure 14, the fitted line to shear stresses for pairing of Granite versus Ainsa lies close to that of Bentheim versus Red Felser. The measure of mechanical contrasts between these two pairings is low and both rock types are somewhat similar. The monzodiorite versus Bentheim pairing however deviates from the two other trend lines by a margin of 4.25° in terms of angle of friction. From this one could conclude that the shear strength of these interfaces is highly dependent on the contrast that exists between the two faces. This will be further discussed in the next chapter. The friction angles obtained from Fig. 14 are illustrated in Table 3.

Table 3: Angle of friction and friction coefficient of experiments shown in Fig. 14

| Sample Pairing | Φ | μ |
|---|---|---|
| GR vs AI | 17.74° | 0.32 |
| MD vs BH | 13.49 ° | 0.24 |
| BH vs RF | 17.74 ° | 0.32 |

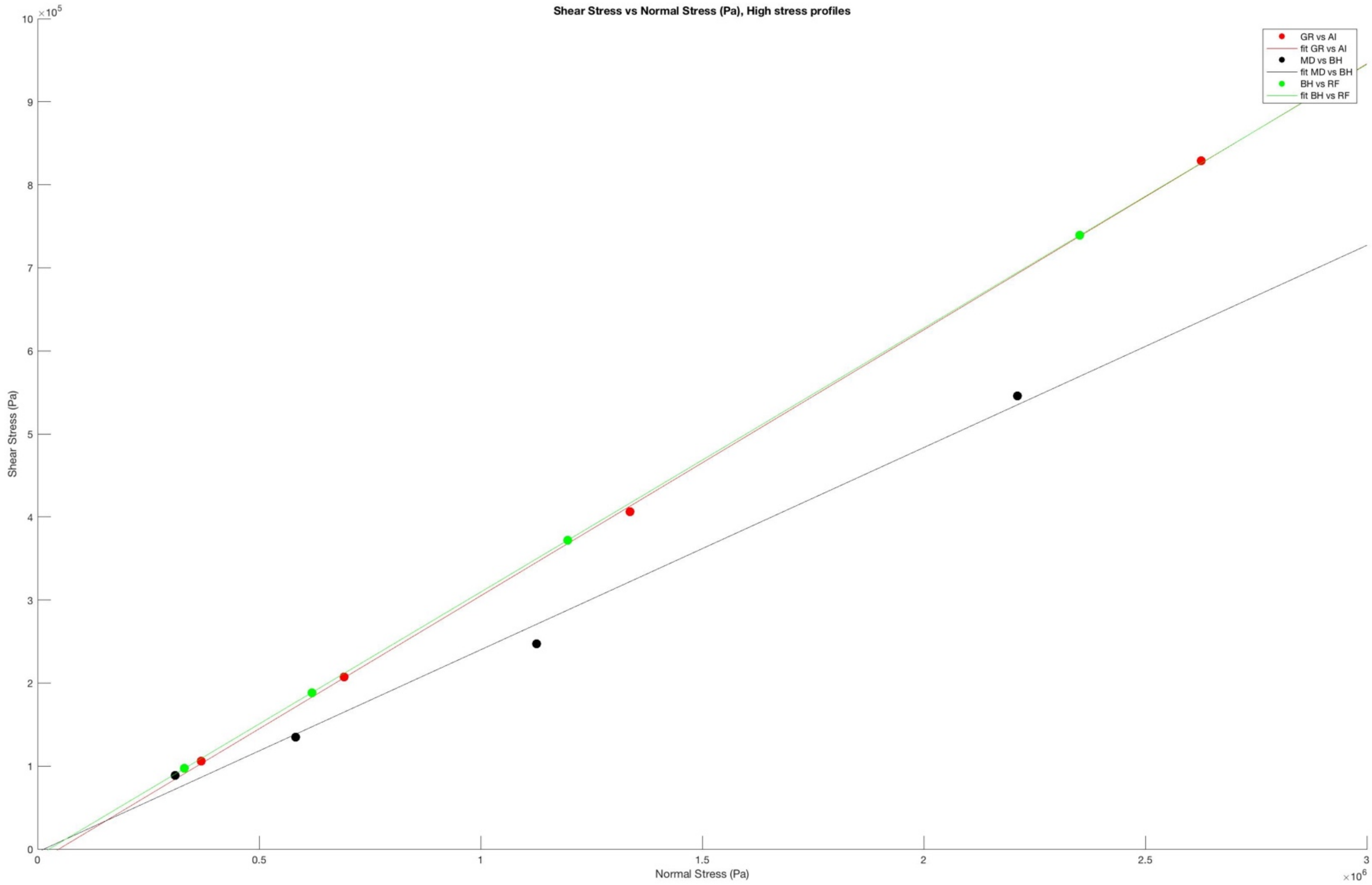


Figure 14: All Results from Stage 2. Sample pairings and fitted lines shown in legend.

Fig. 15 illustrates the combination from data gathered in the first stage for the same sample pairings as the second stage. The friction coefficients obtained from this combination are the same as the ones in Table 3. This combination was done to test the coherence between the experiments.

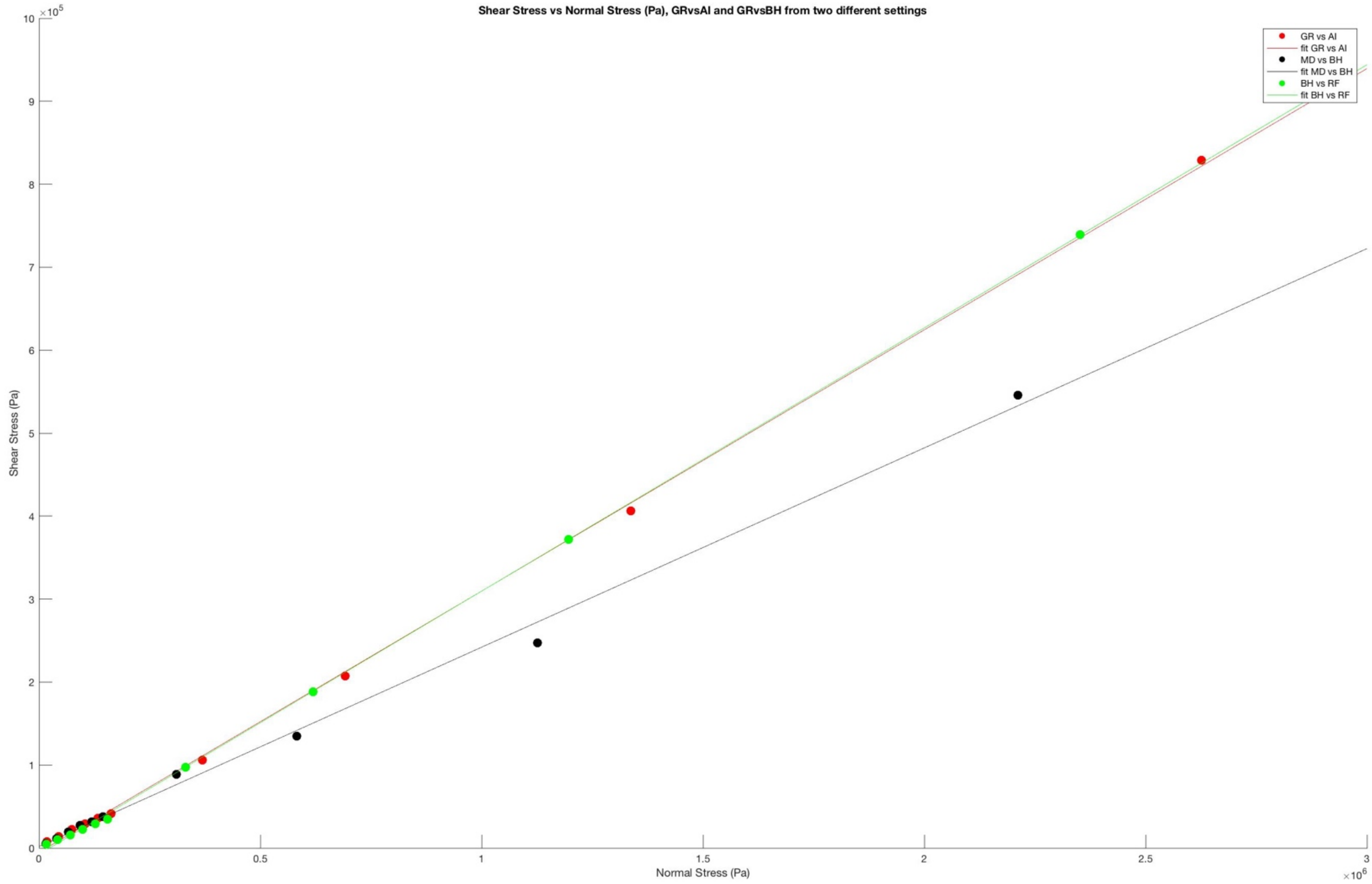


Figure 15: Combined results of Stages 1 and 2

## 3.2. Experiment Set 2: Inconsistency in Surface Roughness

This set of experiments focused on the repetition of experiments that were done at higher loads with pairings of samples that had a high mechanical contrast. In the previously mentioned experiments, the repetition of each experiment showed very little and insignificant differences. This set of experiments was originally meant to act as a continuation of the first set. However, when this set of experiments started, at much higher loads, the differences in shear forces were much more apparent and clear to see. The samples used for this set of experiments consist of Ainsa and Bentheim samples. The surface roughnesses of both samples were initially kept at the same measure that is 125 micro-meters. The samples were then sheared against each under several different normal loads. At a normal load level of 2.6 and 5.5 MN the repetition of experiments began to show a higher measure of shear force between the samples each time (Fig, 16)

As it can be seen, the higher the normal load, the more the repeated experiment deviates from the original trend. This is due to the fact that at such high loads, 5.5 mega Newton's for instance, the surfaces of the samples begin to roughen up against each other. This means that the surface roughness changes with each and every experiment and hence a higher shear force would be the outcome per step. This phenomenon makes the obtained data unpresentable.

Due to this discovery, the decision was made to re-polish the interfaces after each experiment in a predefined surface roughness. This would lead to a presentable set of data in which the experiments will not only emphasize on the importance and effect of surface roughness, but also relate to the theoretical approach that was introduced earlier in this project. The decision was then made to re-polish samples on both sides with grinding material at 125 and 75 micro-meters in order to have the desired difference in surface roughness.

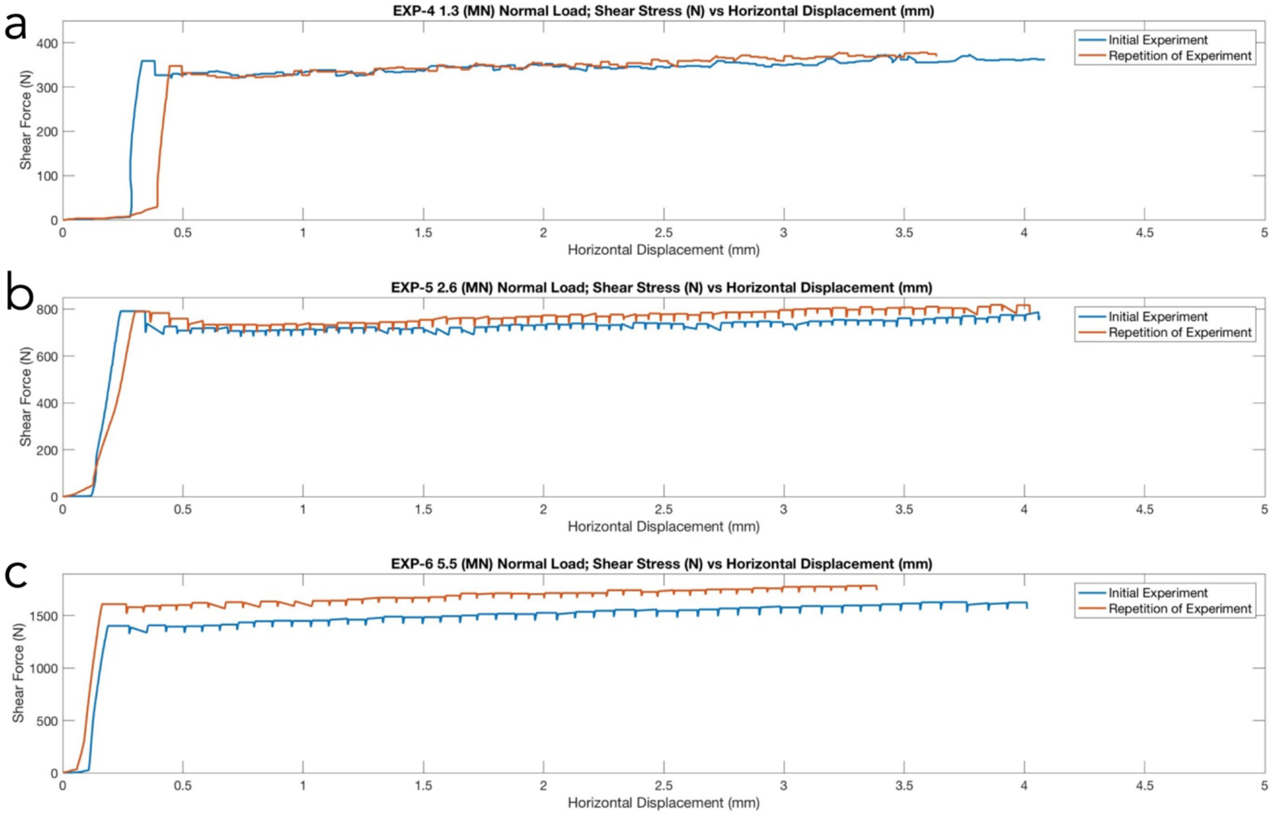


Figure 16: Three Experiments from Set 2. Normal Loads in (MN)

## 3.3. Experiment Set 3: Predefined Changes in Surface Roughness

As mentioned in the previous subchapter, roughnesses of 125 and 75 micro-meters were chosen and 6 Bentheim samples were polished on both sides with the mentioned roughnesses. The samples used in this set of experiments are kept constant as Bentheim samples and then sheared against each other. The direct vertical displacement versus horizontal profiles are illustrated in Fig. 17. The normal loads applied are 171.35 N (a), 347.9 N (b), 681.4 N (c) and 1384.3 N (d).

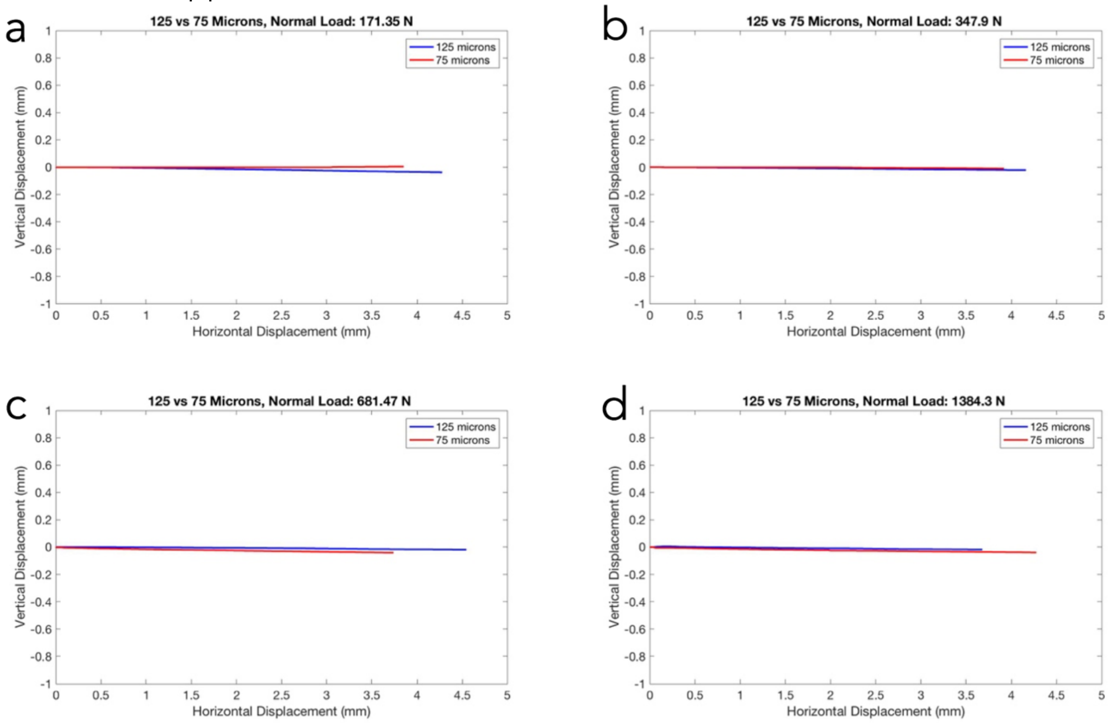


Figure 17: BH vs BH at two different roughnesses Experiment Set 3; Vertical Displacement (mm) vs Horizontal Displacement (mm)

The shear force versus horizontal displacement profiles are illustrated in Fig. 18. As it can be seen in this figure, at 171.35 and 347.9 Newton's, the 75 micro-meter polished Bentheim sample experienced more shear compared to the 125 micro-meter polished sample (Fig. 18 a and b). This is unexpected and with regards to theory, illogical. The expected results would in theory correspond with those of Fig. 2. The other two experiments at the higher loads show results that correspond to the theoretical approach. The obtained results where plotted against the normal stresses applied nevertheless as illustrated in Figure 19.

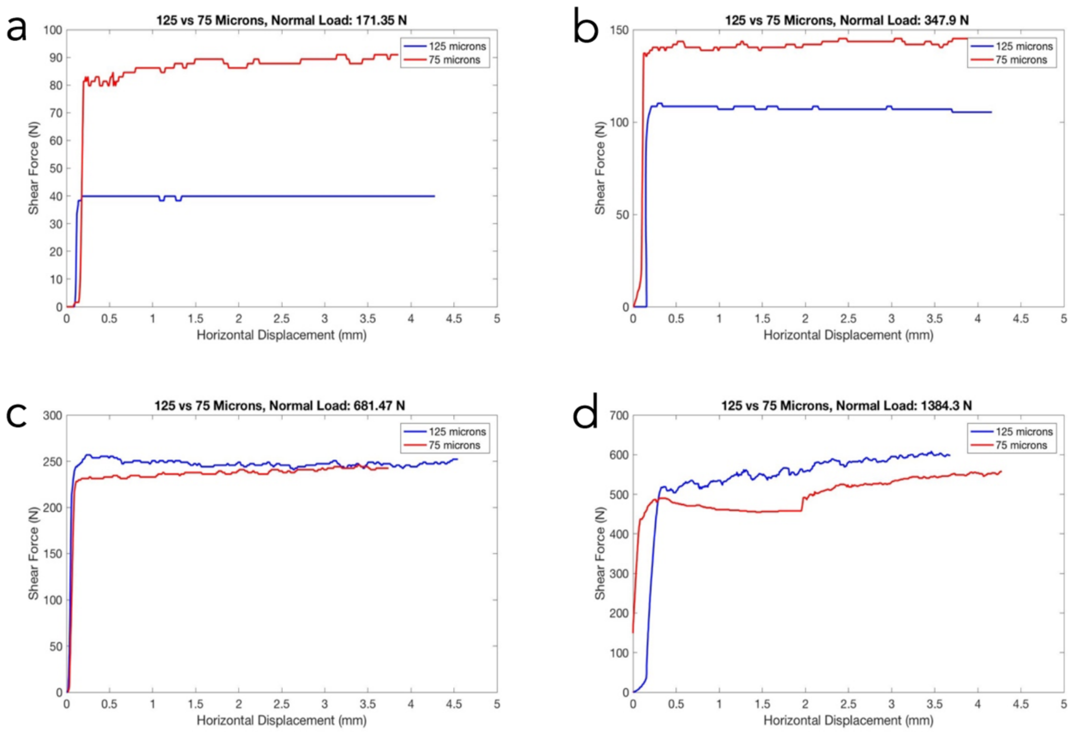


Figure 18: BH vs BH at two different roughnesses Experiment Set 3; Shear Force (N) vs Horizontal Displacement (mm)

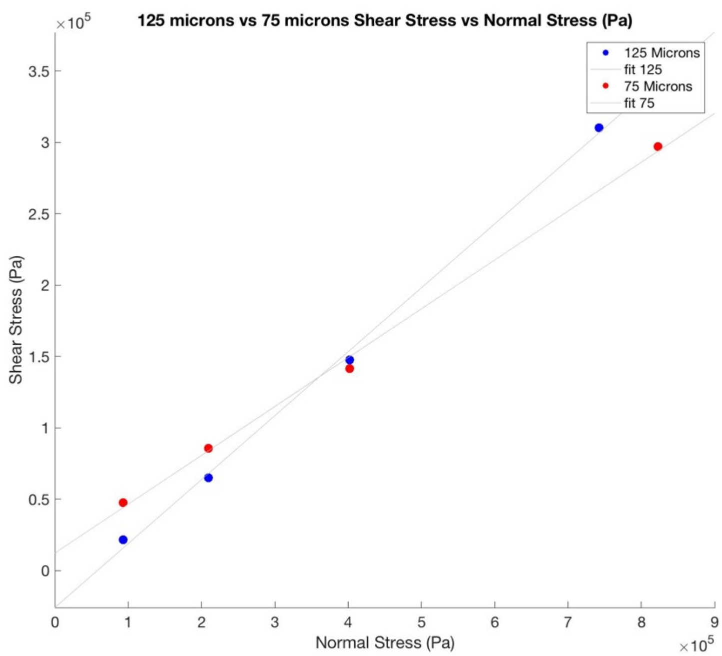


Figure 19: BH vs BH at two different roughnesses Experiment Set 3; Shear Stress (Pa) vs Normal Stress (Pa)

Comparing the results obtained from this set of experiments to the results shown in Figure 2, one can conclude that the results of this section are abnormal and unexpected. There are several reasons to explain the difference in results obtained from this experiment (Fig. 19) and the expected results based on theory (Fig. 2). A possible explanation would be that there was an error in polishing the samples and this caused a difference in surface roughness for the first samples used in the experiment. This error could be due to a misjudgement in the amount of time needed to polish the interfaces to the desired roughness. Another explanation would be the lack of uniformity in the distribution of normal stresses that was experienced during this set of experiments.

Throughout this set of experiments certain flaws were observed in the setup, one of which is illustrated in Figure 20. The disturbance in the normal load distribution can be due to the fact that the samples did not fit within the casket at the right angle. Optimally, the sample would lie within the casket with the bottom face parallel to the bottom of the casket. This was not the case in the experiments conducted at 171. 35 N and 347.7 N normal loads. Therefore, the samples were sheared against each other at an angle which disturbed the data.

As it can be seen in Figure 20, the left side of the samples were clearly sheared against each other with more intensity to a point where parts of the samples were broken. This might be due to the fact that the samples used in this set of experiments were of larger sizes and hence they did not fit within the setup as the previous samples did.

Figure 20: Lack of Uniformity in Normal Stress Distribution

# 4. Discussion

*In this chapter, the results obtained from the experiments are discussed and summarized. The correlation between the results and the theoretical background introduced in first chapter are also discussed.*

The friction coefficient and angles of friction of all the shear stress versus normal stress profiles of the first and third set of experiments are illustrated in Table 4.

Table 4: Angle of friction and friction coefficient of experiment sets 1 and 3.

| Sample Pairing | Φ | μ |
|---|---|---|
| GR vs AI | 17.74° | 0.32 |
| MD vs BH | 13.49 ° | 0.24 |
| BH vs RF | 17.74 ° | 0.32 |
| AI vs BH | 13.49 ° | 0.24 |
| GR vs RF | 14.57 ° | 0.26 |

As it can be seen in the first set of experiments, mechanical contrast acts as a significant factor when it comes to interface strength. The comparison between Bentheim vs Red Felser and Ainsa vs Granite raises the question whether an interface is just a sliding plain with no effect in case of similarity and low measures of mechanical contrast. The fact that the two pairs act in the same manner and even have more or less the same angle of friction at lower stresses emphasises on the importance of mechanical contrast. The results also show that an interface between two rock types acts as nothing but a plain when compared to two other rock types with the exact or similar mechanical contrast.

The second set of experiments proved that at much higher stresses the samples undergo a natural polishing process that is representable of what might happen in a real-time geological setting. For instance, two rock layers sheared against each other on a landslide or fault would experience changes on the interface. This phenomenon has direct effect on the deformation that these rock layers might experience throughout the process of faulting. This realization resulted in the process of deciding to re-polish the samples which of course emphasized on the surface roughness changes in a more pre-determined manner.

As discussed in section 3.3, the samples, once polished, behaved abnormally and not according to expectance. The results taken from the graph illustrated in Fig. 2 from Teufel and Clark and the results obtained from the third set of experiments are compared in Table 5. As it can be seen and as it was mentioned, the results from Teufel and Clark does not correspond to the obtained results in this project. The errors faced in this project as mentioned in section 3.3 have caused this difference from theory.

Table 5: Comparison of friction factors between literature and results of this project
Adapted from *Hydraulic Fracture Propagation in Layered Rock: Experimental Studies of Fracture Containment* (p. 24) by L. W. Teufel and J. A. Clarck. 1981.

| Tennessee Sandstone | | Bentheim | |
|---|---|---|---|
| Roughness (μm) | μ | Roughness (μm) | μ |
| **220** | 0.81 | 125 | 0.45 |
| **110** | 0.73 | 75 | 0.34 |

As it can be seen in Table 5 and Fig. 2, the rougher the surface the higher the friction coefficient would be. This is also the case in the results obtained from the third experiment set. However, the fact that in Fig. 19 the first two shear stresses for the 75 μm roughness are not lower or equal to the first two shear stresses for the 125 μm roughness does not correspond with the trends shown in Fig. 2.

The experiments mentioned throughout this report are prone to errors and can result in outcomes that are unpresentable. The improvement and avoidance of such errors is further discussed in Chapter 5. The expected manner in which the samples would possibly behave is that the rougher the interface, the more shear it will experience.

# 5. Conclusion and Recommendations

To conclude, the main purpose of this report was to focus on the effect of mechanical contrast and surface roughness on the shear strength of rock interfaces. The results obtained throughout this project have reflected on the influence that mechanical contrast and surface roughness have on the shear strength of rock discontinuities. The abnormality within the final results obtained in the third set of experiments is concluded to be due to physical errors. The limitations within the setup of these experiments acts as a challenge that builds a platform for reconsideration and better design.

The concept of surface roughness, though briefly analysed, shows important results. These results emphasize on how the shear sustained by an interface can increase or decrease based on the roughness of the interface. In order to study the interface strength of certain rock types, it is important to alter the surface roughness of the material in question. By this alteration, the true effect of surface roughness on interface strength will be clarified. This project has proven that the results of the mentioned experiments correspond with theoretical expectations and so with error mitigation one can expect the same correspondence with regards to surface roughness. That is if the surface roughness of an interface increases, the measure of shear that it experiences increases as well.

Lastly it is important to realize that the mechanical contrast of different rock types is an influential factor. Mechanical contrast between two rock types has a direct effect on the shear strength of the interface. The interface of two rocks with a certain mechanical contrast shows the same shear strength regardless of the rock types involved. For instance, the pairing of a monzodiorite and Ainsa, with a mechanical contrast of 1.2, showed the same shear stresses as the pairing of a Bentheim sandstone and Red Felser sandstone which had a mechanical contrast of 1.3.

## 4.1. Recommendations

Throughout the experiments certain barricades were faced which could be improved. The possibilities of these improvements are discussed in this section.

### *4.1.1. Samples*

The samples used throughout this project were of a certain size and shape. These factors can be altered in many ways that might be of benefit to the purpose of a future project that concerns itself with the subject in question. For instance, the size of the samples can be smaller in order to have less contact area. This will not only result in higher ranges of normal stresses but it also acts as a tool to have more material.

### *4.1.2. Setup Design and Equipment*

The usage of a direct shear box showed not many difficulties. The design of the setup was subjected to possibilities of errors. It is therefore a thought that the Golder Shear Box can be used instead. In this specific shear box the samples can be casketed within moulds that hold the sample in place, preventing it from wobbling or experiencing sudden disturbance.

### *4.1.3. Error Mitigation and Data Reading*

Although the experiments were repeated throughout this project in order to mitigate errors in the obtained data, it is important to repeat the experiments more and in better conditions to be sure of the data obtained. This of course takes more time and was difficult to manage throughout the project at hand.

#### *4.1.4. Polishing*

The polishing of the samples throughout this project might have been the reason why the abnormalities in the last set of experiments appeared. It is important to make sure the polishing of the samples is done properly and with care.

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# List of Figures

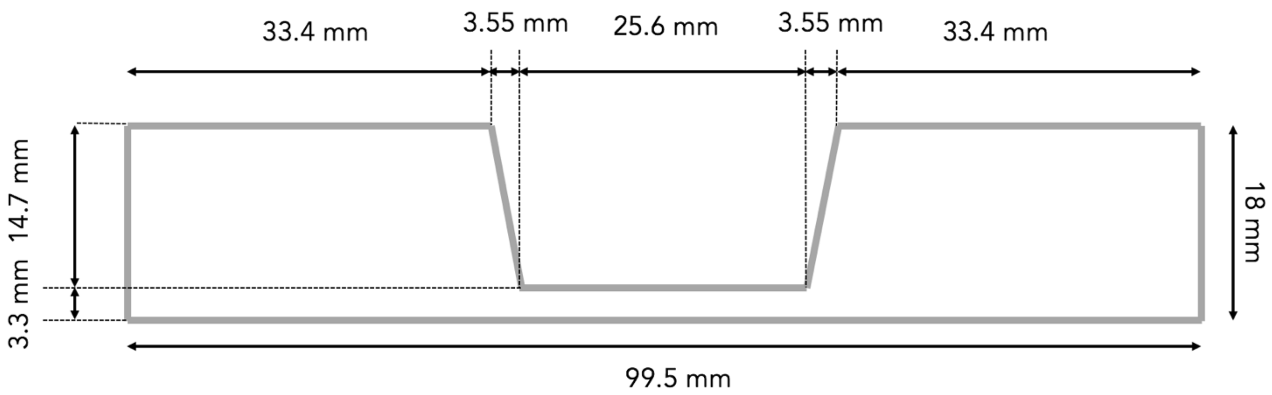


# List of Tables

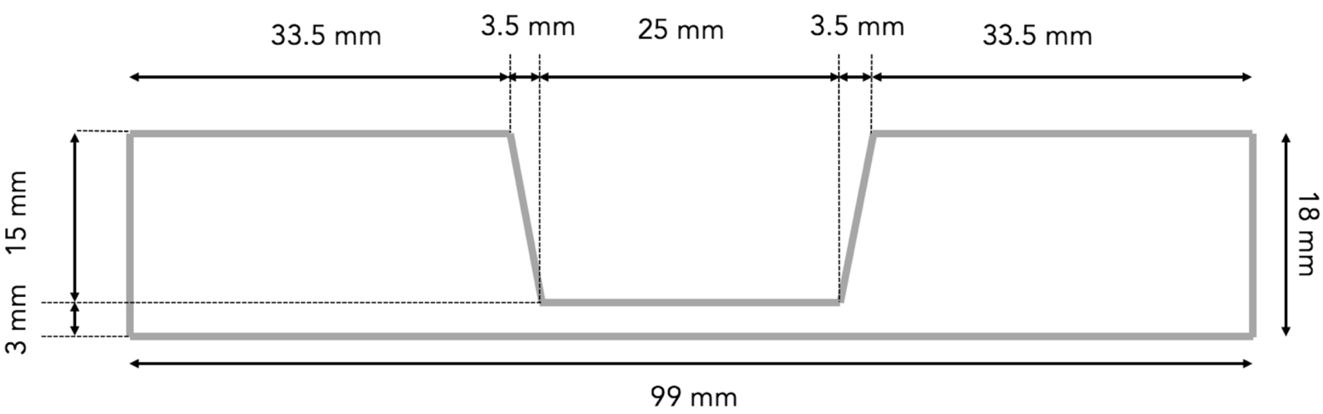
# Appendix

## Appendix 1: Casket Design

TOP CASKET




BOTTOM CASKET



## Appendix 2: Experiment Data

The data analysed throughout this project was obtained through a series of experiments done by Siavash Honardar at Delft University of Technology. To have access to this data you can contact the supervisors of this project. Their contact details are given below.

The data consists of;

- Sets of raw data obtained from the shear experiments
- Several Matlab scripts processing the raw data
- A guide to experiments and processed data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