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Bond Strength Testing of Wellbore Material Composites

DEPARTMENT PETROLEUM ENGINEERING

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This thesis is dedicated to my parents
for their love, endless support
and encouragement.

Affidavit

I declare in lieu of oath that I wrote this thesis and performed the associated research myself using only literature cited in this volume.

Eidesstattliche Erklärung

Ich erkläre an Eides statt, dass ich diese Arbeit selbständig verfasst, andere als die angegebenen Quellen und Hilfsmittel nicht benutzt und mich auch sonst keiner unerlaubten Hilfsmittel bedient habe.

Name, 14 March 2017

Abstract

In the petroleum industry, the maintenance of wellbore integrity is one of the most important tasks. One of these elements is wellbore cementing and the interface between cement and the casing as well as cement and rock.

This master's thesis deals exactly with those interfaces, because only with an intact bonding between cement/steel and cement/rock, wellbore integrity can be given.

The bond interface can easily be damaged due to several wellbore operations in drilling like POOH, RIH, fishing, reaming or freeing stuck pipe with jarring. During all these operations the bond is mainly stressed with shear loads. In this thesis, several shear tests with cement and steel and cement and rock were conducted.

In most of the cases, wellbore leakage occurs due to bad or faulty cement jobs between cement/casing and cement/rock. On one hand side it is possible that formation water, which has a very high salinity, can migrate through micro channels and micro annuli through the cement and react now directly with the surface of the casing and corrodes it. When casing leakage happens, it is definitely possible that several formation fluids can flow behind the casing into other formations, or in the worst case, into ground water formation layers.

To get more information about the bonding strength between cement/steel and cement/rock, several shear tests with steel plates with different surface roughness values and different rock types with and without saltwater saturation were conducted.

Zusammenfassung

In der Erdöl- und Erdgasindustrie ist die Langzeitintegrität von Bohrlöchern eines der wichtigsten Kriterien. Eine wichtige Komponente ist die Verbindung zwischen Zement und der Verrohrung bzw. Zement und dem umliegendem Fels.

Diese Arbeit befasst sich speziell mit diesen Verbindungen, da nur über eine intakte Verbindung die Sicherheit des Bohrloches gewährleistet ist. Die Bindung kann durch Untertageoperationen wie z.B. POOH, RIH, Fishing Reaming und Operationen mit der Schlagschere erheblich geschwächt bzw. vollkommen zerstört werden. Die Bindung wird bei all diesen Operationen auf Scherung beansprucht. Im Zuge dieser Arbeit, wurden mehrere Scherversuche mit Zement auf Stahl bzw. Zement auf Gestein durchgeführt.

Bohrlochleckage ist in den meisten Fällen auf eine schlechte bzw. fehlerhafte Bindung zwischen Zement und dem Casing bzw. Zement und dem umliegenden Fels zurückzuführen. Einerseits ist es durch sogenannte Microannuli bzw Microfractures möglich, dass Formationswasser, welches meist einen hohen Salzgehalt aufweist, direkt mit dem Casing reagieren kann und in weiterer Folge Korrosion auftritt. Wenn eine Leckage auftritt, ist es durchaus möglich, dass unterschiedliche Formationsflüssigkeiten hinter dem Casing, bzw. durch den Zement in andere Formationen oder den Grundwasserbereich fließen können.

Um mehr Informationen über diese Bindungsstärke zwischen Zement und Stahl, bzw. Zement und Fels zu bekommen, wurden mehrere Scher Versuche auf unterschiedlichen Stahloberflächen mit unterschiedlicher Rauheit sowie mit unterschiedlichen Gesteinen mit und ohne Salzwassersättigung durchgeführt.

All diese Versuche und ihre Resultate, die helfen die Integrität des Bohrloches zu verbessern, wurden dokumentiert und in dieser Arbeit veröffentlicht.

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Proof readers Dr. Werner Pochman, Dipl Ing Perhamn Bechrad

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Chapter 1 Introduction

Structural integrity is the most important task in every well, in the petroleum industry. A borehole is not a simple hole in the ground, it is more a pressure containment vessel, which has to withstand deformation, fatigue, fracturing and corrosion. Every wellbore is sealed with various barriers of cement and steel pipes, which are called casing.

It is to say, that a wellbore faces loads like geothermal, geomechanical and geochemical stresses several times in its lifetime. Temperature changes in wells vary by hundred degrees of Celsius when borehole treatment is done, formation pressure changes linked with vibrational forces, which fluctuate up to 700 bar for different completion operations. Also naturally occurring phenomenon's like CO_2 or H_2S brines and water, weaken the borehole sealing. So it simple can be said that the downhole environment is very harsh and the wellbore architecture must be designed to withstand this harsh environment for the whole lifecycle of the well.

Boreholes in the petroleum and geothermal industry are designed to be a conduit to produce and recover hydrocarbons or geothermal steam from the reservoir to surface. The design of wells is almost the same principle. Several casings with diminishing diameters are set, starting with the conductor casing and end with the production casing, when the well has a cased hole completion. When the well is drilled, the hole created is normally not a perfect round hole with the shape of a circle, it is more like a general curve, because rock is a heterogeneous material and does not behave consistently when the bit drills through. It is now easy to understand, that the created hole has a bigger diameter than the outside diameter of the casing. The void space between borehole wall and outside diameter of the casing is called annulus and this void space is filled with cement, which is pumped through the casing into the annulus. The cement provides a seal such no formation fluids reach the outside diameter of the casing respectively, no flow of formation fluids between the different formations or even the ground water level happens.

The used cement is not a typically cement such in the construction industry is used, this cement is designed to meet specifications for pump ability and set times for the unique downhole condition of the individual well. The cement needs to remain in a fluid state when it´s pumped and has to gain strength rapidly to resist an inflow of any formation fluids or gases. The cement stabilizes the casing and adheres to surface throughout the annulus to create a hydraulic seal. As said before this cement sheath is used as a barrier to prevent any formations fluids or gases migrating up the annulus into other formations, ground water level or surface. Figure 1 illustrates the design of a vertical cased hole well.

The global energy consumption of oil and gas will approximately increase by one percent per year over year for the next 30 years. (This projection is from the EIA). [30] This means that in over 100 years, trillion barrels of hydrocarbons were produced and the next trillion hydrocarbons will be produced only in the next decades. It is easy to understand that reservoirs need to be produced in areas, which are located in forbidding and harsh environments, like ultra-deep water operations, extreme downhole conditions of pressure temperature, corrosive, environment and unconventional source rock (fracking) and also arctic areas.

Wellbores are getting more complex and so does the cement job. If the cement does not withstand these requirements, it could fracture, crack or otherwise fail with the result of an annular pressure build up (flow behind the casing), that could directly have an impact on the integrity of the steel casing or even worse and unwanted flow of different formation fluids and gases across different layers. End of this story is that the operator has to deal with diminishing or lost production or even the worst scenario the loss of the well. Cement plays a more critical role in wellbore integrity than ever. In 1920, pumping cement through casing to stabilize the wellbore, was a complete new service and nowadays wellbore cementing is mandatory in every well and must not be ignored. In modern wells, cement is pumped through more than 6000 m casing which may also include horizontal sections of approximately 3000 m or more. In offshore deep-water operations, wells routinely span distances higher than the summit of Mt. Everest. So if the cement job was faulty, there is the danger that one of the listed scenarios happens, and we have to be very careful with our remaining resources which are not infinite, such the potential loss of cement sheath integrity will increasingly become a larger issue.

The behavior of rock formation is very complex, because it is not a homogenous material, according to the consisting minerals. So the cement comes in contact with different minerals and therefore will behave differently. In other words, the resulting bond at the interface could be always different and it´s very difficult to predict the bonding strength.

Not so much attention was given to cement/formation bonding within the whole topic of wellbore integrity. Other important factors have been studied much more. One study about cement/formation interface was done by Carter and Evans. [2] For this study Indiana Limestone and Berea Sandstone was used. The study was about shear bond strength, compressive and hydraulic bond strength, by treating the rock samples with different drilling muds and by cementing those samples with different cement slurries.

The findings of their experiments are listed below:

- Maximum bond strength observed in dry cores.
- Zonal isolation can´t be given without mud removal from the borehole.
- Filter cake presence minimizes the strength of hydraulic bond.
- With effective mud removal, effective bond strength was obtained.
- The intimate contact of cement slurry with the formation determines the strength of hydraulic bond.

H.K.J Ladva [3] used these studies and further investigating the bond strength at shale cement interface. He studied all the factors listed above in achieving the strong bond at cement formation interface. His experiments were performed with dry rock samples, as well as by treating them with OBM and WBM. The findings of his experiments are listed below:

- Maximum bond strength in dry rock samples
- WBM and OBM treatment of rock samples reduces the bond strength at the interface
- When cement was placed against the mud filter cake, the failure area was within the mud cake and gas could flow along this conduit.
- H_2O transport along shales also affects the bond strength.

This thesis is reclined to the work that has been done before, but additionally investigates the steel cement interface, which represents the casing cement interface as well as two rock types. The rocks, which were chosen, are sandstone, which represents the reservoir rock and Serpentinite, an impermeable metamorphic rock which represents a seal rock. Within the idea of studding the shear bond strength, an experimental setup was developed. Several tests were made on steel plates with different surface roughness and the sandstone rock samples was investigated by using dry samples of it as well as such ones which have been treated with two different concentrations of salt water before. A comparison of difference in the bond strength is presented as well. For the test, different cement slurries were used.

The used slurries are listed below:

- Class G Cement (Schlumberger)
- Class G Cement (Fangmann)

Chapter 2 Well Cementing Fundamentals

In Petroleum Industry well cementing is a critical step, because only a good cement sheath provides the barrier which is needed to avoid wellbore leakage or unwanted flow of formation fluids across different layers. The lifetime of a well depends on a good cementing job. The main tasks for a cementing are:

- Zonal Isolation
- Stabilizing and support of the formation
- Casing support and prevention from corrosion
- Restriction of fluid movement between permeable zones (Crossflow)
- Plugging and or abandoned portion of the well

Wellbore cementing is differed into different operations.

- Primary cementing
- Secondary cementing
- Multistage cementing
- Squeeze cementing

2.1 API Classification Systems for Cement

The API established different specifications for well cement, because the conditions in wells differ drastically to those in the construction industry. Currently 9 different classes of API Portland cement exist (A-J). They are designed to the different setting depths and the various temperatures and pressures they have to face there.

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Class	Depth	Application	Chemical Composition
A	0-1830 m	Special properties not required	C_3A (Similar to Cement Type I)
B	0-1830 m	Moderate to high sulfate resistance required	C_3A content lower than for Class A (similar to Cement Type II)
C	0-1830 m	When conditions require high early strength	C_3A and high content of C_3S (Roughly similar to Cement Type III)
D	1830-3050 m	For high temperature and pressure	Reduced concentration of C_3A and C_3S
E	3050-4880 m	For high temperature and pressure	Reduced concentration of C_3A and C_3S
F	3050-4880 m	For extreme high temperature and pressure	Reduced concentration of C_3A and C_3S
G	0-2440 m	Used for basic wells	C_3A and C_3S
H	0-2440 m	Used for basic wells	C_3A and C_3S
J	3600-4880 m	For extreme high temperature and pressure	Reduced concentration of C_3A and C_3S

Table 1: API Classification System, (E. B. Nelson 1990) [12]

2.2 Primary Cementing

Primary cementing is the key process in drilling. The cement sheath acts as a barrier and provides a hydraulic seal and thus avoiding fluid communication across different zones, called zonal isolation. Another important duty of cementing is anchoring the casing and protecting the casing from fluid or gas contact against corrosion. A bad cement job would mean that the well will not have the postulated life span and it also could be that the well is not able to produce it´s full capacity or, in the worst case, has to be given up prematurely.

The most commonly used type of primary cement jobs is the two plug cement placement method. When a section of the wellbore is drilled to a certain depth, the drill string is removed and the well is filled with drilling mud, otherwise the well would begin to flow. In the next step, the casing string is screwed together segment per segment and is lowered slowly into the wellbore. The edge of the first casing segment is protected by the guide shoe or float shoe. After the first or second joint, a float collar is installed, the space between the float collar and the shoe is called shoe track.

The shape of these shoes are bullet nosed which helps to minimize the friction in the lowering process, because a wellbore consists of various sharp edges and wash outs created from the bit during the drilling process. The float shoe or collar is a little different from the guide shoe and consists of a check valve, which avoids fluid to be U-Tubed reversed from the annulus into the casing.

To place the casing uniformly into the hole a certain number of centralizers are used which are calculated during the planning phase of the well. The centralizers help the casing to be placed in the center of the wellbore, because when the conduit of the annulus on one side is much bigger than on the other side, the cement will displace not uniformly and this would lead to a faulty barrier and wellbore leakage would be the result. Before the cementing process starts, the drilling fluid must be removed from the wellbore with a so-called spacer because a contamination of drilling fluid on the borehole wall would influence the cement bonding with the casing and the rock respectively.

Usually cement slurries and drilling fluids are incompatible but when they mix up, the result is a gelled mass, which is very hard to remove from the surfaces. At first the so-called lead slurry is pumped, it is a low density, high yield slurry designed to fill and cover the upper sections of the annulus. It´s pumped from the cementing unit through the cement head into the casing. The tail slurry is of high density and used to cover the lower section of the annulus.

To provide a mechanical barrier and to avoid a fluid mix up inside the casing, so-called wiper plugs are used. The bottom plug separates the cement slurry from the drilling fluid and it is especially designed with a predetermined breaking point, which ruptures when it lands on the bottom of the casing string. Now there is a flow path for the cement to enter the annulus. The top plug is differently designed to the bottom plug and does not have a predetermined breaking point and therefore does not rupture, when it lands on the bottom plug. The bottom and top plugs are not removed from the well, they are drilled when the next section is built. After cementing, the slurry begins to harden and which is another critical stage in cementing. When the cement hardens, the hydrostatic pressure of the slurry decreases and the cement becomes self-supporting. When the hydrostatic of the slurry decreases, there is also a resulting volumetric reduction in combination with compressibility and downward movements. (Schlumberger, 2013) [13]

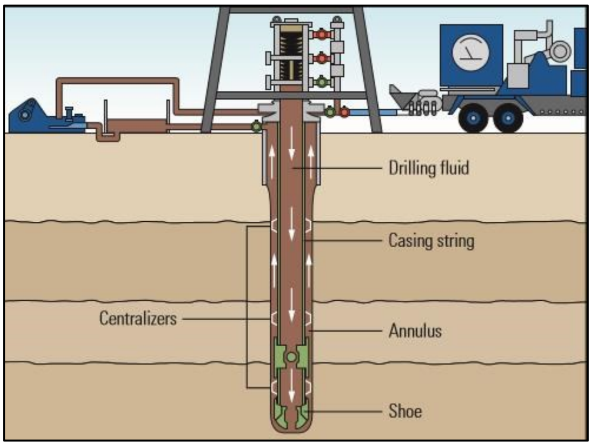


Figure 1 Circulating drilling fluid

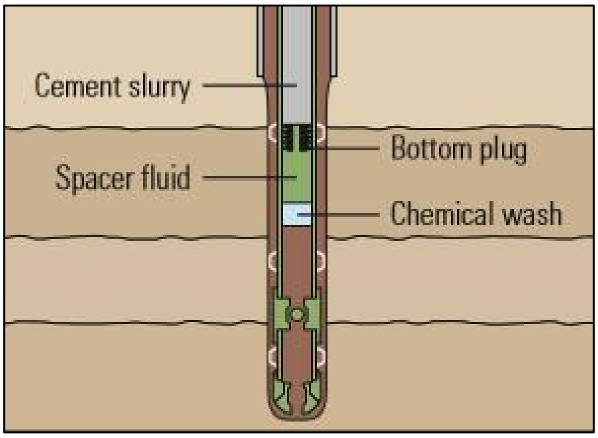


Figure 2: Pumping Wash, Spacer and Cement Slurry

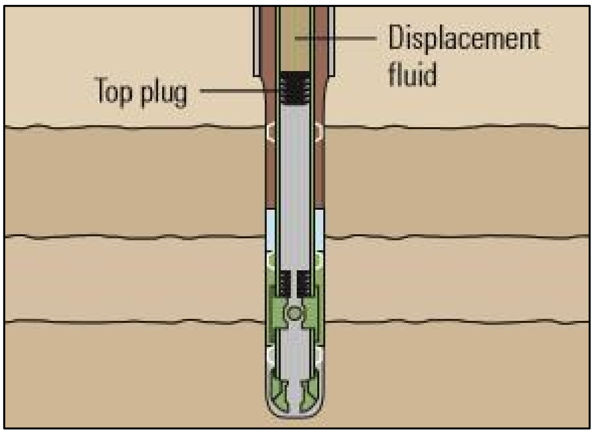


Figure 3: Cement Displacement

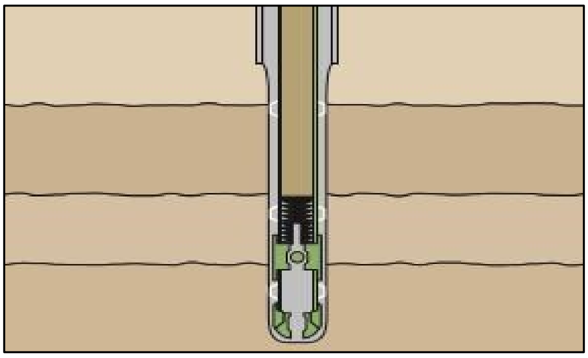


Figure 4: Completed cement job

(Schlumberger, 2013) [15]

2.3 Secondary Cementing

If the primary cement job was faulty or the interface of the cement bonding fails over time, it may be necessary to repair the problem. The purpose of squeeze cementing is to repair improper zonal isolation, eliminate water intrusion and repair casing leaks. Another objective for secondary cementing would be plug back cementing, where the hole is plugged by cement in order to initiate a new drilling operation. Plugging back a hole, could be done due to the following reasons

- Abandonment of the hole
- Sidetracking
- Seal off lost circulation
- Shutting off of water or gas encroachment (Recommended Practice for Testing Well Cements 1997) [16]

2.4 Multistage Cementing

Multistage cementing is a technique which is necessary when a hole section is so long, that the formation cannot support the hydrostatic pressure exerted by the cement column. Therefore a good cement bond between casing and cement, as well rock and cement can be provided with this technique.

It is done when the upper zone needs to be cemented with uncontaminated cement and when cement is not required between two widely separated intervals. (Applied Drilling Engineering 1984) [13]

2.5 Squeeze Cementing

Squeeze cementing is performed to get complete zonal isolation of the annulus. In this application, cement under high pressure is squeezed into the weak zones behind the casing. The pressure, which is applied, forces the cement into these new channels.

This could be for the following reasons:

- Repair of primary cement job
- Shut off water invasion within the productive zone
- Isolating gas zones to reduce GOR
- Repairing of casing leaks due to corrosion
- Shut off nonproductive zones
- Seal off lost circulation zones
- Protection of fluid invasion into productive zone
- De-bonding of cement caused by alkali reaction [26]

In squeeze cementing, high hydraulic pressure is applied with a pump to create new conduits. The high pressure forces the rock to be fractured. (Halliburton 2007) [4]

2.6 Liner Cementing

A liner is a casing string, which does not go all the way up to the surface. The liner is anchored at the last casing string of the intermediate section. An advantage over a production casing is that the costs can be reduced, because less steel for the well is needed. When a liner is cemented, the bottom plug is sometimes not available, due to characteristics of common liner tool systems. The bottom plug is responsible to mechanically separate the cement slurry from the spacer ahead. This limitation results in increased front end contamination of the cement slurry with spacer and even mud.

The contamination of the cement slurry occurring in liner cementing has the potential to affect the cement bond higher up in the annulus. [35]

(Standard Oil Dev Co, Oil well Cementing 2005) [7]

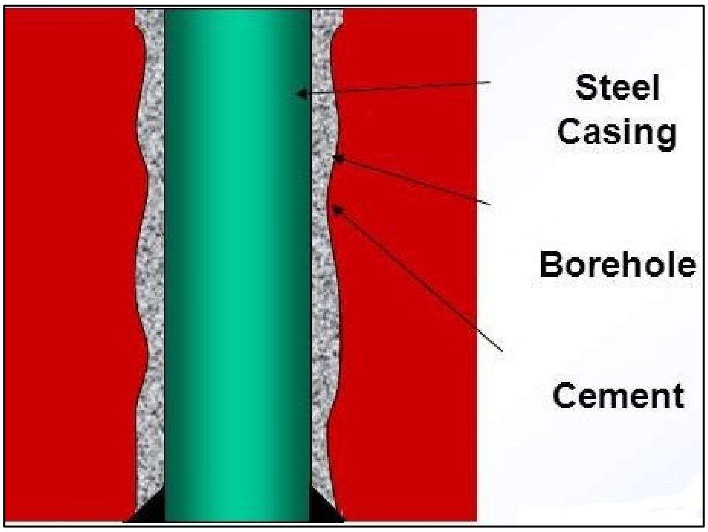


Figure 5: Full string cementing

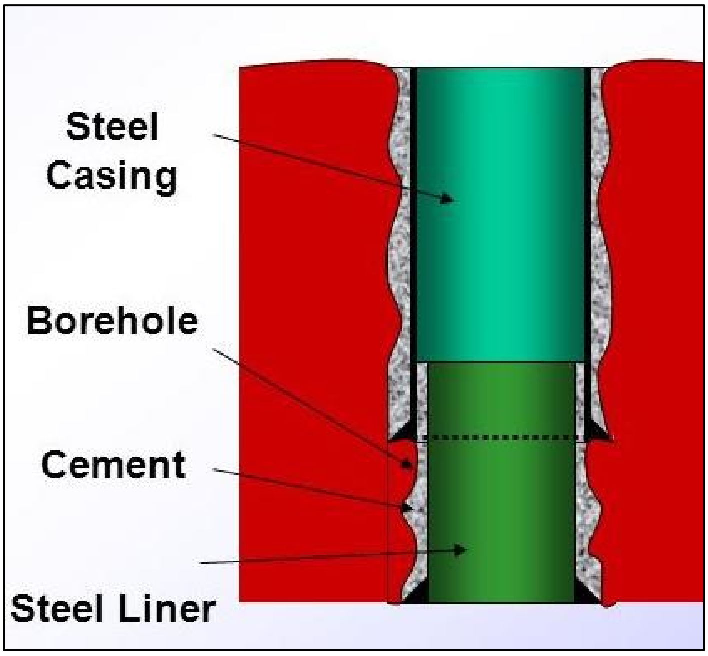


Figure 6: Liner cementing

(Standard Oil Dev Co, Oil well Cementing 2005) [8]

2.7 Drilling Mud Removal

Cementing is one of the most critical situations in drilling. Only a good cement sheath can provide zonal isolation and therefore prevent any fluids to flow behind the casing, or crossflow into other formations.

To provide a good cement sheath, the drilling mud, which is needed to stabilize and clean the hole from the cuttings during drilling, needs to be removed. To achieve that, the drilling mud needs to be thinned and dispersed and lifted out of the well. Before the cement is pumped into the well, a spacer needs to be inserted before, because when drilling mud and cement got mixed, they will form an un pump able high viscous mixture. The spacer also cleans the drilling mud from the casing and the formation walls.

It is important to be said, that the fluids, which are pumped need to a have a rheological hierarchy, which means, that each fluid which is pumped needs to be more viscous than the fluid pumped before. When the well is drilled with an OBM, the casing and the formation walls wettability are left in an oil wet condition, such weakening the cement bond. To overcome this problem, special surfactants are added to the spacer in order to transfer the wettability from an oil wet condition into a water wet condition.

Another important factor for hole cleaning is the appropriate flow regime. The predominant flow regimes for wellbore cleaning are:

- Laminar Flow
- Transition Flow
- Turbulent Flow

(FLUID MECHANICS 1994) [6]

2.7.1 Laminar and Turbulent Flow

Laminar flow is a flow regime where the fluid flows in parallel layers meaning there are no cross currents or eddies or swirls in the fluid. In a laminar flow regime the momentum of diffusion is high and the momentum of convection is low. This means that the motion of the fluid particles look like a solid surface.

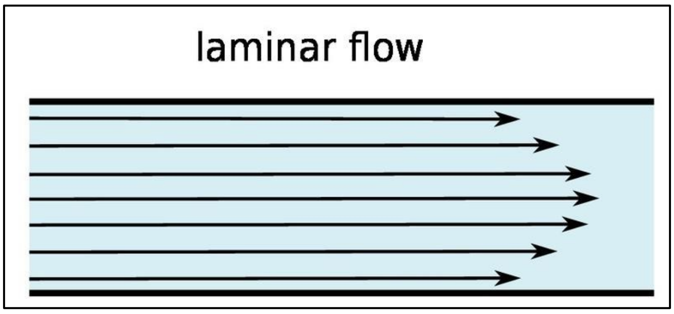


Figure 7: Laminar flow

In a turbulent flow regime, the fluid patterns are not parallel at all. This means, that the fluid behaves chaotic, there is a nearly unpredictable change in pressure and velocity. In other words, the inertial forces, are dominating the viscous forces.

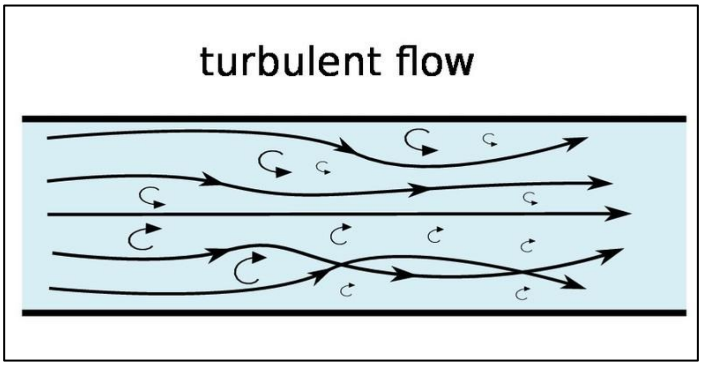


Figure 8: Turbulent flow

(Rogers 1992) [29]

2.7.3 Transient Flow

The transition between laminar and turbulent is not smooth, it is a sharp transition and acts from one second to the other. This is a very complicated process, which is at present not fully understood. The transition can act from laminar to turbulent as well as from turbulent to laminar.

2.7.3 Reynolds Number

The Reynolds Number is a dimensionless number and describes if a fluid flows laminar or turbulent. Laminar flow occurs at Reynold Numbers from 0,1~2500. If the Reynolds Number is greater than 2500 the flow is turbulent.

$$Re = \frac{v * D}{\vartheta}$$

Equation 1: Reynolds number

2.8 Flow Regimes for Drilling Mud Removal and Cement Slurry

In this case, several experiments were done in the past namely Clark and Carter [34] (1973) did some interesting experimental studies on this topic. Cement was used to displace drilling mud from the annulus. The results of mud removal were very poor when the cement was in laminar flow.

The results and the efficiency of mud removal improve when the slurry was pumped under partial turbulent flow conditions. As a conclusion of their studies it can be said, that drilling mud should be removed in turbulent flow and cement should flow in effective laminar flow.

In laminar flow, the flow lines are parallel to each other which means that the particles accumulate near the wellbore wall, because the velocity on the wellbore wall is zero, this makes fluid displacement difficult. Normally a spacer fluid is used to displace drilling mud, because cement and drilling fluid tend to gel. So when the spacer fluid is pumped in turbulent flow, the currents in the fluid move surfactants throughout the wellbore and this will destroy the static mud layer at the wellbore wall.

Since turbulent flow causes high friction pressure losses, it is recommended to use a laminar flow for cementing, because in narrow sized and tight holes a high pressure can fracture the formation and lost circulation may be the result.

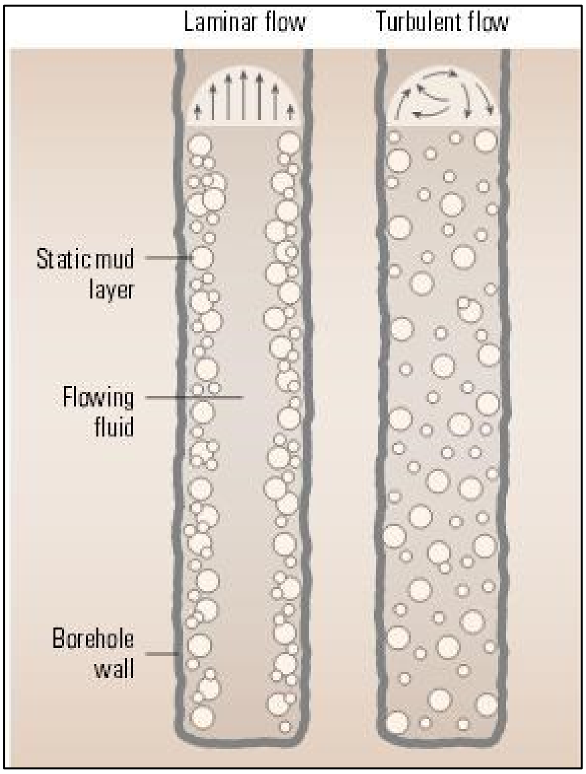


Figure 9: Drilling mud removal

(Schlumberger 2016) [23]

2.8.1 Density Differential and Fingering

To displace drilling fluid from the annulus and to provide a good cement job, engineers designed a spacer fluid. A spacer fluid is a fluid, which has a higher density than the drilling mud. The higher density is needed to displace the lower density fluid and to provide a flat and stable interface between the two fluids. A stable and flat interface only can be provided, if the displaced fluid has a lower density than the displacing fluid, otherwise fluid fingering or viscous fingering happens, which means that the fluids would mix up and improper hole cleaning may be the result. It can be described with syrup being filled carefully on a water surface. The syrup is the more dense fluid and will "finger" into the water. For displacing and displaced fluids, friction pressure is another important issue. To improve the cleaning efficiency for drilling mud removal, the friction of the displaced fluid must be lower than the friction of the displacing fluid. (Schlummberger 2016) [5]

2.8.2 Mud Cake

Drilling a well without a drilling fluid is impossible, because the cuttings created when the rock is crushed, have to be removed. Engineers designed special drilling fluids to handle this problem. When the drilling fluid is pressed against a porous formation wall, a so-called mud or filter cake is the result. Usually the filter cake has a thickness of 2-5mm but is depending on the drilling fluid and the hydraulic conditions. When the drilling fluid is forced against the formation wall, a certain fluid loss happens into the porous formation. The same scenario happens when the cement slurry is pressed against the formation wall.

The water in the slurry penetrates into the porous formation and as a result, the cement slurry will have a higher viscosity. So a high fluid loss means, that the viscosity of the fluid increases as well as the friction pressure. Dewatering of a cement slurry means that not only the viscosity increases, also the compressive strength does. Fluid loss of cement slurries into the formation should be in a certain limit to achieve a proper zonal isolation. Definition after Hartog et al:

Oil Wells	200mL /30min
Gas Wells	50mL /30min

So usually, a filter cake takes care, that the drilling fluid stays inside the hole and does not press into the formation, because a fluid invasion can alter the rock and may reduce the production rate. On the other hand if the cake is too thick, various problems like differential sticking could be the problem.

Another characteristic of filter cake is that it acts as a wellbore strengthening material. The particles in the cake plug small fractures into the pores of the rock and this means that no fluid can enter the pores that would allow the fracture to grow.

For well cementing, a good filter cake is bad for every cement job, because the cake on the wellbore wall hinders the cement to establish a good bond with the formation. Filter cakes can be removed physically/ mechanical or chemically. When they are removed mechanically, a solid free brine is circulated at high flow rates with turbulent flow. But this technique removes only the external drilling fluid damage.

If the cake is removed, chemically alkaline tannate solution and other similar chemicals are used to reduce the viscosity of the drilling mud and tend to soften the mud cake.

Another option to remove the mud cake would be to increase the abrasiveness of the cement slurry to scratch off the mud cake. Under some circumstances, it is a good choice to combine the mechanical and chemical techniques. In this combination, a dispersing agent is pumped ahead of the cement slurry and additionally abrasive particles are added to the cement. (Rogers 1992) [29]

2.8.3 Investigations and Experiments with Steel Pipe and Formation

In 1962 several experiments concerning the bonding strength between cement and rock were carried out by Carter and Evans [2]. For their experiments they used Indiana limestone and Berea sandstone. The problem in their studies with sandstone was that the bonded interface was stronger than the matrix of the rock. The experimental setup was to bring a dry rock sample in contact with the cement slurry. The slurry was squeezed against the formation.

In the next step, the rock samples were treated with drilling mud and the interaction with the cement slurry was observed. The result of their tests was that the shear strength is reduced dramatically when the slurry comes in contact with drilling mud. Carter and Evans also tested the hydraulic bond of formation. In these experiments also no correlations between shear strength and hydraulic bond strength were found. Conclusion was that both properties vary as a function of the same external parameters. A decrease in shear and bond strength happens with decreasing surface roughness, bad drilling mud removal and if the wettability is oil wet.

Bond strength also changes with the variations of internal casing pressure and temperature. Cement is known to be a good material in case for taking pressure forces, but is very bad for tensional loads. Therefore also temperature changes have a big impact on bond strength. The final conclusion of their work was that hydraulic bond failure is a function of pipe expansion or contraction and the viscosity of the pressurized fluid.

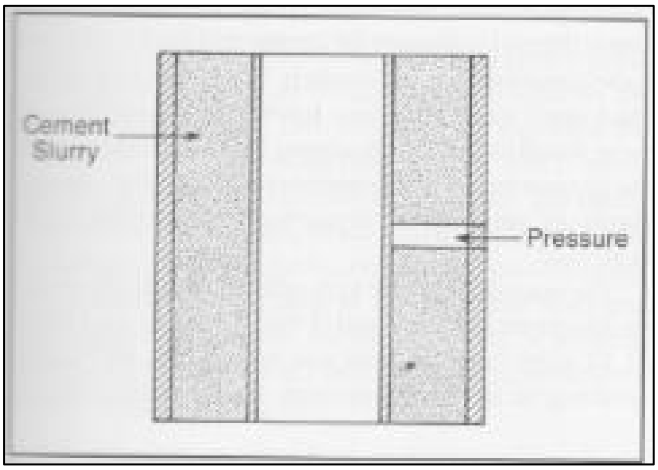


Figure 10: Testing Cell from Cater and Evans

(E. B. Nelson 1990) [12]

In 1963, Becker and Peterson did an independent experiment on shear bond and tensile strength and they reached similar results like Carter and Evans [2]. In the experiment of 1963, it was shown that the bonding between cement and casing is connected to adhesive forces at the interface. The investigations showed that wettability of the casing surface and the degree of hydration of the cement plays a mature role in bonding strength.

Nearly 20 years later in 1984, Parcevaux and Sault combined the shear and hydraulic bond strength between cement and steel pipe with total chemical contraction and stress/strain relationships. Their investigations showed that bonding of cement and steel gets better when the chemical contraction is low and the cement deformability is high. In all those investigations no evidence of micro annuli was found in case of cement shrinkage, but it was found that cement shrinkage could cause bonding failures on the surface area.

All experiments, which were done in the past indicate out that the causes for bonding defects at the cement/casing and cement/formation interfaces are:

- Lack of casing and formation roughness
- Cement bulk volumetric shrinkage
- Mud film or channel at the interface
- Free water channel or layer in deviated wells
- Excessive downhole thermal stresses
- Excessive downhole hydraulic stresses
- Excessive downhole mechanical stresses

(E. B Nelson, 1990) [12]

2.8.4 Push Out Tester

Another method to investigate the cement bond strength is the push out test. Therefore, a rock sample was cemented into a steel chamber which consist of two half cylindrical shaped segments. With a push-out tester, it was tried to push the rock sample at the interface between rock and placed cement. Tests were conducted with dry and drilling fluid contaminated rock samples. In this test shear strength was calculated as a measure of bonding strength. [36]

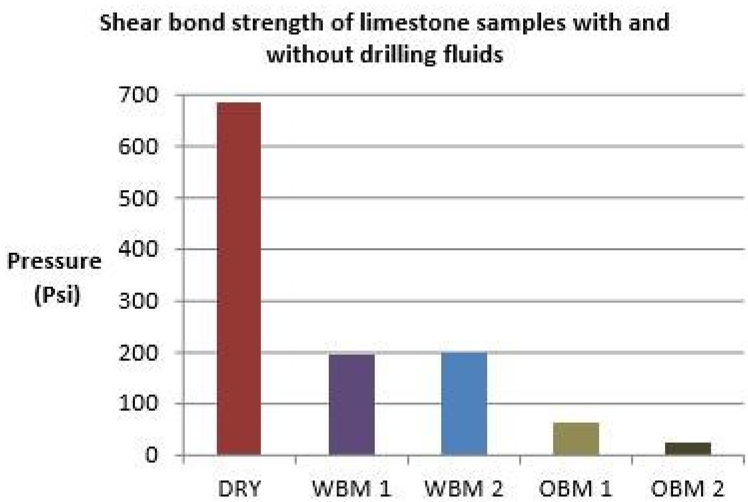


Figure 11: Shear bond strength of limestone with and without drilling fluids

Chapter 3 Stresses and Deformation of Rock

Stress is known as a force, that acts on a body and produces strain. The unit for stress in SI Units is [N/mm²].

Pressure is a stress where the force acts equally in all directions. If the latter is not the case, differential stress is the result, three kinds of which can occur.

- Tensional stress
- Compressional stress
- Shear stress

When a stress is acting on a rock or a rock element, the rock is deformed, so size, shape or volume of the material are changing.

3.1 Stages of Deformation

Elastic deformation:

Elastic deformation is a deformation, which is temporary, reversible and is related to the Hooks Law:

$$F = k * X$$

Equation 2: Hooks Law

k is a constant factor of the material and X is the elongation until the material can be deformed without permanent deformation.

Ductile deformation:

If the material is deformed over the Hooks Area, ductile deformation is a permanent result. The ductility varies over different materials. Steel is more ductile compared to rock.

Fracture

Fracturing happens, when the material is deformed over the ductile area.

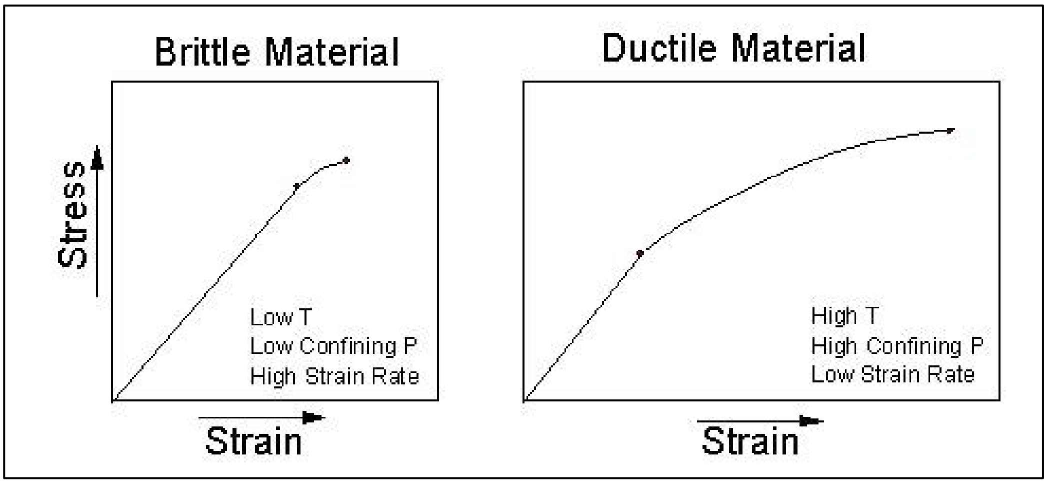


Figure 12: Brittle and ductile materials

(Nelson P. S., 2015) [9]

3.2 Behavior of Materials

How materials behave, depends on several factors, which are:

- **Temperature:**

  At elevated or high temperatures the molecules and their bonds strain, which has the effect that the material is more ductile. A very good demonstration of this effect is to cool down a steel pipe with frozen Nitrogen to a temperature of -196°C. If this steel hits the floor, it will break immediately. But if the steel is heated up 1000°C the distance between the molecules increases as well as the ductility, while the stability of the steel decreases during the process of cooling or heating.

- **Confining pressure:**

  If the confining stress around a material is high, it is less likely to fracture, because the surrounding pressure hinders the material to fracture. At low confining stress the material behaves brittle and fracturing happens sooner.

- **Strain rate**

  The strain rate is defined as:

$$\epsilon = \frac{L(t) - Lo}{Lo}$$

Equation 3 Strain rate

If the strain rates are high, the material tends to fracture easier than at low strain rates, because at low strain rates the molecules have more time to move.

Composition:

The composition of the material is pivotal, if the material is brittle or not. Quartz and feldspar are very brittle materials, which comes from their chemical bonding.

Clay is a very ductile mineral, because clay consists of various thin layers, which can be shifted easily.

Another aspect is the presence of water. Water tends to weaken the chemical bonds and act like a film layer over the molecules and slippage can happen easier. This is the reason why wet rock tends to behave more ductile than a dry rock does.

(Nelson P. S., 2015) [9]

Chapter 4 Cement

Cement is a material, which is used to fill the conduit between the drilled hole and the casing. The three major tasks of cement are:

- Zonal isolation
- Corrosion Control
- Formation stability and improvement of the pipe strength

Most cement compositions, which are used in the Petroleum Industry mostly consist of Portland cement. The name Portland relates to a British Channel Island with a limestone deposit, that was used as source of stone for the development of *Portland cement*. In 1824, *Joseph Aspin* patented this special type of cement. Nowadays cement is produced in the factory in a continuous process, predominantly from naturally resources in a special dry process. Depending on the facility size, the output of cement varies between 3000 to 10000 tons per day.

The raw materials, which are typically limestone, clay, sand and iron ore are produced from stone pits and are crushed. This powder is mixed with the other raw materials and dried, at the same time. The so called “raw flour” is put into a rotary furnace at a temperature around 1450°C and the so called clicker brick is burned, which is cooled at around 200°C in the next step. The resulting grey brown granular is blended with $CaSO_4{*}2H_2O$ (Gypsum) and $CaSO_4$ (Anhydrite) and milled in a ball mill to the final product. Due to the blending of additives, such as granulated cinder or pozzolan, fly-ash and limestone, cements with different properties can be produced.

4.1 Hydraulic Properties of Cement

Cement is a hydraulic binder, this means it hardens as well as in air as under water and is resistant. Cement is not like chalk, which hardens with the presence of CO_2 in the air, it reacts with H_2O and forms insoluble stable chemical connections. Those bonding’s are called “Calcium silicate hydrates” or “Ettringite” (Equation 4) and the congeal form is Portlandit. (Equation 5)

$$[3CaO{\cdot}Al_2O_3{\cdot}3CaSO_4{\cdot}32H_2O]$$

Equation 4

$$[CH\ (Ca(OH)_2)]$$

Equation 5

The “Calcium silicate hydrates” form fine needle like crystals, which interlock into each other and such creating a highly stable cement. This makes cement to the perfect construction material which is needed in wellbore cementation. [22] [21]

Portland cement, which is produced through milling of clinker, gypsum and anhydrite is chemically seen:

55-66%	CaO	Calcium oxide
18-26%	SiO_2	Silicon dioxide
4-10%	Al_2O_3	Alumina oxide
2-5%	Fe_2O_3	Iron oxide

Table 2 Composition of Portland cement

During the firing process, crystals are formed of the main components, which are important for the different properties of cement. The most prominent are:

$3\ CaO \times SiO_2$	Tri calcium silicate	C_3S
$2\ CaO \times SiO_2$	Di calcium silicate	C_2S
$3\ CaO \times Al_2O_3$	Tri calcium aluminate	C_3A
$4\ CaO \times Al_2O_3 \times Fe_2O_3$	Tetracalciumaluminatferrit	C_4A

Table 3: Main components of cement

(Locher, 2000) [10]

4.2 Protective Coating Theory

If cement comes into contact with water, C_3S and C_2S react to form "Calcium silicate hydrate" gel. (C-S-H). At this stage initial surge, due to heat or hydration of free lime, occurs. External reactions of C-S-H are inhibited by a semi permeable gel coat, but the internal reactions continue. This phase is called the "dormant" or "induction" phase.

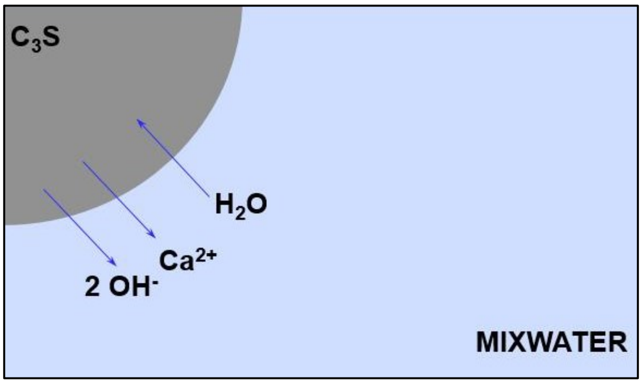


Figure 13: Ion change of C_3S and H_2O

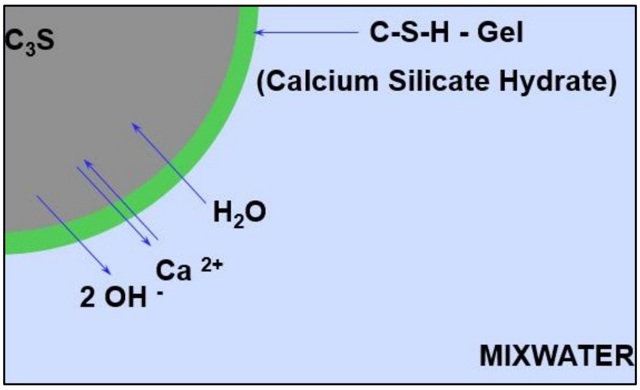


Figure 14: Semi permeable gel coat of C_3S

(UCSI, 2014) [33]

The protective coating theory implies, that an osmotic pressure builds up during the internal reactions. This causes the C-S-H structure to rupture and materials like $Ca(OH)_2$ are released. The C-S-H tubulars grow and form a network interlocking with other hydration products.

(UCSI, 2014) [33]

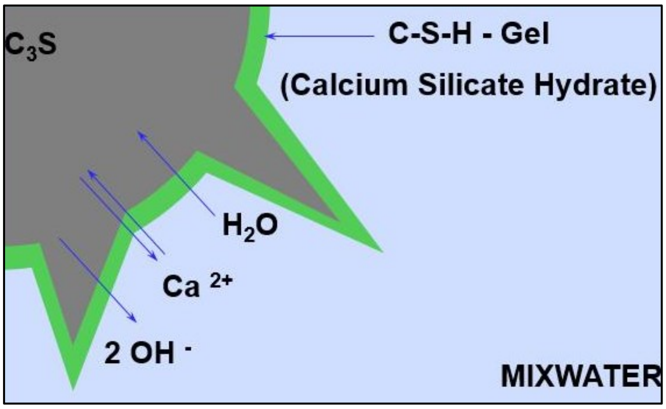


Figure 15: Rupturing of C-S-H structure

4.4 Delayed Nucleation Theory

The delayed nucleation theory is based on the reaction between C_3A (Tri calcium aluminate) and gypsum/anhydrite which forms "Ettringite" (Figure 16). Ettringite coats the surface of C_3A and reduces the reaction, until all gypsum present, is consumed. In the next phase "Ettringite" converts to aluminate hydrates.

(UCSI, 2014) [33]

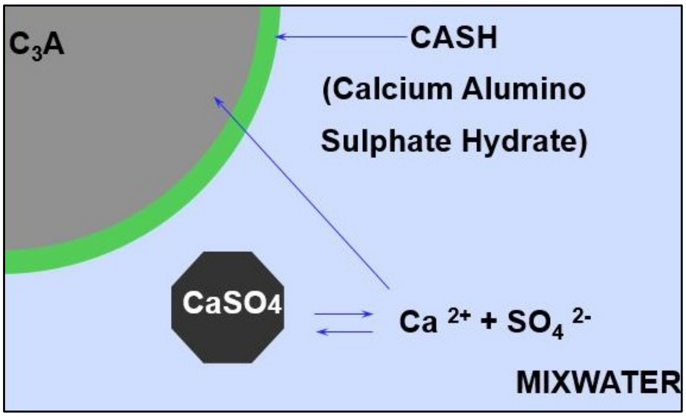


Figure 16: Ion exchange between C_3A and Anhydrite

Chapter 5 Experimental Setup

The experimental set up for the shear force test is a simple test bench, where 4 steel/cement tests can be run as well also 6 rock cement/ tests at the same time. Figure 16 shows the shear test bench.

Figure 17: Shear Test Bench

To measure the required shear force, which is needed to break the bond at the respective interface, a plastic cylinder of a height of 50 mm and a diameter of 40 mm was filled with wellbore class G cement. It represents the annular cement in the wellbore and was cemented on steel plates, which represents the casing wall, as well as on rock which represents the borehole wall. Figure 17 shows the casing steel plate and Figure 18 shows the borehole rock element. To measure the shear force, a steel wire was put around the cylinder and the rope was guided over a sheave. At the end of the rope, a bucket was fixed to put in the weights.

To provide good testing boundaries, the steel plates were put on wooden bars and screwed on the table to fix the steel plate. To provide that bending moments are zero, the steel plates were put on wooden bars, such taking care that the surface of the steel is in the same height as the wheel of the sheaves. To test the rock-cement interface, special steel cubes were used, where the rock cubes fit in perfectly. The rock surface was also mounted on woodbars in order to provide that the surface of the rock is on the same height as the surface of the sheaves. As test weight Barite was used, because Barite has a high density (4,5 g/cm³) and is therefore better useable than water. Another advantage of Barite is that it is a solid powder and does not transfer vibrations, such as water would do. The Barite was filled in small plastic bags, with a weight of 100 g, 200 g and 400 g.

Figure 18: Casing steel plate

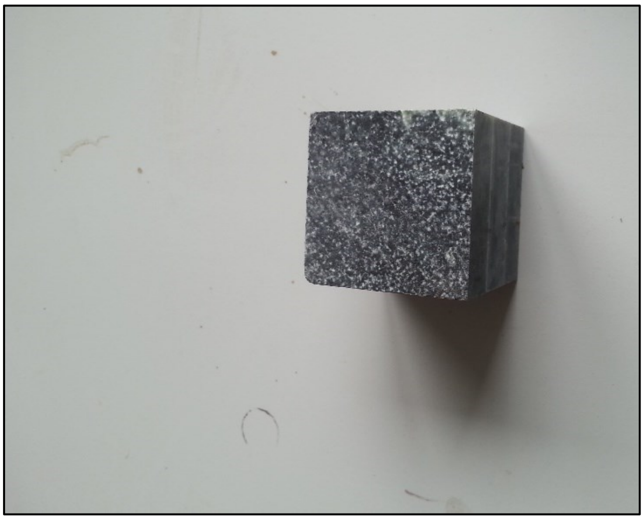


Figure 19: Rock element (Serpentinite)

The plastic cylinders were cut with a band saw and the edges where re-treated with sandpaper in order to provide that the cement will stay in place when it´s liquid.

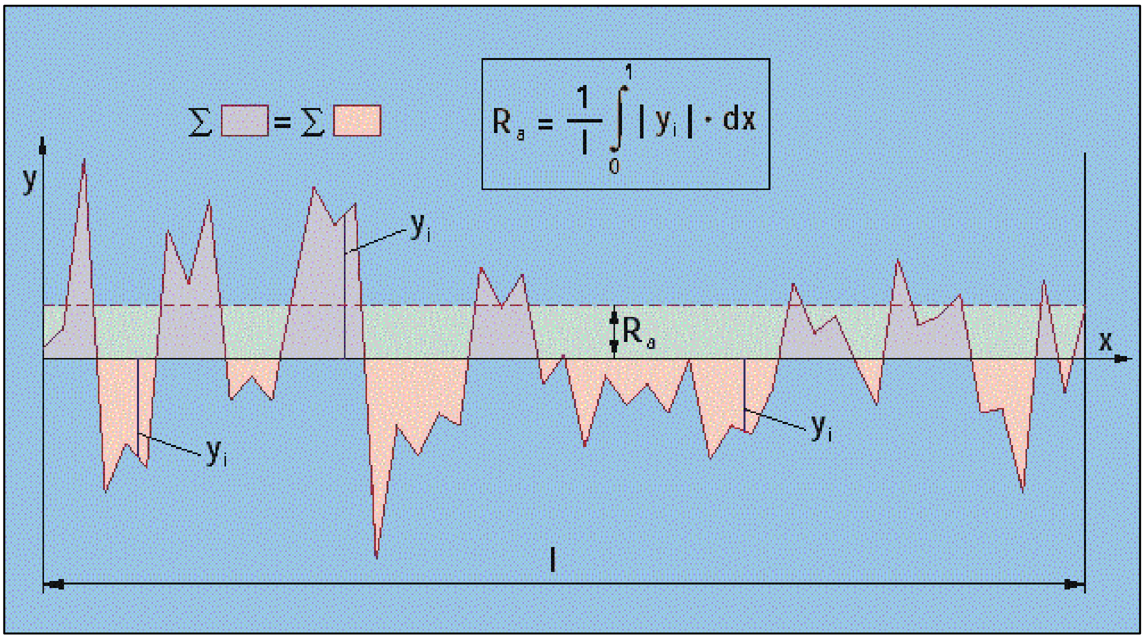
Cement was mixed with a blender under API guidelines (Affected Publication: API Specification 10A/ISO 10426-1, Specification for Cements and Materials for Well Cementing, Twenty-third Edition, 2005). After filling the cement into the cylinder, the curing time was 3 days, to provide a solid interface between cement and the tested surfaces.

The rock samples, which represent the borehole wall were cut in 50 mm x 50 mm cubes with the Gölz Rock saw.

To provide a good bonding interface, the ratio of H_2O and cement needs to be at approximately between 44-48% H_2O and 54-56% cement. For all these experiments API guidelines were applied and the ratio therefore is 44% H_2O and 56% cement.

Chapter 6 Surface Roughness Test

Before the shear tests could be conducted, the surface roughness of each test sample had to be taken. The surface roughness can be interpreted as “Mountains and Valleys”. Figure 19 shows the schematic of a surface.



(Tiefbohrlexikon/ Oberflächenkennwerte, 2014) [32]

Figure 20 Schematic of a surface

Ra [µm] is the mean surface index and is determined by a predefined measuring section of the measuring device. The device consists of a small needle and touches the surface in the measuring section and with Equation 6 the mean surface index is calculated.

$$Ra = \frac{1}{l}\int_0^l |yi| * dx$$

Equation 6: Mean surface index

Surface roughness is an important parameter in case of shear force, because the possibility that the Ettringite needles (formed by the cement) migrate into the surface increases with increasing roughness of the surface. The following tests show the different results in relation to the different surface roughness values.

(Tiefbohrlexikon/ Oberflächenkennwerte, 2014) [32]

Chapter 7 Steel/Cement Shear Test

The first shear test cycle included 5 tests and which were conducted with Schlumberger Class G cement and steel plates. Because no reference was available, the first tests were used to get a feeling for the material.

In the first test, the steel surface had a roughness of 7,5 µm. As mentioned above, there was no reference, at which load the bonding would fail. So this first test should help to find the boundary for the next tests. The starting weight was 2441 g (2000 g Barite and 441 g was the weight of the bucket). When the weight was applied, no sound was detected. Weight was applied uniformly until the bond failed. Vibrations when applying weight, were prevented during the whole test.

7.1 Test 1 Steel/Cement

At a weight of 6000 g Barite, the interface was still in integrity, so the decision was made to break up here and continue the test the next day. Next morning, the cement bonding was still intact. The test was continued with adding Barite in 100g intervals. When the load reached 7000 g a noise was detected and the cement bonding failed after 3min.

Results Test 1:

Weight [g]	7441
Force [N]	73
Stress [N/mm²]	0,076

Table 4: Results Test 1

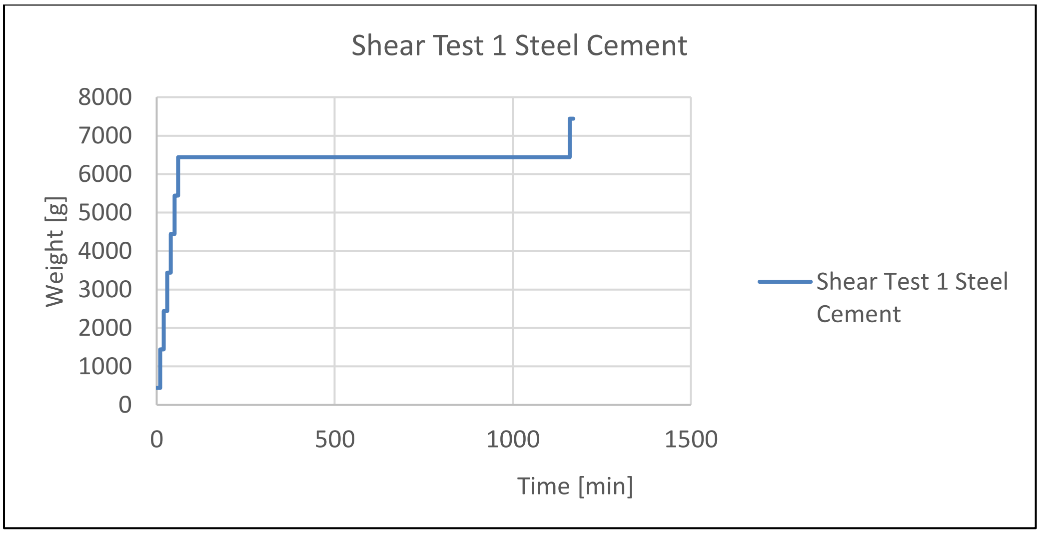


Figure 21 Shear Test 1 Steel/cement

Figure 22: Test sample 1 Steel/Cement

The first test showed, that the load that the cement bond can take, must be around 7,4 kg. With this information, the next test could be performed.

7.2 Shear Test 2 Steel/Cement

Shear test 2 had a surface roughness of 8,3 µm. Test procedure for this test was similar to the first one. Weight was applied up to 7000 g in 1000 g steps. After this, the additional load ups were reduced to 500 g, because 7441 g was the maximum load capacity for shear test 1. After reaching the 8441 g mark, a crack noise was detected and which was a clear indication that the bonding begins to fail. Before the bonding failed completely, another 1000 g could be applied to the bonding. Failure happened immediately in this test.

Results Test 2

Weight [g]	9441
Force [N]	93
Stress [N/mm²]	0,096

Table 5: Results Test 2

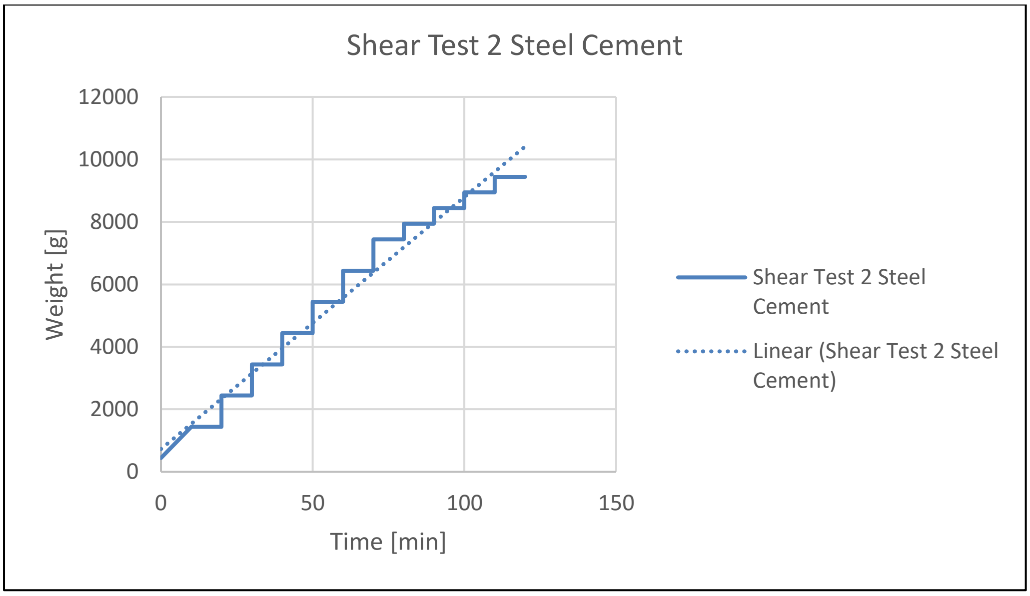


Figure 23 Shear Test 2 Steel/cement

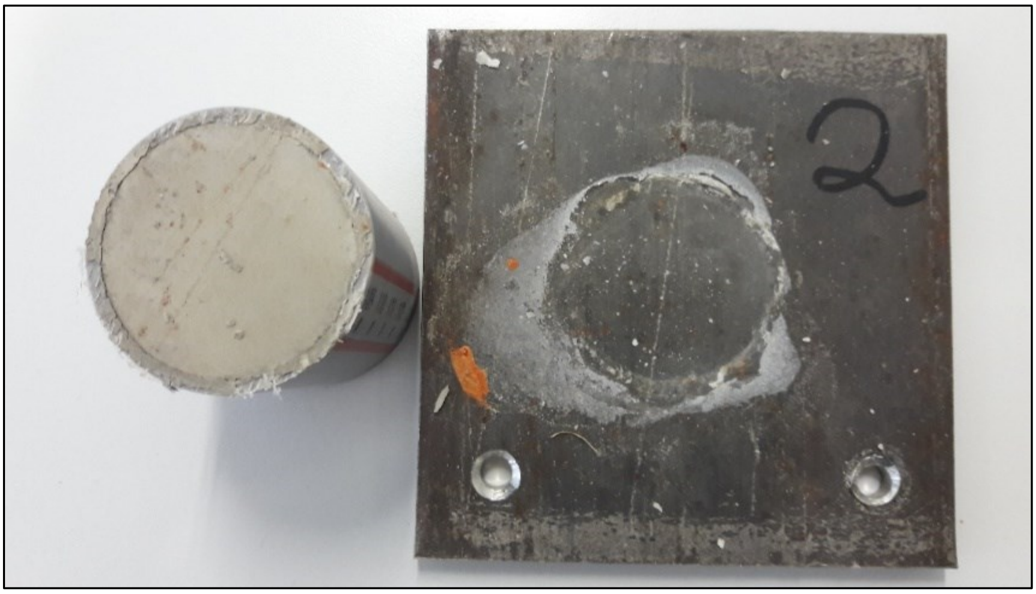


Figure 24: Test sample 2 Steel/Cement

7.3 Shear Test 3 Steel/Cement

Considering that the cement bonding is very strong, the expectation for the additional weight for the third shear test was also 8-9,4 kg, because the surface roughness was 8,68 µm likewise . In the third test, also a sound was detected during the test at 9441 g and the weight steps were reduced to 500 g each, such as it was performed in test 2. The bonding failed at an additional weight of 9941 g. It was not so, that the bonding failed immediately; this time it held another 10 minutes before the failure happened. Test plate 2 had some deep scratches on the surface, pointing to the load direction. If the deep scratches would run perpendicular to the load direction, the shear load might have been higher than 9441 g, due to the gearing effect of the Ettringite needles.

Results Test 3:

Weight [g]	9941
Force [N]	98
Stress [N/mm²]	0,1

Table 6: Results Test3

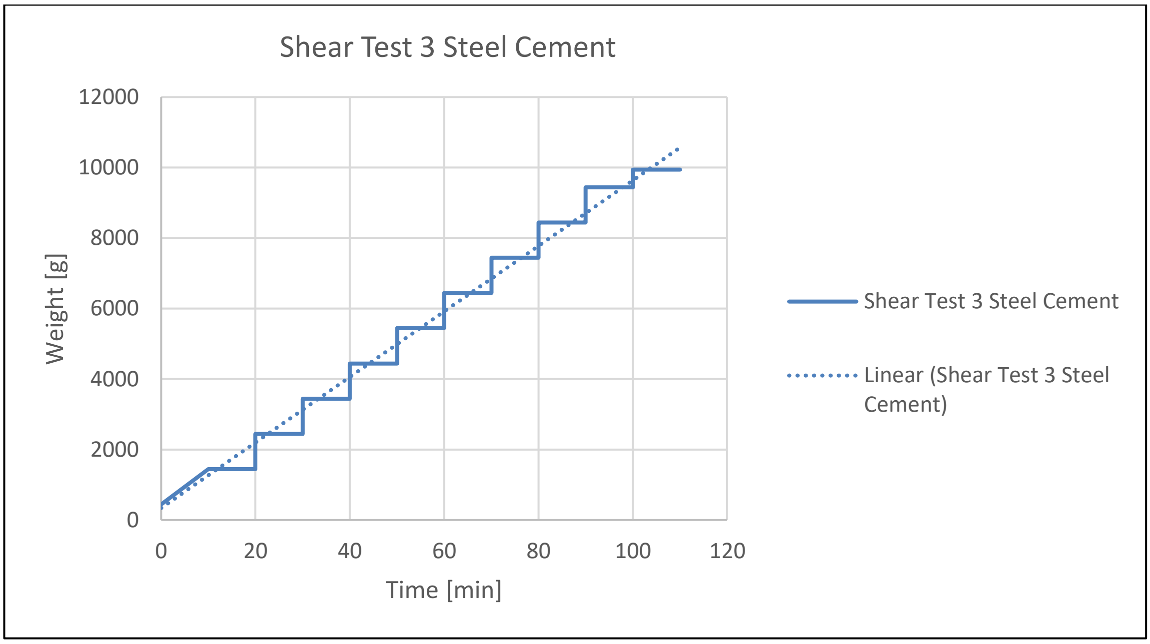


Figure 25: Shear Test 3 Steel/Cement

Figure 26 Test sample 3 Steel/Cement

7.4 Shear Test 4 Steel/Cement

The surface roughness of the steel plate used in the fourth test was around 7,3 µm and therefore lower than the roughness of test 2 and 3. The expectation of failure was about 7,4 kg, as it was like it was in test 1.

Weight was applied up to 7000 g and this time no sound was detected at any time during the test. As expected, failure happened at 7441 g. The bonding did not fail immediately, the interface between steel and cement was able to withstand the load for another 2 minutes. Shear plate 4 had also deep scratches on the surface, pointing in the load direction likewise, thus giving no additional hold points for the Ettringite needles.

Results Test 4:

Weight [g]	7441
Force [N]	73
Stress [N/mm²]	0,075

Table 7: Results Test 4

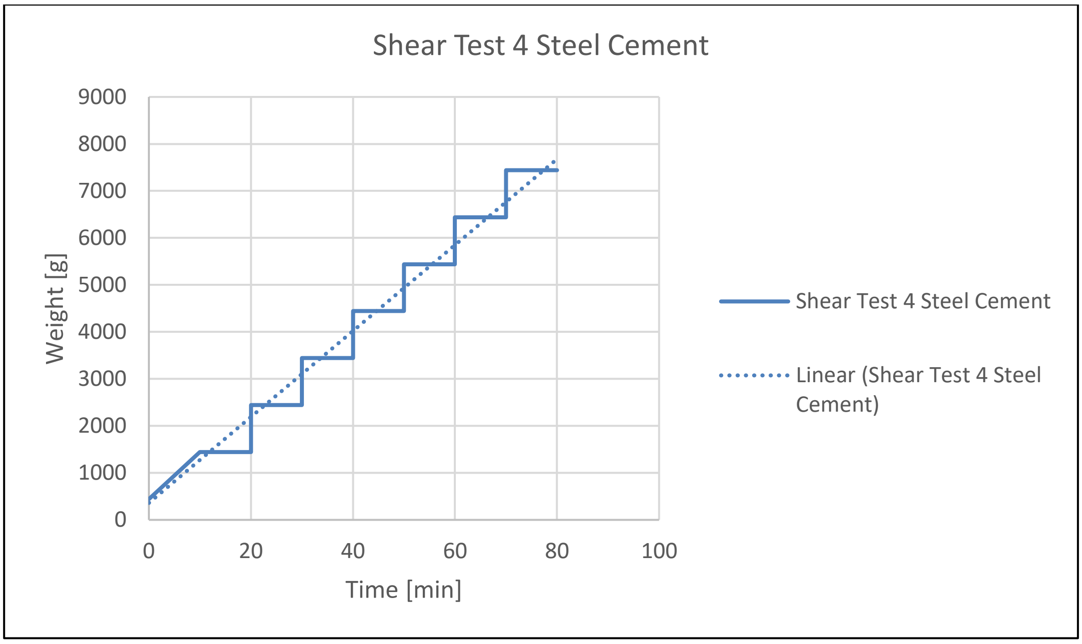


Figure 27: Shear Test 4 Steel/Cement

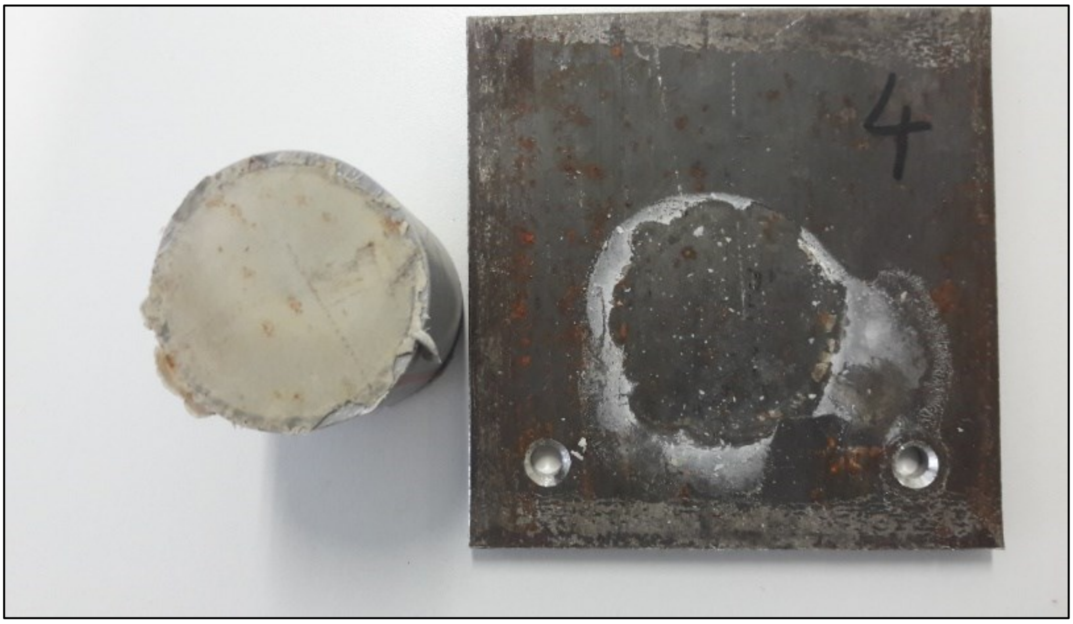


Figure 28: Test sample 4 Steel/Cement

7.5 Shear Test 5 Steel/Cement

For the fifth and last test of test cycle 1, the surface roughness test showed that the roughness of steel plate 5 was the lowest in this test cycle. The surface roughness for this test was 3,4 µm and therefore the expectation for failure was much lower than 8 kg.

Weight was applied up to 2500 g and a crack sound was detected when the weight was applied. The same sound was detected in test 2, which was a clear indication to reduce the load increment to 1000 g each. At an additional weight of 3500 g, a second crack sound occurred and the load increment was reduced to 500 g. At this point, the decision was taken not to go beyond a load weight of 4441g, instead it was decided to see, how long the bond could withstand a weight of 3941 g. The bond was able to handle this load for another 8 minutes, before the failure happened.

Results Test 5:

Weight [g]	3941
Force [N]	39
Stress [N/mm²]	0,04

Table 8: Results Test 5

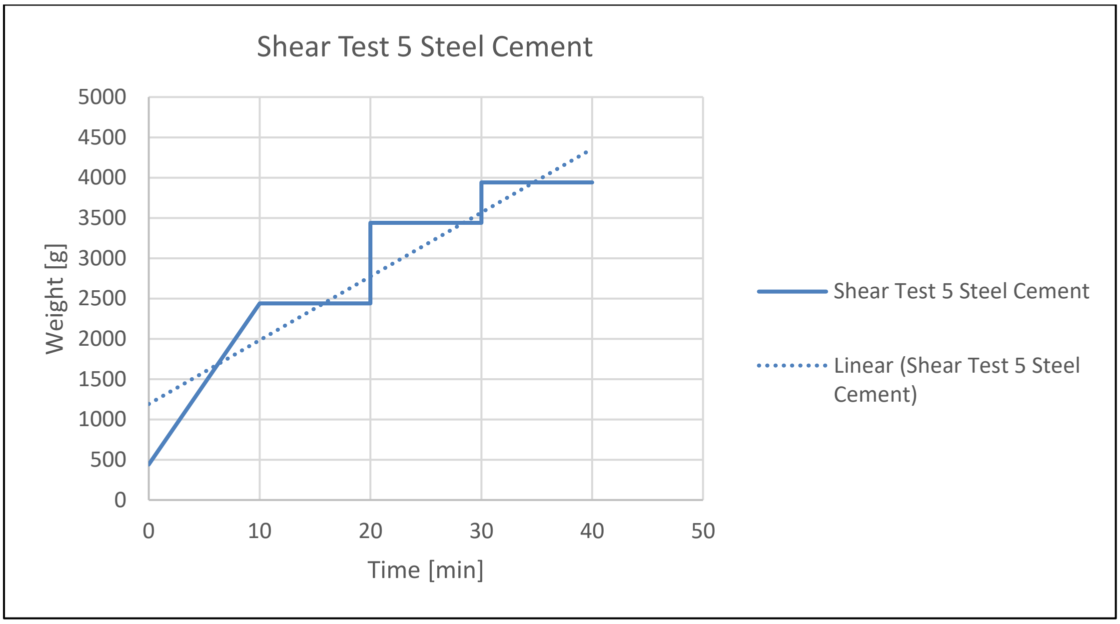


Figure 29: Shear Test 5 Steel/cement

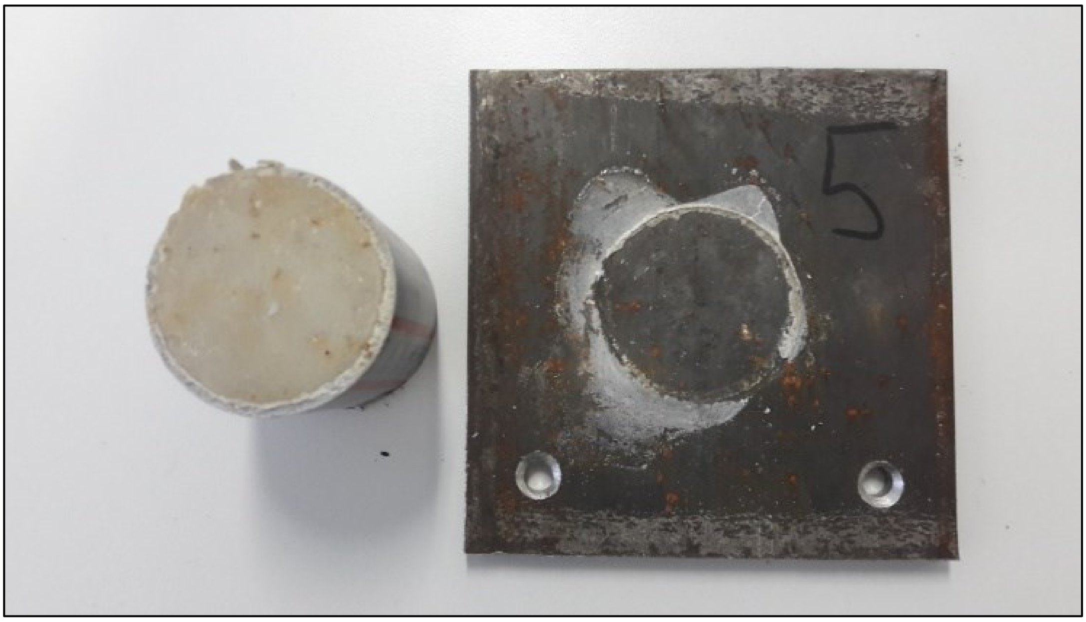


Figure 30: Test sample 5 Steel/Cement

When taking a closer look on shear plate 5, it is obvious to see, that this plate had no deep scratches, either in or perpendicular to the load direction. Also the surface roughness test showed, that the roughness was only 3,4 µm. This might be the reason why the Ettringite needles, which the cement forms, were not able to gear into those "valleys" and therefore the load, which can be applied is much lower than in the other four tests.

For the cement/ steel shear tests, 24 tests were made with quite different results. Test 1-5 were done to get a feeling about the load boundaries. Test 6 and 7 failed because of tube tightness.

As shown before, the surface roughness might play a big role for shear force. When the surface roughness is about 3,4 to 8,7µm, the maximum shear load is between 39 N (0,04 N/mm²) and 98 N (0,1 N/mm²).

7.6 Shear Test 8 Steel/Cement

Surface roughness for test 8 was 12,6 µm and the assumption was, that the shear force must be much higher than 98 N. In this test, weight were applied up to 14000 g and when a crack sound was detected, weighing up was stopped immediately and the bonding was able to withstand this load for another 8 minutes. For the other tests, the surface roughness was between half to a third of the roughness of shear plate 8 and the shear force values behaved accordingly. Shear plate 8 had also no deep scratches in the surface, but there were a few steel knuckles on it, were Ettringite needles were able to gear in , being also the reason for the higher load.

Results Test 8:

Weight [g]	14441
Force [N]	141,6
Stress [N/mm²]	0,15

Table 9: Results Test 8

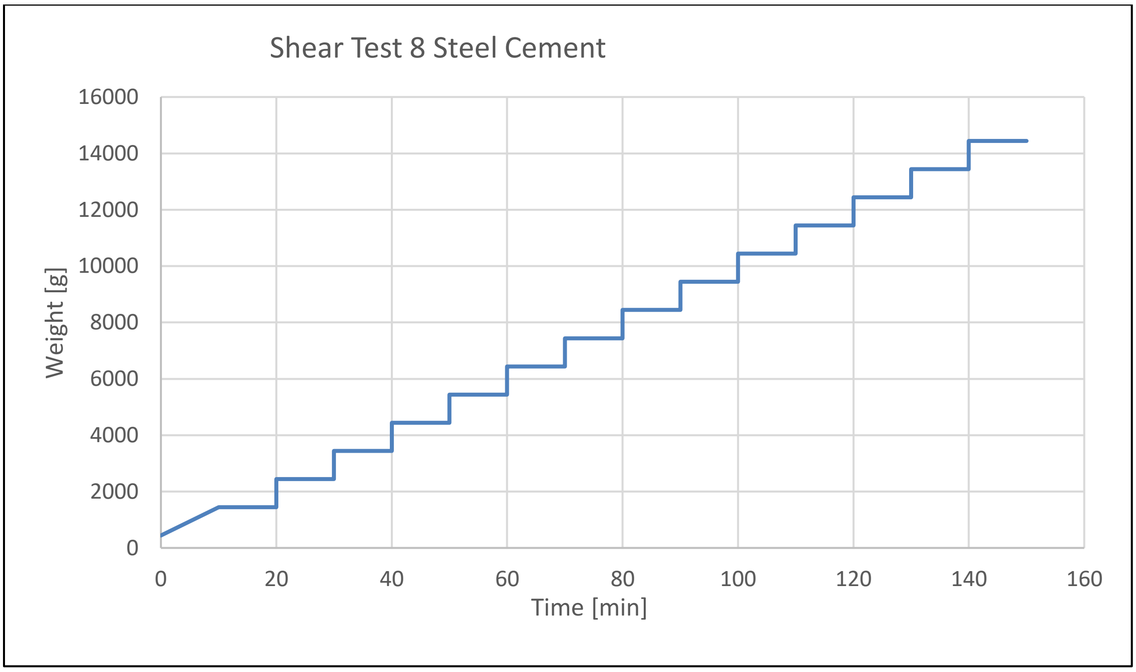


Figure 31 Shear Test 8 Steel/Cement

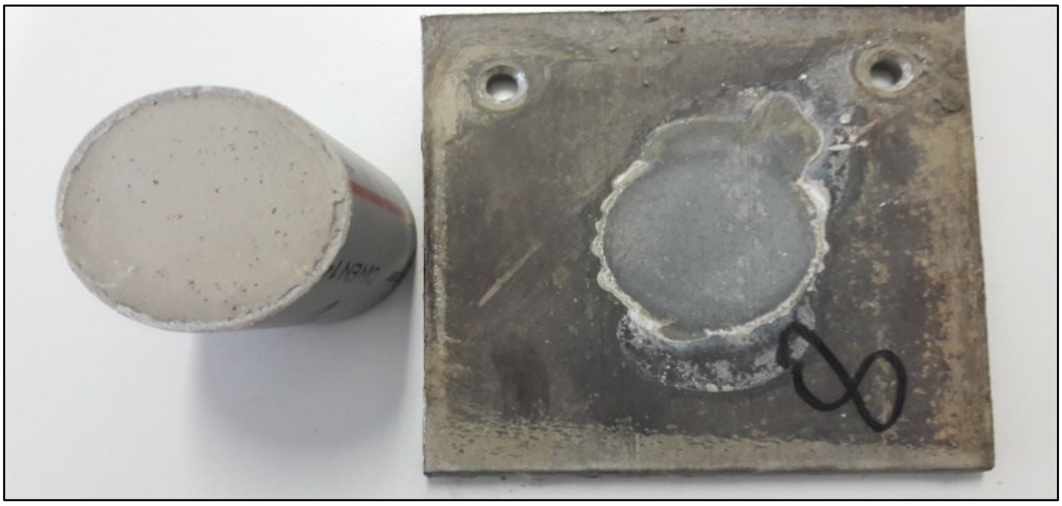


Figure 32: Test Sample 8

7.7 Comparison of Steel/Cement Tests

The following graphs show a comparison of the maximum tension of all 19 steel cement tests and the impact on surface roughness and shear load.

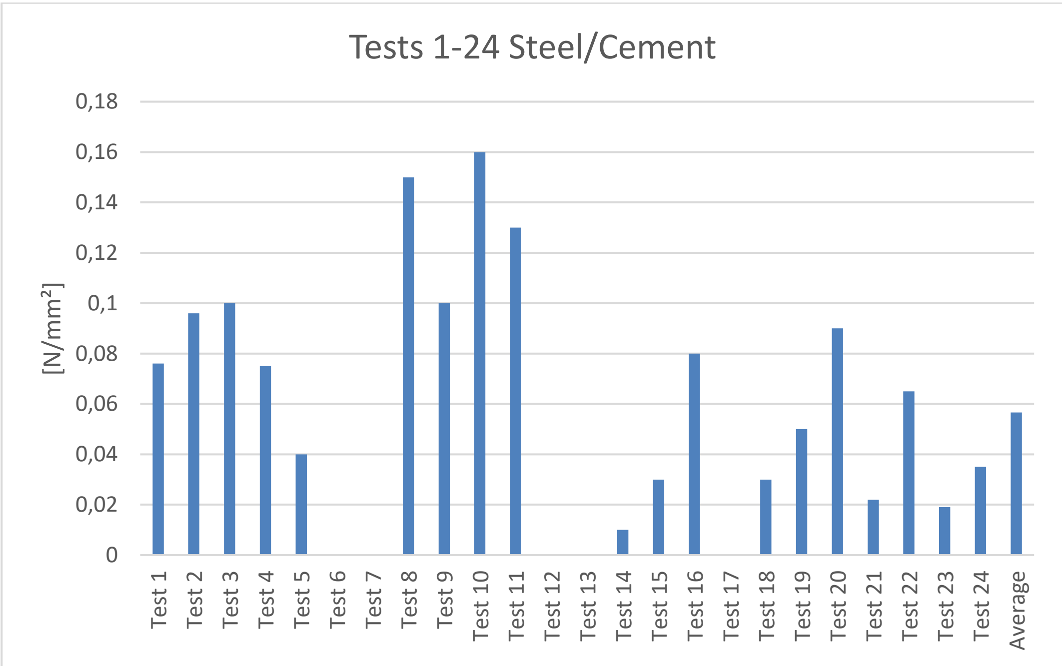


Figure 33: Comparison Test 1-24

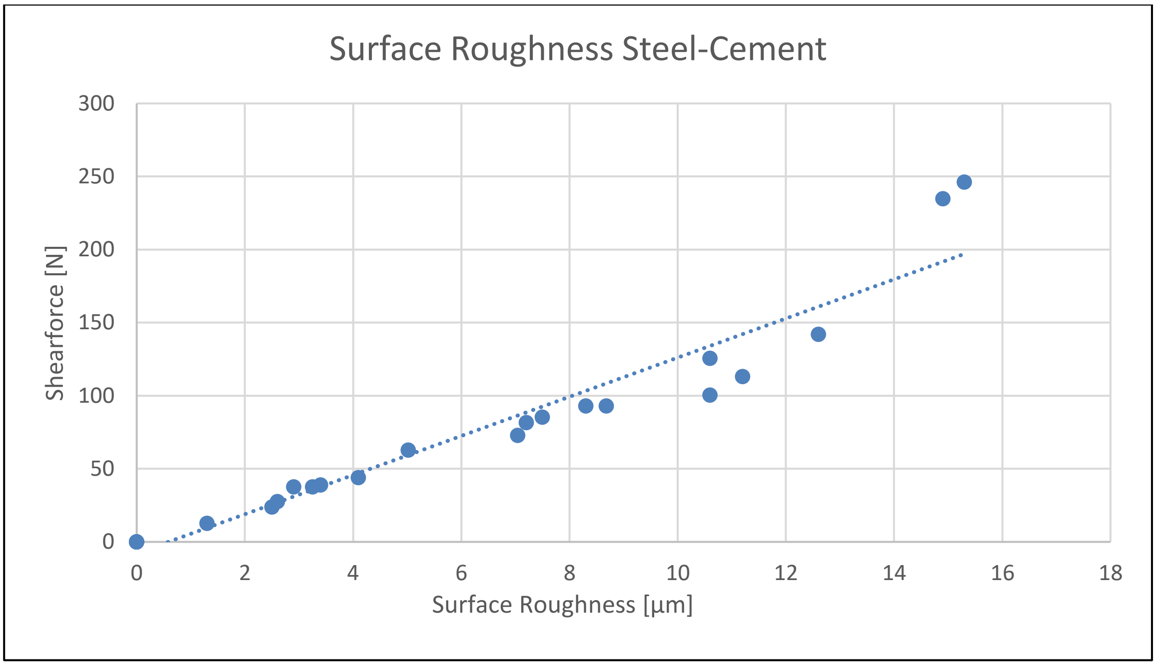


Figure 34: Surface Roughness Steel/Cement Test 1-19

7.8 Grounded Steel/Cement Tests

The following test procedure was made with grounded steel. Four steel plates were grounded to a surface roughness of 15.5 µm, 16,25 µm, 15,25 µm, and 15,68 µm. The reason why not all 4 plates had the same roughnesses was, that the equipment used is not designed for accurate surface grounding. For grounding, an angle grinder was used and Figure 34 shows the surface roughness of the plate. On all four plates dip of cleaves were 45° to the shear direction, which is an effect of the rotating grinding paper of the angle grinder.

All four tests were conducted like the tests before and the expected shear weight was between 22 and 26 kg. The graph below shows the results and it clearly can be seen, that the behavior between surface roughness and shear force is of linear nature.

Figure 35: Grounded steel

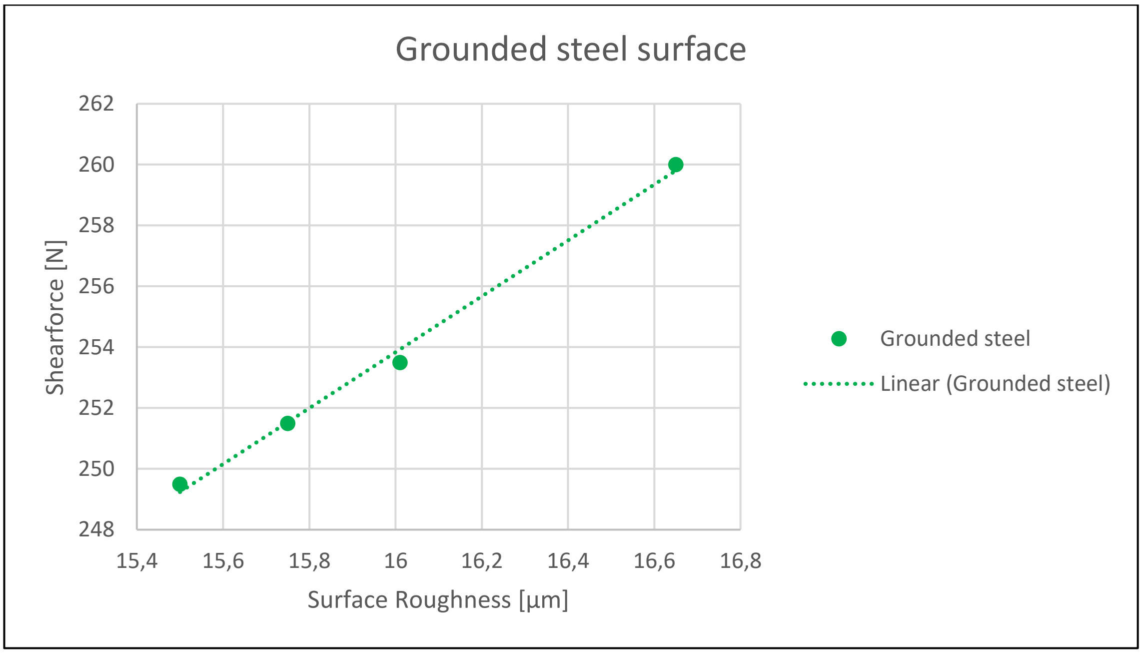


Figure 36: Surface roughness grounded steel

Figure 36 shows a comparison between the steel and the grounded steel surface. In this graph, also the linear connection between shear force and surface roughness can be seen.

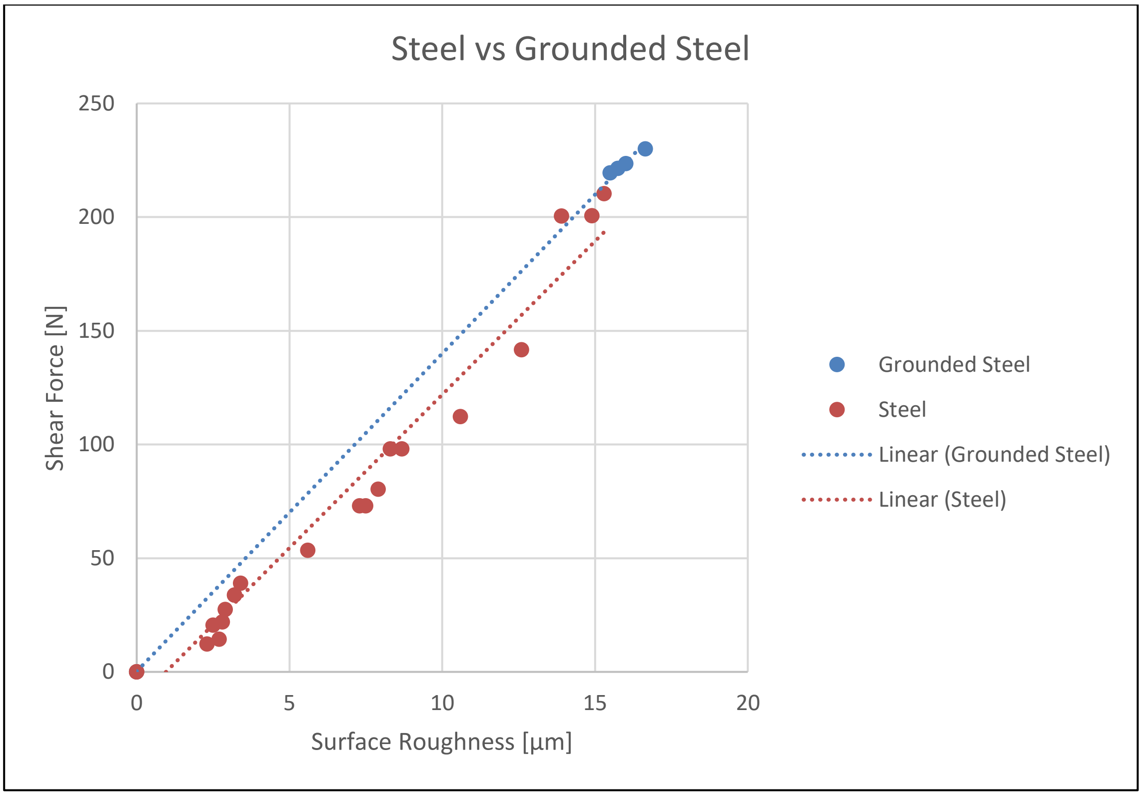


Figure 37: Steel vs grounded steel

Chapter 8 Serpentinite/Cement Shear Test

The second test cycle included 19 tests, with Serpentinite rock samples. The rock samples were put into steel cubes and the steel cubes (Figure 37) were fitted into the test bench.

The first 6 tests were used to find out the boundary of the maximum applicable load which the cement interface can take. Before the test started, roughness tests were carried out, on all 19 samples. The tests were really tricky, because the surface roughness of the serpentine rock samples consist of many deep valleys. The surface roughness tester investigates the surface via a small needle and if the surface consists of deep valleys, as it is the case with serpentine, the needle gets stuck and the test has to be repeated. The surface roughness varies between 8,1 and 34 µm.

Figure 38: Steel cube

8.1 Shear Test 1 Serpentinite/Cement

The surface roughness for the first test was 13,3 µm and the expectation for the maximum load was 14000 to 16000 g. Weight was applied up to 12000 g in 1000g steps and after reaching this mark, the weight increments were reduced to 500 g steps. At a load of 15500 g a crack sound was detected and this was a clear signal, that the cement bond has reached its maximum load capacity. After adding additional 500 g of barite, the bond failed after 2min at a maximum weight of 16550 g.

Results Test1:

Weight [g]	16500
Force [N]	161,9
Stress [N/mm²]	0,17

Table 10: Results Test 1 Serpentinite

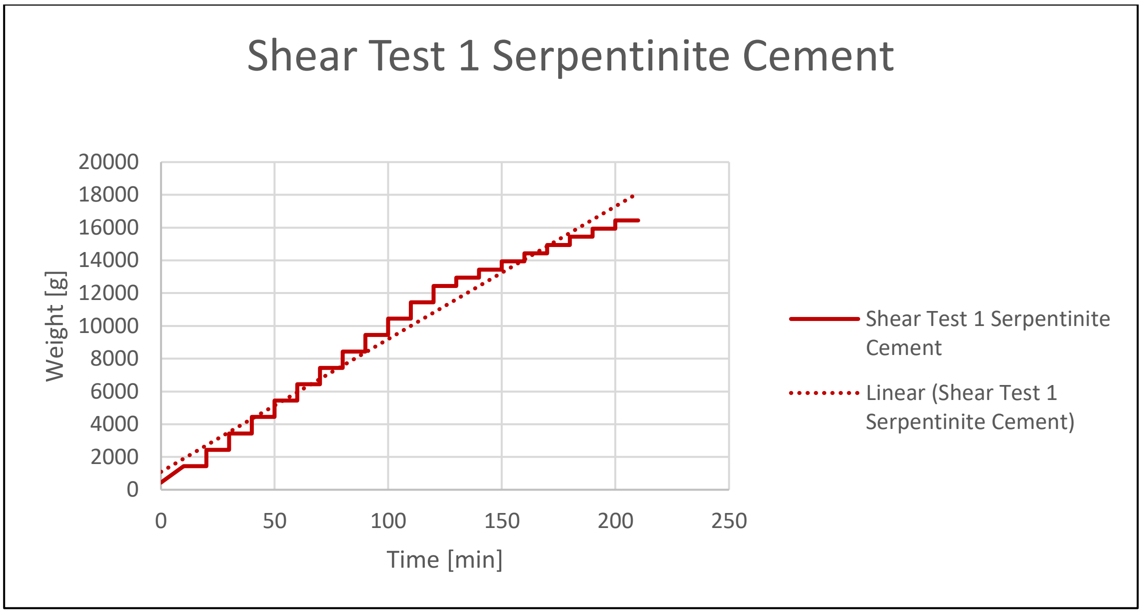


Figure 39: Shear Test 1 Serpentinite

Figure 39 shows where the bond begins to break.

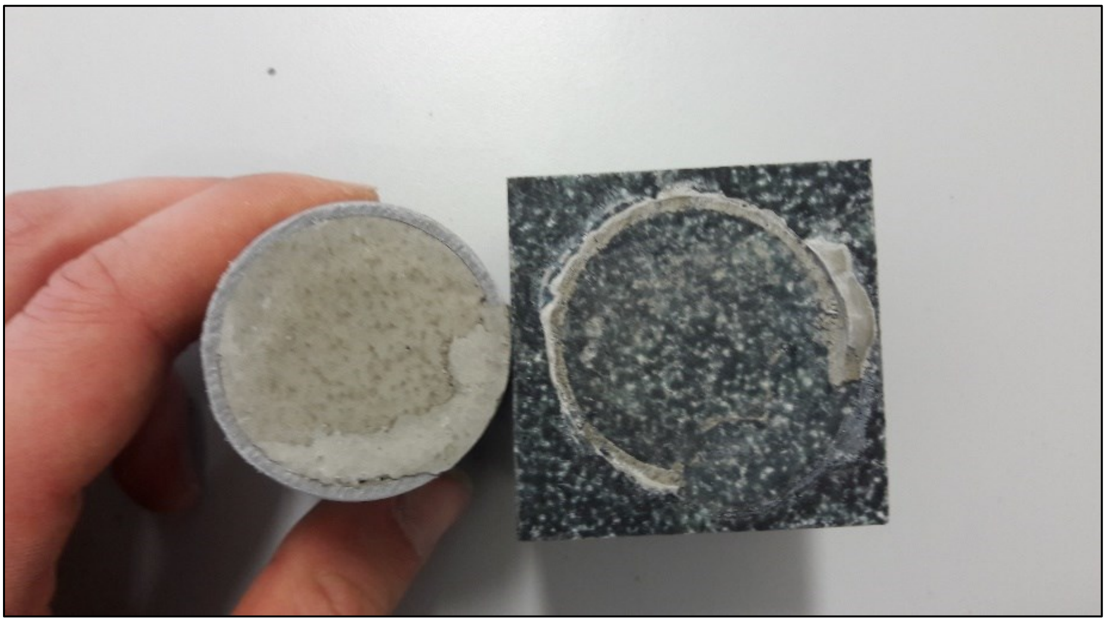


Figure 40: Test sample 1 Serpentinite

Tests No. 11 and 13 were very interesting, since both rock samples had the highest surface roughness of the whole test series. Surface roughness for test 11 was 32,4µm and for test 13 the surface roughness was 33,6 µm. Due to those roughness measurement results, the bonding failure prediction for this tests was between 40 and 45 kg.

8.2 Shear Test 11 Serpentinite/Cement

The load increment was done in 1000 g steps up to 38000 g. At that stage the increments were reduced to 500 g, because based on the data of the previous tests, the load limit would be reached soon. Weight was applied up to 40000 g, where a soft crack sound was detected. It was not the same sound as it was in test 1, because the sound stopped after a few seconds.

A possible reason for this could be, that the Ettringite needles of the cement gear stronger into the rough surface and in the case, where the surface roughness is lowest, the bond fails earlier in case of high roughness. At a weight of 44500 g a second crack sound was detected and the bonding failed immediately.

Results Test 11:

Weight [g]	44500
Force [N]	436,5
Stress [N/mm²]	0,45

Table 11: Results Test 11 Serpentinite

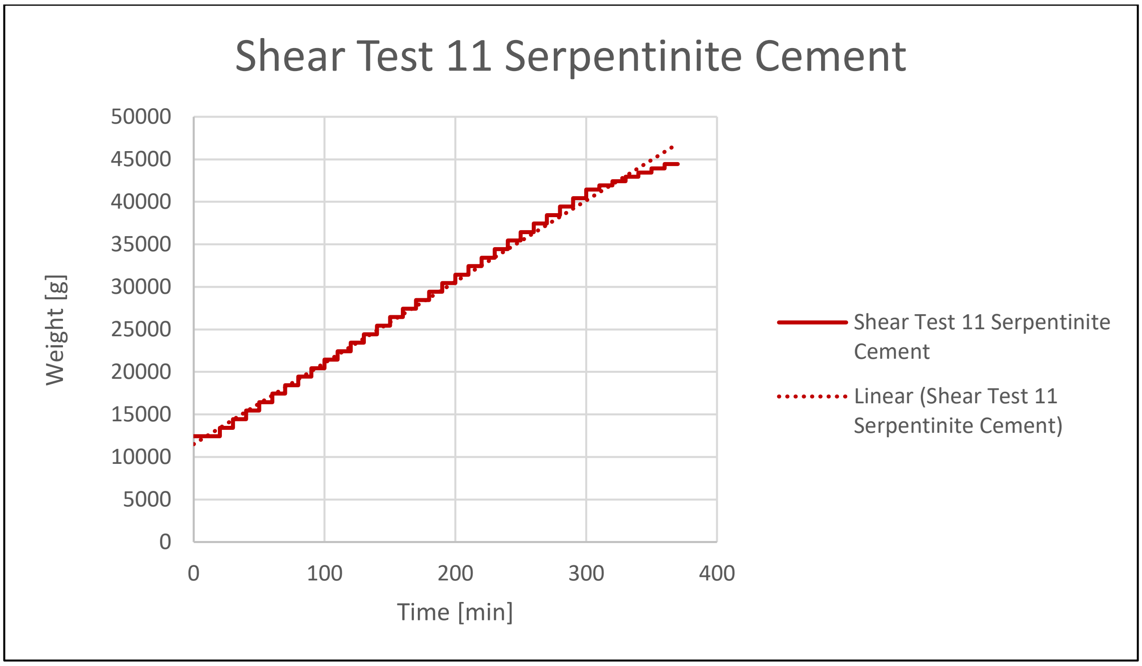


Figure 41: Shear Test 11 Serpentinite

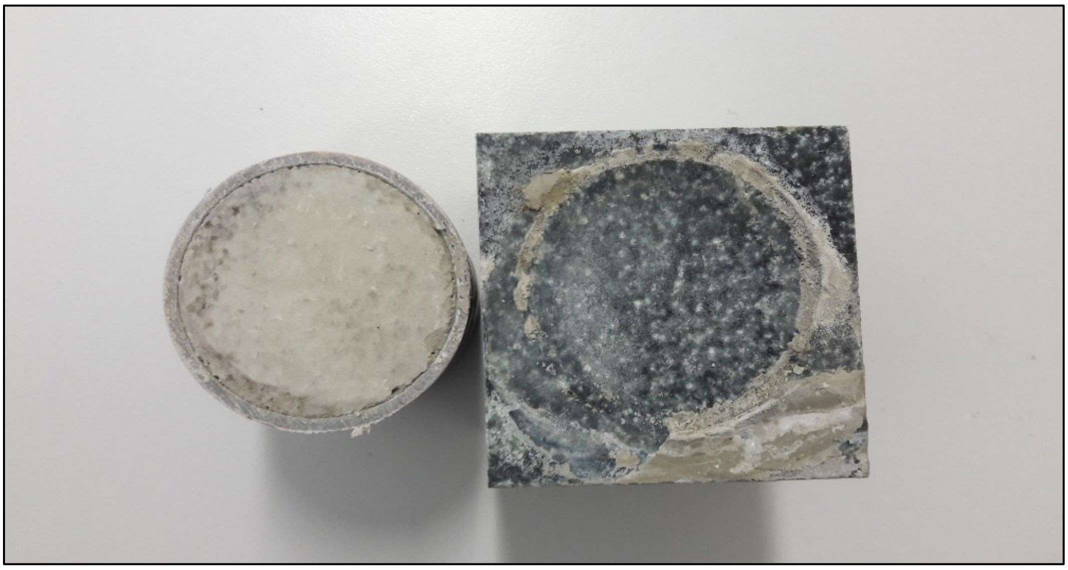


Figure 42: Test sample 11 Serpentinite

8.3 Shear Test 13 Serpentinite

For test 13 the surface roughness was 33,6 µm and which was the highest surface roughness of all 19 Serpentinite cubes. The test procedure was conducted as in the previous experiments. Weights were applied up to 38000 g in 1000 g steps. At this point, the additional weights were reduced to 500g increments, because in test 11 a crack sound was detected where the surface roughness was 32,4 µm and the cement bond failed at 44500 g. The expected shear weight for test 13 was also in this range. Weights were applied up to 45000 g and a crack noise was detected, but the cement bond was still in full integrity. After applying additional 1500 g, a second crack sound was detected and after 2min with 46500g shear weight, the cement bond failed.

Results Test 13:

Weight [g]	46500
Force [N]	456,1
Stress [N/mm²]	0,424

Table 12: Results Test 13 Serpentinite

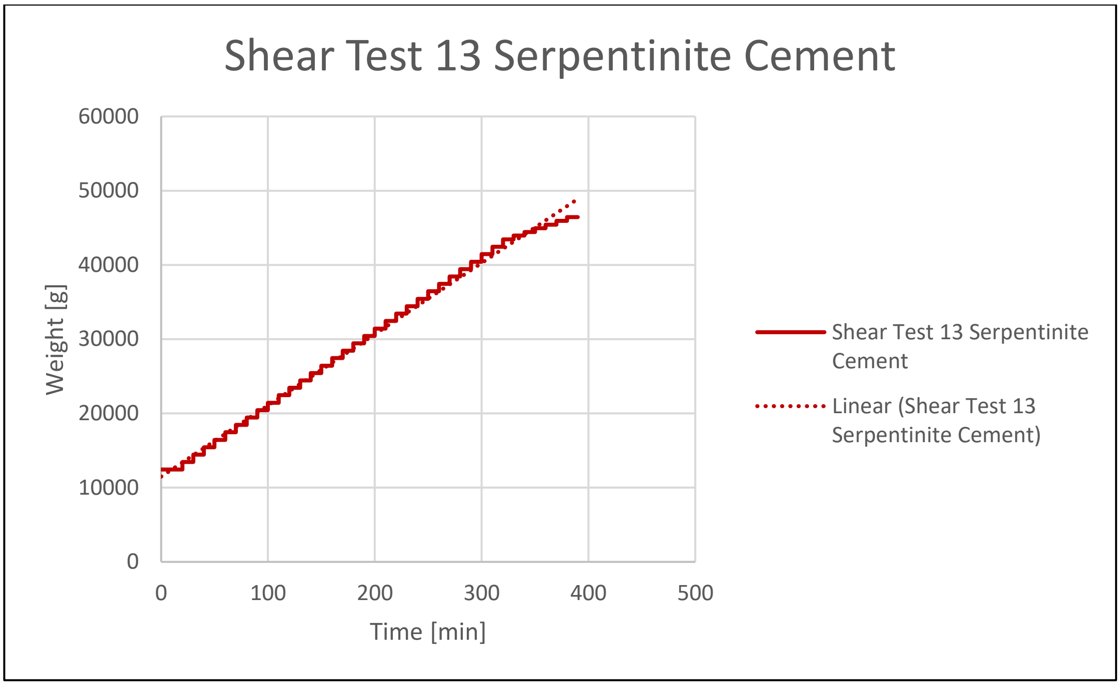


Figure 43: Shear Test 13 Serpentinite

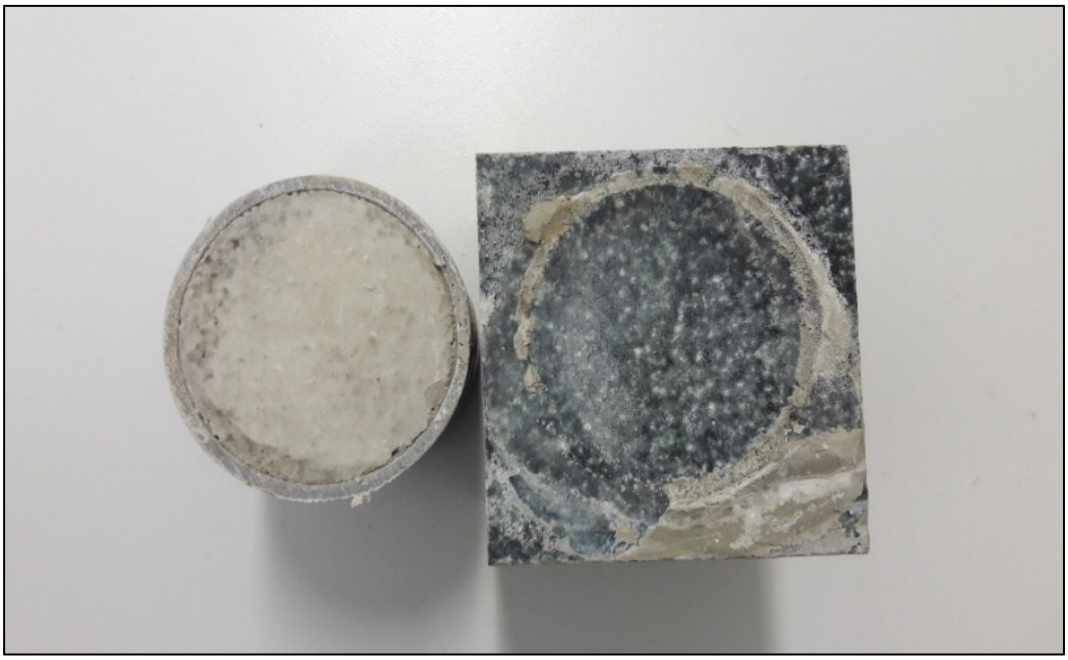


Figure 44: Test sample 13 Serpentinite

8.4 Comparison of Serpentinite/Cement Tests

The following graphs show a comparison of the maximum tension of all 19 Serpentinite cement tests and the impact on surface roughness and shear load. Additionally a direct comparison between steel and Serpentinite shear force, in dependency of surface roughness, is presented.

The following graph shows a direct comparison between steel and Serpentinite shear forces in relation to surface roughness. It clearly can be seen, that the relation of surface roughness and shear force follows an almost linear behavior as it was shown for the grounded steel plates.

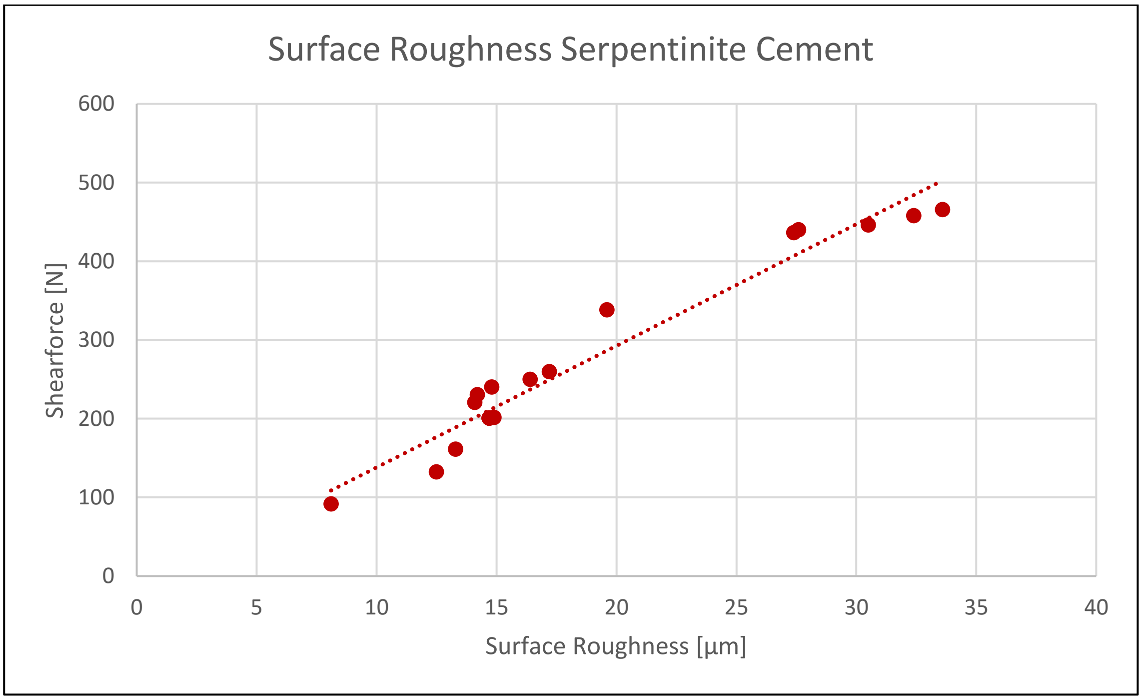


Figure 45: Surface Roughness Serpentinite/Cement Test 1-19

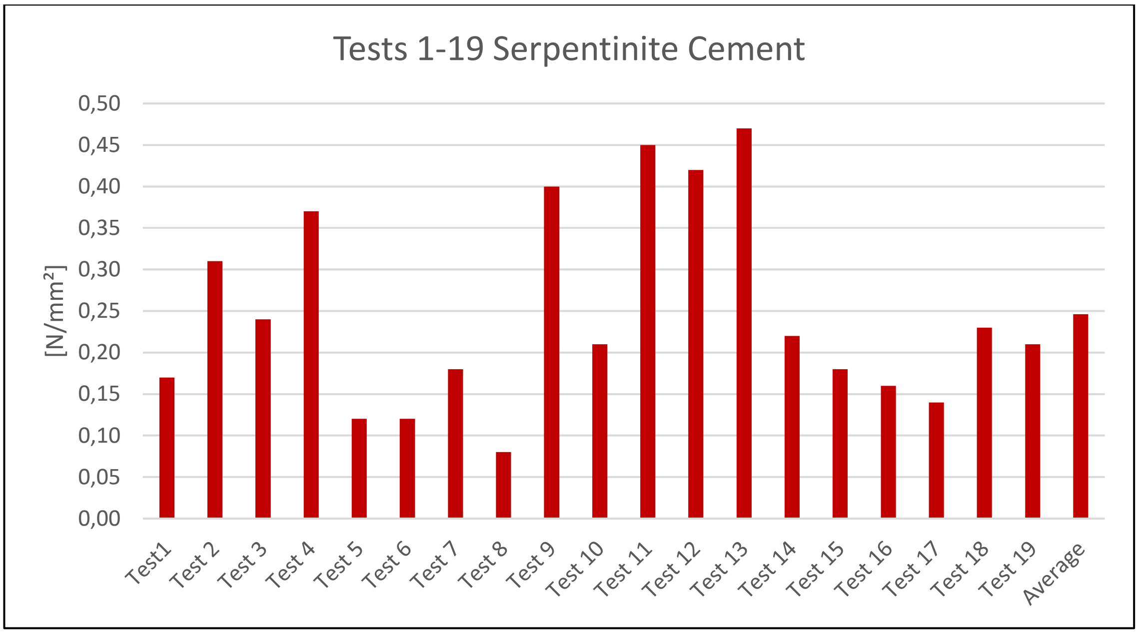


Figure 46: Comparison Test 1-19 Serpentinite

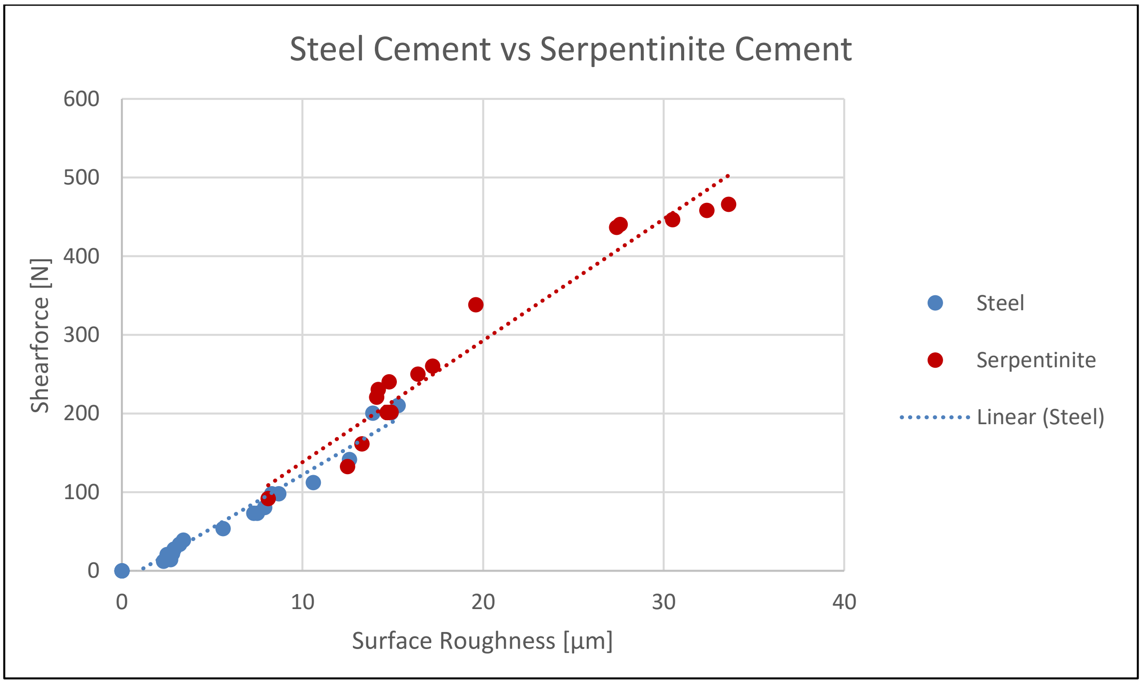


Figure 47: Steel vs Serpentinite

Chapter 9 Sandstone/Cement Shear Test

The last shear experiments were conducted with sandstone samples. The tests were done with dry and with salt water saturated sandstones. First of all it is to say, that these tests were already conducted in the 1960´s by Carter and Evans with Barea sandstone. Aim of their investigation was to find a relationship between bonding strength and shear force. The problem of the tests with sandstone was, that it was impossible to find any relationship between bonding strength and shear force, because the bond between cement and rock was always stronger than the matrix of the rock.

9.1 Sandstone/Cement Dry Test

The setup for the sandstone tests was similar to the one for Serpentinite tests. Sandstone cubes of 50x50 mm were cut with the "Gölz Rock Saw" and put into the support cubes, which were fitted into the test bench. For dry shear tests, 11 samples were taken.

Before the test was conducted, the surface roughness of the sandstone sample needed to be determined. The problem with the surface roughness testing was, that it failed completely, because sandstone is a porous medium. The pores in the sandstone make it impossible for the roughness tester to drive the testing lane, because the needle in the testing head, which measures the "mountains and valleys" of the surface, gears into the pores and testing result is invalid. It can´t be measured with this technique and another testing method was not available. It was decided to compare the test results with the results of "Carter and Evans" instead. If the cement bond is stronger than the rock matrix, the surface roughness can be neglected.

For the dry tests, weight was applied up to 70 kg and rock as well as cement did not show any indication for shearing action. The test was aborted at 75 kg, because at this weight the test bench showed signals to be unstable.

The test was aborted with a hit on the test cylinder by a hammer and the result was very interesting. The rock matrix was weaker than the cement bond and approximately 1cm of rock broke out of the surface. Figure 47 and Figure 48 show the breakout of the rock surface.

Figure 48: Breakout Top view

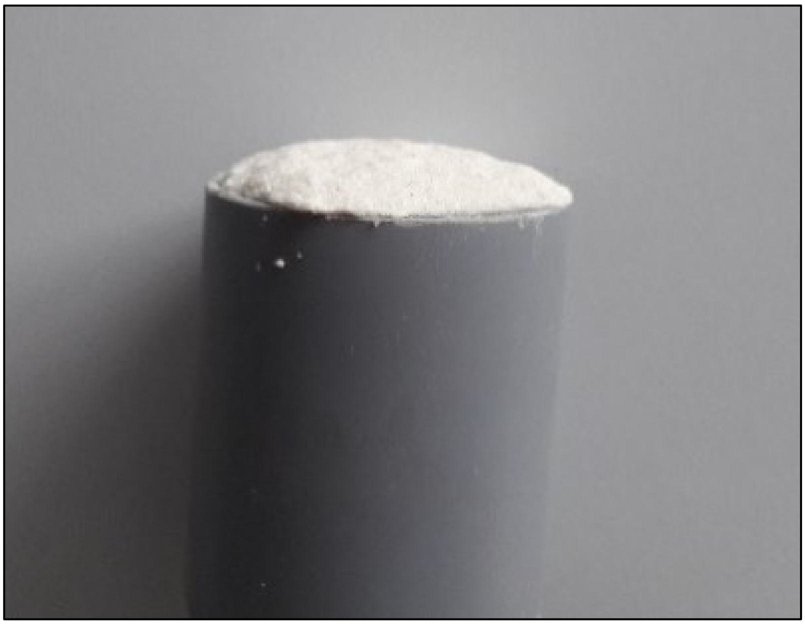


Figure 49: Break out side view

Figure 49 shows typical unconfined compressive strengths of various rocks under dry and saturated conditions. This information is mandatory, because using the compressing strength, achieves to calculate the needed shear force to shear of the cement cylinder. This is done with the equivalent stress hypothesis from “Huber van Mises and Hencky”, which is stated in Equation 5.

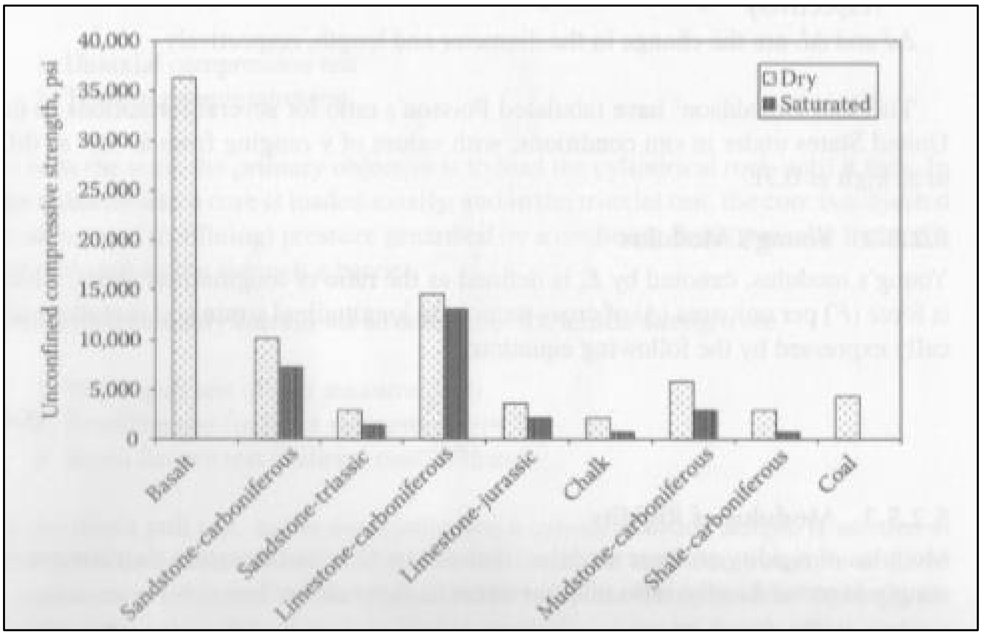


Figure 50: UCS for different rocks

(Dandekar, 1998) [15]

$$\sigma_v = \sqrt{\sigma^2 + 3\tau^2}$$

Equation 7: Equivalent stress hypothesis

(Häfele P. 2003) [1]

In the shear situation $\sigma^2 = 0$ because there is no additional normal force acting on the cylinder. Equation 7 is then transformed to the shear stress τ.

If the compressive strength value for sandstone (2500 psi ≈17 N/mm²) from figure 49 and the shear area from the cylinder (962 mm²) (Equation 9) are taken, the force needed to shear the cylinder of the rock is 16354N (Equation 10), which equates to approximately 1667 kg. (Equation 11). This mass cannot be applied to the shear test bench and therefore another experimental setup has to be taken.

$$\tau = \sqrt{\frac{\sigma v^2}{3}}$$

Equation 8

$$A = \frac{D^2 * \pi}{4}$$

Equation 9

$$\tau = \frac{F}{A}$$

Equation 10

$$F = m * g$$

Equation 11

9.2 Sandstone/Cement Wet Test

The NaCl concentration in water, was investigated with the “Fann” Resistivity Meter Model 88C. The resistivity meter measures the concentration of dissolved NaCl in water. The resistivity of water is the ability of water to resist an electric current, measured in ohm. If the concentration of dissolved salt in water is high, the resistivity is low and vice versa. Figure 50 shows a graph of NaCl concentration and resistivity.

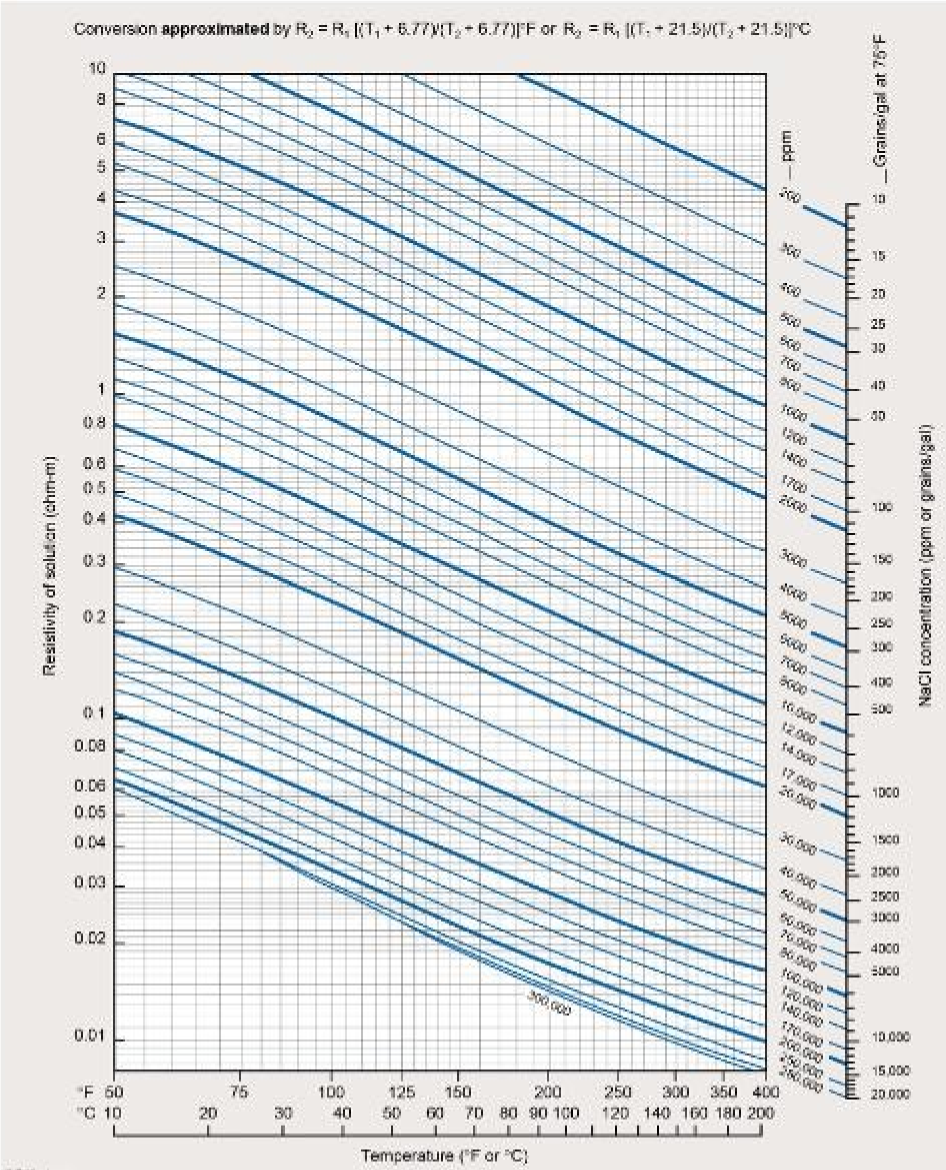


Figure 51: NaCl concentration and resistivity

(Meter, 2014) [33]

9.3 Sandstone/Cement Wet Test

For the wet shear tests, the sandstone samples were laid into a brine of 6 weight% NaCl and 8,4 weight% NaCl for 2 days. The 6% and 8.4% solutions were taken, because they represent a typical range for the salinity of formation water while the dry cement sandstone shear test simulates water wet sandstone.

The volume of water was 7000 ml for each type of brine and resulting in 6 weight% NaCl are 420 g NaCl and 8.4weight % NaCl are 590 g NaCl. The sandstone samples were put into steel cubes, as it was in the dry tests, to kept the samples wet during the whole test.

In Figure 49 the comprehensive strength for wet sandstone is given with approximately 1225 psi (8,4 N/mm²). If this is converted with into shear stress and then into mass, using equation 6, it results, that a weight of 824 kg is needed to shear off the cylinder. Also this weight can´t be applied to the shear test bench used. The critical weight for the tests was around 80 kg. The tests were aborted at this weight by a hit on the cylinder with a hammer, but the results were totally different, to those of the dry tests.

As it was assumed, the bonding between cement and salt water wet sandstone is less strong than the bonding between cement and dry rock. Reason for this is that brine consists of positive Na^+ and negative Cl^- ions, which are able to “walk” through the cement when they are solved in water. Figure 51 shows the chemical reactions which are present, when a NaCl brine ingresses cement. Due to the incorporation of Cl^- Ions into hydration products of the cement, Na^+ are released and interact with OH^- Ions to Sodium Hydroxide. Due to this swap (OH^- ions from Calcium Hydroxide in cement), additional OH^- ions are created, thus increasing the pH-value. The cement stone phases act as an ion changer.

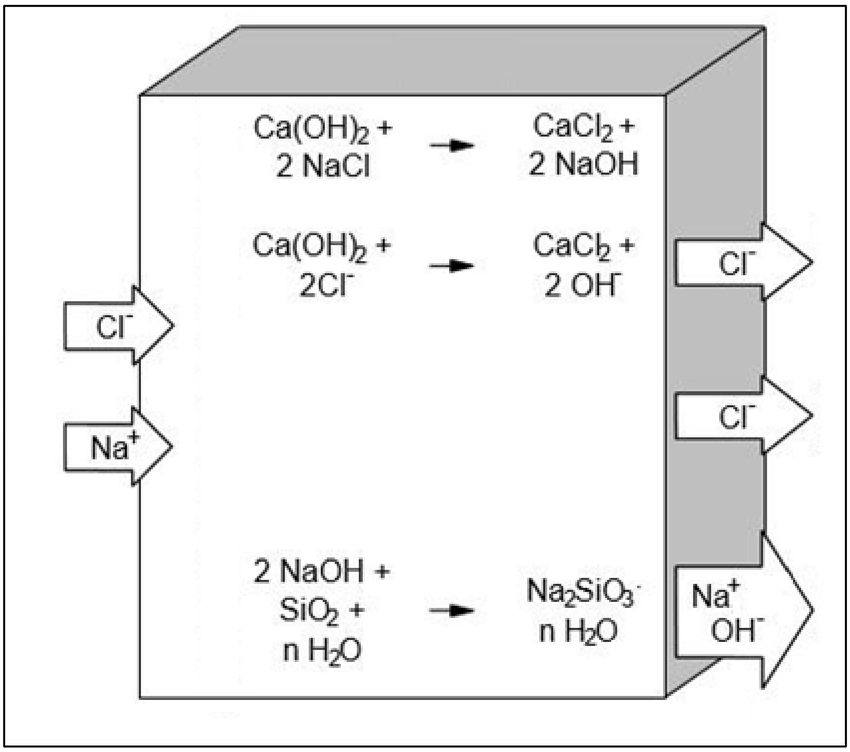


Figure 52: Ion changing in the cement stone phase

(Thoke-Weidlich, 2002) [27]

The $Ca(OH)_2$ content in the pore fluid of the cement decreases due to NaCl interaction.

$$Ca(OH)_2 + 2NaCl = CaCl_2 + 2NaOH$$

Equation 12

The created NaOH increases the effective alkali content in the cement, which makes the cement vulnerable, due to the formation of alkali-silicic acid.

(Thoke-Weidlich, 2002) [27]

Figure 52 and 53 shows the effect of NaCl acting brine on cement. If the shear areas are compared, it clearly can be seen, that the higher percentage brine hinders the cement of interacting with the sandstone surface. The breakouts of the rock which was placed into the 8,4% brine were much smaller than for 6% brine.

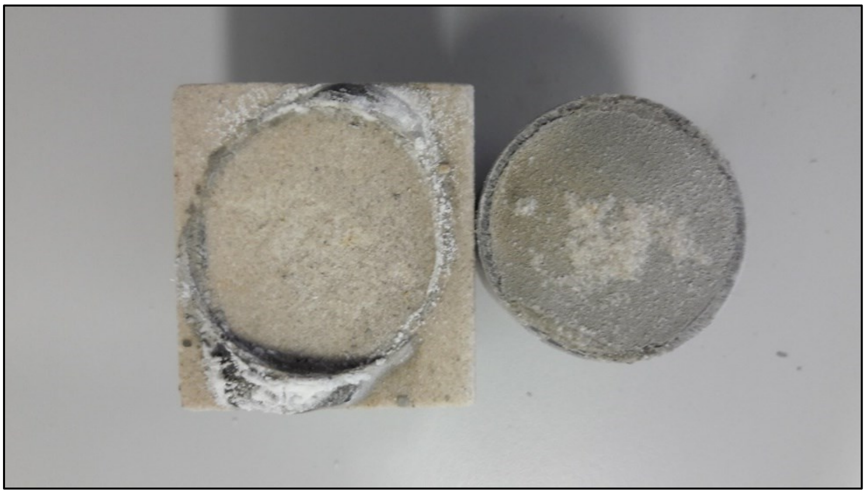


Figure 53: Breakout 8,4% NaCl

Figure 54: Breakout 6% NaCl

So it can be concluded, the wet cement tests with a NaCl brine, is a more realistic than the tests with the dry rock.

Chapter 10 Surface Roughness/Shear Force Linear

The previous tests showed that there is a linear relationship between the surface roughness and the shear force. Figure 54 shows the comparison of the steel, Serpentinite and grounded steel shear tests. The linear curve has its origin at zero, because when the surface roughness [µ] is zero, the shear force is also zero. This is determined by equation 13.

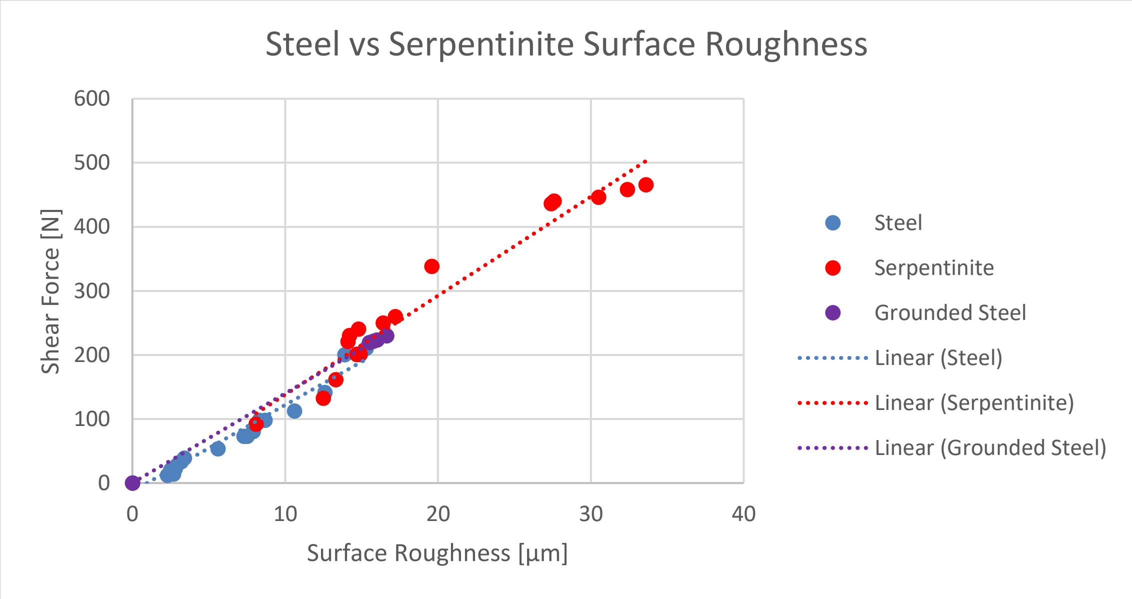


Figure 55: Shear force linear

$$Fr = Fn * \mu$$

Equation 13

Because of this argument, the linearity can be described roughly with a simple linear equation. (Equation 14)

$$y = k * x + d$$

Equation 14

d is the distance on the y-axis and which is zero, because without a surface roughness (µ=0) the shear force, or pulling force, is zero. Figure 55 illustrates this.

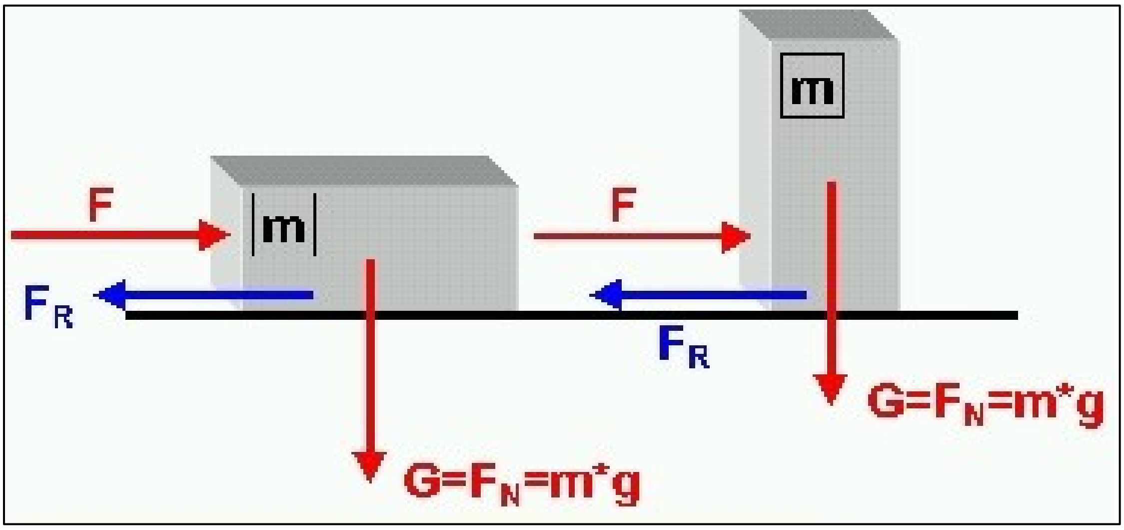


Figure 56: Drag force

(Physik 2004) [29]

Based on this argument, it is roughly possible to make a careful prediction of surface roughness and shear force

Chapter 11 Rock comparison Serpentinite/Sandstone

Based on the results of the Serpentinite shear tests, it was found, that the maximum load was 465,9 N and the surface roughness is factor for the cement shear strength. For sandstone the surface roughness is not the resulting factor for cement shear strength, it is the permeability of the sandstone, which determines the bond strength. The better the permeability of a rock is, the easier it is to fill its' pores with cement.

Due to this pore filling, the cement has now an additional surface, where Ettringite can gear in. Figure 56 illustrates the penetration depth of cement in sandstone.

Figure 57: Cross section sandstone/cement

The following graph shows a direct comparison between the maximum shear load for Serpentinite and the calculated shear load for sandstone. Due to the fact, that the relationship between shear load and surface roughness is linear, the surface roughness for sandstone, can be interpolated linearly.

For sandstone, only the results of the dry tests are shown, because the assumption to interpolate the surface roughness is wrong in this case. Reason for the weaker bond in the salt water tests is that NaCl hinders the formation of Ettringite with the sandstone surface.

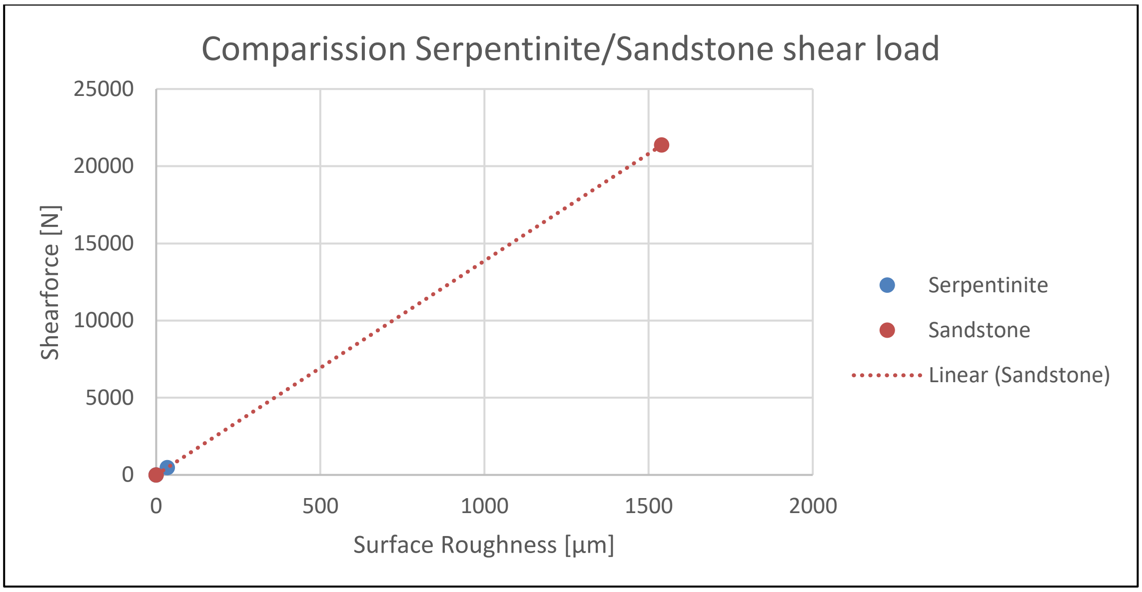


Figure 58: Comparison Serpentinite/Sandstone

Chapter 12 Conclusions

The bond of cement/ steel and cement rock, is of complex nature. In reality, this bond is the most important component in wellbore integrity. Cement is a material that deals perfect with compressive loads, but is very weak in tensional and shear loads. For all shearing tests, a plastic cylinder was put on the different surfaces and filled with class G cement. Aim was to investigate the shear resistance of the bond between cement and steel, and cement and rock. As a first step, 4 steel plates were grounded on a surface roughness of 15,5 µm, 16,25 µm,15,25 µm and 15,68 µm. The steel was grounded with an angle grinder and on all four plates dip of cleaves were 45° to the shear direction, an effect of the rotating grinding paper of the angle grinder. All four tests had a shear weight between 215,85 and 255,06 N. The steel grinding tests were done, in order to have a reverence point.

The results of the steel tests were between 12,2 and 255,06 N and showed that there is a linear behavior and, that it depends on the surface roughness, how good the bond establishes on a material. In the case of steel, the bond is the weak, when the surface roughness is low, but when a casing is run in hole, it will get some deep scratches in the surface and this means that the shearing resistance is higher at this point. In the rock case, the tests showed equivocal results.

For Serpentinite, which is an impermeable and non-porous material, the bonding strength depends like for steel on the surface roughness and the results were between 62 and 465,9 N. The tests also showed a rough linear behavior such as for steel.

When a well is drilled, the borehole wall is not very smooth and will have edges and break outs. These break outs and edges are very important for the shear strength between rock and cement. Results show that the rougher the rock surface, the better the bonding between cement and the non-porous rock.

For sandstone, there is a different behavior however. Sandstone is a permeable and porous rock, with a very rough surface. For the surface roughness tests in this thesis, a mechanic device was used which touches the surface with a needle and calculates the roughness.

For the sandstone investigation, dry and wet tests with NaCl brine of 6 and 8,4 weight-% were undertaken. It was not possible to test the surface roughness for all the samples, because, the needle of the testing device geared into the pores and did not move within its testing range. When the shearing tests with cement were done, this problem was irrelevant, because the strength of the rock was weaker, than the bond between cement and rock. A typical value of the compressional strength of dry sandstone is 2500 psi (17 N/mm²) and for wet saturated sandstone 1225 psi (8,4 N/mm²). This was calculated back with Huber van Mises, to a shear force of around 5886 N to 19620 N. Hence, such a weight could not be applied to the test bench. The tests showed that dry sandstone is perfect for high shear loads.

As it was mentioned above, the cement bond is stronger than the rock matrix, and the weak point is not the cement. The wet tests showed that NaCl brine weakens the cement bond, because Cl^- and Na^+ are diffusing into the bond. But also in this test, the rock matrix is weaker than the bond itself, and the breakouts are smaller than in the dry case.

Finally, it has to be emphasized, that more investigation and more strength tests for cement bond strength have to be carried out because the integrity of the annular cement in a wellbore is the major seal to prevent borehole leakage.

For future work on this topic, it is recommended to carry tensional tests in addition in order to evaluate the strength of the cement bond and to find possible links between shear resistance and tensional resistance.

It can be assumed, that during certain operations, for instance hydraulic fracturing, lead to an increase in pipe diameter and circumference. Those movements lead partially to a combined appearance of shear and tension loads, potentially leading to a bond failure in an earlier stage. These combined scenarios definitely need to be investigated for their impact on well integrity.

Another recommendation for next generation tests would be to develop and build a full-value test bench, which can apply both, static and dynamic loads under more realistic test conditions, ideally under high pressure and high temperature. Furthermore, it would be important to work with actual wellbore geometries and materials in order to improve the value of the test results.

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Acronyms

GOR…Gas Oil Ratio

POOH... Pull out of hole

RIH…Run in hole

CO_2 Carbon dioxide

H_2S…Hydrogen sulfide

WBM…Water Based Mud

OBM…Oil Based Mud

EIA…Energy Information Administration

CaO…Calcium oxide

$Ca(OH)_2$…Calcium hydroxide

Al_2O_3…Corundum

SO_4…Sulphate

SiO2…Quartz

Fe_2O_3… Hematite

C-S-H…Calcium silicate hydrate

Fe_2O_3…Hematite

C_2S… Di calcium silicate

C_3S… Tri calcium silicate

C_3A… Tri calcium aluminate

C_4A… Tetra calcium aluminate ferrite

Symbols

m	mass	[kg]
D	radius	[m]
Ra	Mean surface index	[µm]
F	Force	[N]
F_N	Normal Force	[N]
F_R	Drag Force	[N]
G	Gravitational Force	[N]
σ_v	Equivalent Stress	[N/mm²]
σ	Normal Stress	[N/mm²]
τ	Shear Stress	[N/mm²]
A	Area	[mm²]
g	Gravitational constant	[m²/s]
µ	Surface roughness	
ε	Strain rate	
k	Spring constant	[kg/s²]
X	Path	[m]
Re	Reynolds number	
v	Mean velocity	[m/s]
ϑ	Kinematic viscosity	[m²/s]
Dh	Hydraulic diameter	[m]
ε(t)	Strain rate	
L(t)	Length at each time	[mm]
L_0	Original length	[mm]

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