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Abstract

Shallow gas can create challenges for well integrity, local and global environment. During drilling and completion of wells, shallow gas can create dangerous situations resulting to human, environmental and economic consequences. Emission and contributors to global warming is a hot topic in the media these days, and the oil industry is caught up in it. Due to the Paris agreement, Norway is obliged to reduce its emission of climate gas.

Gas leaks from abandoned wells shallow sections is seen as a contributor to climate gas emissions from Norway. The leaking methane provides for a substantial portion of the total emission from the oil and gas industry on the NCS. What causes these leaks and how can it be avoided for future wells?

Leaking wells can be caused by insufficient zonal isolation by the cement. This is mostly caused by gas invasion during the cement settling at low temperature. In this thesis I will be looking into what effect cold temperature conditions has on neat class G and class A cement rheological and strength properties. Can class A cement be of better use than class G in shallow sections?

Acknowledgements

I would like to express my gratitude to everyone who has made my assignment possible:

With help and guidance from my supervisor Jan Aage Aasen I got an experimental assignment involving three different cement slurry commonly used on the Norwegian Continental Shelf. Through testing and studying I have obtained a broader understanding of the work performed by cement and shallow gas. The assignment has given me a better understanding on the environmental aspects regarding offshore drilling. From being in the picture with a narrow sight, I can now see clearer a part of the “bigger picture”.

Mahmoud Khalifeh, this thesis would be a lot harder (and less interesting) if it wasn’t for you taking time out of your busy schedule to reply to my questions and thoughts. Also, throughout my hours in the different labs I have received fantastic support and help from engineer Jostein Djuve and Kim Andre Nesse Vorland. Troubleshooting, training, and learning how equipment works has been enjoyable, but most importantly helpful in learning to understand what happens when we run testing. This experience has also given me an insight into what can go wrong with testing and uncertainties you must consider while doing research. Due to the good mentoring the bachelor thesis has been completed with zero HSE incidents! Arild Saasen has been a wonderful resource and our discussions have been enjoyable. This has definitely increased my understand of fluid behaviour. The great group of PhD candidates working tirelessly in the cement lab, you are all superstars. I have been able to discuss results and procedures with you, which has given me confidence and reassurance in my work. Your opinions have been well appreciated. A special mention to Mohammadreza Kamali, Fawzi Chamssine and Madhan Agista, I feel very lucky to have your support in this thesis. Thank you Samdar for letting me borrow the SE378 temperature logger! This proved to be a more valuable tool than I first thought it would be.

From outside the university there are several people who have been there for me as well. I want to thank my patient fiancé Anne Lise, for carrying the family and what goes with it, while I have been busy studying all these years. My friends who have been supporting even if they haven’t received a lot of attention or time from me. My colleagues at work for believing in me and providing me with motivation to continue progressing through studies. The load has been heavy these years, but with you supporting me I have found strength to stay on top of it.

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Abbreviations

API – American petroleum institute

BHA – Bottom hole assembly

BOP – Blow out preventer

CTS – Cold temperature samples

DG – Dyckerhoff class G

DH – Down hole

DHC – Down hole conditions

DW – Drill water

EAC - (well barrier) element acceptance criteria

ECD – Equivalent Circulation Density

NA – Norcem class A

NCS – Norwegian continental shelf

NG – Norcem class G

NCS – Norwegian Continental Shelf

P&A – Plug and abandonment

PSA – Petroleum Safety Authority

PV – Plastic viscosity

ROV – Remote operated vehicle

RTS – Room temperature sample

UCS – Unconfined Compressive Strength

YP – Yield point

1 Introduction

Shallow gas is often mentioned as a potential threat during drilling offshore wells. Precautions are made, previous drilling data is looked through for possibilities, pilot holes are made, remote operated vessels are submerged. All of this to minimalize the risk of drilling into shallow gas and the dangers that come with it. But the risks of shallow gas do not stop here. Even if you successfully drill your well down to target without hitting any shallow, or less shallow gas pockets there is still a risk of gas migrating into your well. Once the casing is put in place, pressure can leak from the reservoir and still find a path to the well bore and annulars.

In case of a temporary plug & abandonment operation where a well is temporary left. The well will then be opened again on a later basis for either permanent P&A or perhaps a side-track, completion, recompletion etc. If during this temporary abandonment the well experiences gas leak into the annulus it can provide a big threat to the company opening the well again. In 2016 the Petroleum Safety Authority published numbers where 102 out of 274 temporary abandoned wells experience a barrier fault (Petroleumstilsynet, 2016). This combined with the potential of shallow gas exposes the environment and drilling vessel for a risk when the well is entered again.

In some cases, permanently plugged and abandoned wells experience gas seepage due to improper initial cementing jobs (L. Vielstädte *et al, 2020)*. The cement acts as a barrier, and a barrier letting anything past is not serving the purpose of a barrier. In most cases during cementing in shallow formations, using ordinary Portland cement does not suffice to ensure permanent zonal isolation. Poor isolation is mostly caused by gas invasion during the cement solidification process at low temperatures (R. B. Stewart and F. C. Schouten, p. 77–82, 1988). Portland cement is known to have degradation performances such as compressive strength when cured in low temperatures (Husem, Gozutok, 2005).

Nevertheless, in 2021 one of the world's biggest challenges if not the biggest, is the current global warming. Methane is seen as the worst climate gas after CO2. Leaking wells are then considered as a contributor to global warming. In the battle against global warming every little battle matters. Due to the Paris agreement Norway has agreed to cut emissions by 50% by 2030 (Regjeringen.no, 22.10.21). In the long term the Norwegian government has also planned to cut emissions even further. One of the major obstacles for cutting emissions is the current production of climate gas.

There is a lot of hard work done with regards to reducing CO2 emissions, but how much emission can one risk producing from offshore wells leaking methane due to cement jobs not being good enough? Since the first offshore well was drilled on the NCS in 1966, more than 7000 wells have been drilled. If every well leaks just a little methane every day, it adds up and in total we have a problem when it comes to the contribution for emission of climate gas. It is estimated that the total emission of methane in the North Sea could reach between 900 to 3,700 tons annually (C. Böttner *et al, 2020)* This comes as an addition to the natural leaks already in place on the Norwegian continental shelf (Tveit, 2018 ,p.44). Every event of natural seepage on the NCS cannot be stopped, but one can make sure the wells aren't leaking on top of that.

Every event of natural seepage on the NCS cannot be stopped, but one can make sure the wells aren't leaking on top of that. In the standard for drilling well integrity set by the Norwegian petroleum industry, NORSOK D-010 it says that the acceptable leak rate is zero, unless specified otherwise in the barriers EAC. This means that we are obliged to make sure our barriers and sealing elements are without leaks in an eternal perspective.

The cement involved must be strong enough to handle potential future pressure build-ups when solid and have the right rheological properties to be displaced where it's supposed to and with it being able to withstand potential gas migration.

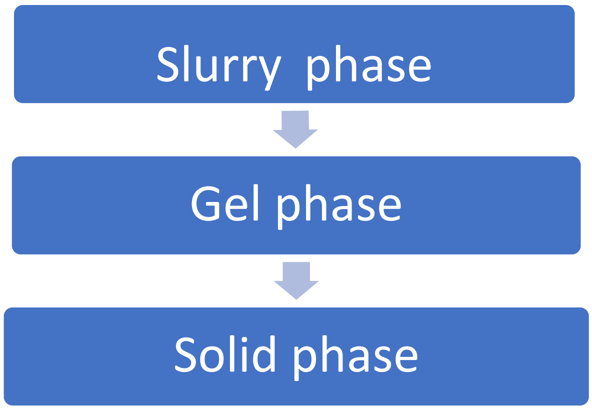
2 Objective

The main objective of this thesis is to investigate the difference in properties of cement slurry bases for use in shallow sections at the Norwegian Continental Shelf. The cement between casing and formation keeps the well in place and performs work as zonal isolation in shallow gas zones. The settling of the cement is a critical period for the integrity of the cement job. When the cement is displaced and starts to gel, and finally solidify the foundation for an impermeable cement is laid. At low temperatures this process takes a longer time, meaning from an economical perspective you must wait longer for enough strength to build up before drilling through. This due to the hydration process being slowed down by the cool environment. There is also an increased risk of losing water to the formation during the delay in hydration process

To battle the challenges at low temperatures you can mix different additives into the cement slurry. Accelerators can be added to the mixture to speed up the hydration and fluid loss additives to reduce the loss of water to the formation. Another possibility is to use a different cement base with smaller particles, meaning the slurry will be fully hydrated faster, resulting in less time spent waiting on cement. For this thesis the additives are outside of the work scope.

The thesis is limited to three types of cement slurry and cement conditions in the North Sea. For temperature reference I will use well schematics from a well drilled on the Balder field (Appendix c and d) which had a risk of hitting shallow gas while drilling. Meaning it is likely that the well when producing can be exposed to shallow gas.

I will be performing measurements on two commonly used Class G cements and compare them with a Norcem Class A cement. The Norcem Class A contains smaller particles and because of this it will hydrate faster than the Class G cements. As hydration time is a challenge during cold conditions for cements. For looking into cement properties, you can divide the cement process into three phases.



The scope for this thesis looks into the slurry and solid phase. Covering this I will be looking into the rheology of the samples at temperatures equal to the temperatures the cement will be experiencing down hole. How much difference in viscosity and the slurry shear stress does the well conditions make. For the solid phase I will investigate how curing at different temperatures and different time interval affect the UCS and Youngs modulus.

3 Theory

Three common well cements used are Norcem class G, Dyckerhoff class G and Norcem A. I am going to be studying the shear strength vs shear rate for these cement slurries mixed and conditioned at cold and room temperature to measure any potential difference in viscosity. I will also be looking into the yield stress of each slurry and measured strength at hot and cold conditions.

The different cement slurries were also put away for curing at cold and room temperature conditions over 8 and 16 days. After curing they were tested for Unconfined Compressive Strength, looking for changes in strength based on how curing time and temperature plays its part. Due to the shallow gas section temperatures in the North Sea being between 4-25 degrees Celsius. The shallow gas zone can occur between 200-600 meters below seabed (Skogvoll, 2007,p. 12).

From these depths looking into a temperature gradient for the offshore well 25/11-GT-3 H on the Balder field the temperature gradient is 4,3 ° Celsius per 100m of formation. (Vår Energi, Balder Phase 4 25/11-GT-3 H drilling program). I decided to run cold testing at 4 degrees Celsius and to use room temperature as the warm option. The room temperature was steady at 23 degrees during the curing process. This is within the temperature range for what is regarded as the temperature for the potential shallow gas zone.

When cement is exposed to lower temperatures the hydration of cement slows down. Which then results in the cement curing process slowing down (University of Illinois, Concrete, 12.12.2021). This then affects the strength of the cement as it is depending on the hydration to create the strength. The formula for cement maturity can be describes as this:

*Maturity = time * temperature* (Maturix, 12.12.21)

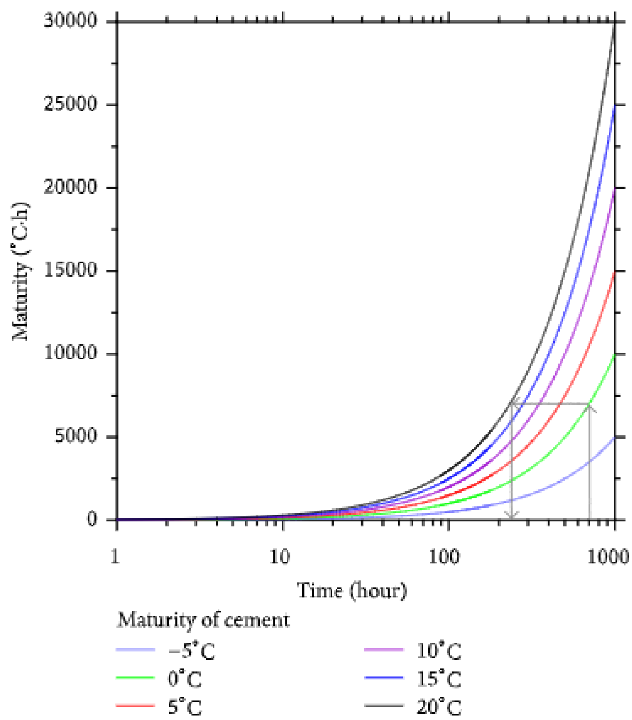


Figure 1 Cement maturity from Calculation and Experimental Study by Zhuangzhuang Liu)

As one can observe in figure 1 and by the formula of Maturity, the colder the temperature, the larger amount of time is necessary to achieve matured cement.

Looking into this it is expected that the room temperature samples will have a larger strength than the cold ones, though how much difference does time make in this case? As the casing is cemented it can go from 3 to 14 days before a section is drilled. 3 days is an average value calculated by Vår Energi (Balder drilling program). This goes mostly towards the surface casing which is the last section drilled before the BOP is run down prior to drilling through the 20" casing shoe. To run the BOP you need calm conditions and during wintertime this can take several days due to bad weather. For other casings the time for curing before drilling can be shorter, depending on well conditions and additives to the slurry.

During batch drilling you drilling several holes with the same BHA (Hestetun og Mitchell 05.11.15). You can go with even bigger time intervals between cementing and drilling through the cement, giving the cement more time to mature. The cement is designed to stay strong, be impermeable and in place in eternal perspective (Norsok, 2013, p.98).

Due to a limited work scope for this bachelor thesis, I have gone with 8- and 16-days curing time. This made the sample curing repeatable within my timeframe if in need of further samples for testing. The time for curing also makes the research easier to reproduce. If a sample fails it will take less time to make a new one, compared to if the curing time was 28 or 42 days.

Measuring of cement strength is important because it is holding the well in place while also having to be strong enough to act as a barrier for future potential gas leaks and pressure build-ups in the annulus. Without the necessary strength we can risk massive pollution and emissions to the environment, further contributing to global warming.

3.1 Rheological models

Drilling fluids and slurries have different properties and behave differently from each other. To determine and be able to calculate behaviour outside testing boundaries we have models for these fluids. The four most common models for drilling fluids are

- Newtonian Model
- Power law Model
- Bingham Plastic Model
- Herschel-Bulkley Mode

3.1.1 Newtonian fluid model

"A fluid is said to be Newtonian if its viscosity—a measure of a fluid's ability to resist flow—only varies in response to changes in temperature or pressure. A Newtonian fluid will take the shape of its container.

Under constant temperature and pressure conditions, the viscosity of a Newtonian fluid is the constant of proportionality, or the ratio, between the shear stress that builds in the fluid to resist flow and the shear rate applied to the fluid to induce flow; the viscosity is the same for all shear rates applied to the fluid.

Water, sugar solutions, silicone oils, light-hydrocarbon oils, air and other gases are Newtonian fluids. Most drilling fluids are non-Newtonian fluids.

$$\tau = k(\gamma)^n$$

$$\tau = shear\ stress$$

$$\gamma = shear\ rate$$

$$k = viscosity$$

$$n = exponent$$

(Newtonian fluid, 04.12.2021)

3.1.2 Power law model

“A fluid described by the two-parameter rheological model of a pseudoplastic fluid, or a fluid whose viscosity decreases as shear rate increases. Water-base polymer muds, especially those made with XC polymer, fit the power-law mathematical equation better than the Bingham plastic or any other two-parameter model. Power-law fluids can be described mathematically as follows: » (Power law model, 2021)

$$\tau = K(\gamma)^n$$

$$\tau = shear\ stress$$

$$\gamma = shear\ rate$$

$$K = consistency$$

$$n = exponent$$

3.1.3 Bingham Plastic Model

“A two-parameter rheological model widely used in the drilling fluids industry to describe flow characteristics of many types of muds. It can be described mathematically as follows:

$$\tau = YP + PV(\gamma),$$

where,

$$\tau = shear\ stress$$

$$\gamma = shear\ rate$$

$$YP = yield\ point$$

$$PV = plastic\ viscosity$$

Fluids obeying this model are called Bingham plastic fluids and exhibit a linear shear-stress, shear-rate behaviour after an initial shear stress threshold has been reached. Plastic viscosity (PV) is the slope of the line and yield-point (YP) is the threshold stress.” (Bingham Plastic Model, 2021)

3.1.4 Herschel-Bulkley

“A fluid described by a three-parameter rheological model. A Herschel–Bulkley fluid can be described mathematically as follows:

$$\tau = \tau_0 + k(\gamma)^n,$$

where,

$$\tau = shear\ stress$$

$$\tau_0 = yield\ stress$$

$$k = consistency\ factor$$

$$\gamma = shear\ rate$$

$$n = flow\ index, a\ power\ law\ exponent$$

The Herschel–Bulkley equation is preferred to power law or Bingham relationships because it results in more accurate models of rheological behaviour when adequate experimental data are available. The yield stress is normally taken as the 3-rpm reading, with the *n* and *k* values then calculated from the 600 or 300 rpm values or graphically. “(Schlumberger, 04.12.2021)

3.2 Choice of preferred model

After doing the initial measurements of the cement slurries it can concluded that it behaves like a Herschel-Bulkley fluid. The Power Law model is very similar in behaviour, but its calculated values are very inaccurate on lower shear rates due to the missing yield stress. With the shear stress doing important work against shallow gas, and the lower shear rates being the ones the cement will be operating at during displacement in the annular, these needs to be as accurate as possible. Herschel-Bulkley fluid model will be the preferred choice. This has the same shape and behaviour as a part of the power law model, but it also takes into account the yield stress of the slurry. See attached figure for the graphical explanation of this on the Y axis of Power law model and Herschel-Bulkley model.

‘

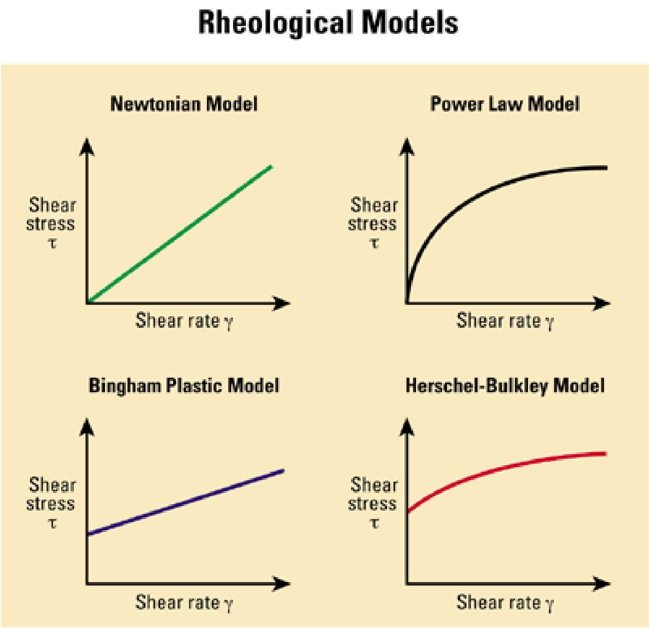


FIGURE 2 RHEOLOGICAL MODELS FROM SCHLUMBERGER GLOSSARY

3.3 Calculation of slurry density

To calculate the different recipes, a volume balance equation was used. Since these slurry bases are neat cement it is only a two-part combination. One part will be water and the other part will be a pure solid from the different cements. To determine the density, I looked into what defines specific gravity.

$$Density = \frac{Mass}{Volume}$$

For calculation neat cement density, the following formula can be used

$$\frac{Weight\ of\ cement + weight\ of\ water}{Volume\ of\ cement + volume\ of\ water} = Slurry\ weight/volume$$

By mixing according to API 10RB recommendations. "A slurry volume of 600 ml should be mixed based on mix water, cement, and additives mass requirements expressed in grams.»

The following recipes were decided to use for this research.

TABLE 1 MASS AND DENSITY

Solid material	**Mass of solid (g)**	**Density of solid (g/cm^3)**	**Mass of water (g)**	**Density of water (g/cm^3**
Norcem class G	792,00	3,18	348,00	1,00
Norcem class A	792,00	3,10	475,00	1,00
Dyckerhoff class G	792,00	3,18	348,00	1,00

The mass of solid and liquid is described, but the volume of these substances is unknown. To find this the following equation can be used:

$$Volume\ of\ solid = \frac{Mass\ of\ solid\ g}{Density\ of\ solid\ \frac{g}{cm^3}} = Volume\ described\ in\ cm^3$$

The same principle can be used for calculating the volume of liquid:

$$Volume\ of\ liquid = \frac{Mass\ of\ liquid\ g}{Density\ of\ liquid\ \frac{g}{cm^3}} = Volume\ described\ in\ cm^3$$

By putting these volumes into the formula first mentioned. We get these slurry densities:

TABLE 2 SLURRY DENSITIES

Cement slurry	Total mass (g)	Total volume (cm^3)	Density for slurry (g/cm^3
Norcem class G	1140,00	597,10	1,91
Norcem class A	1267,00	730,50	1,73
Dyckerhoff class G	1140,00	597,10	1,91

3.4 Yield Point

" The yield point (also called yield stress) is the lowest shear-stress value above which a material will behave like a fluid, and below which the material will act like a solid[2].

Typical examples of materials that have a yield point are creams, ketchup, toothpaste, and sealants. The yield point is the minimum force that must be applied to those samples so that they start to flow.

Substances with a yield stress only start to flow once the outside force acting on them is larger than their internal structural forces. Below the yield point, the substance shows "solid-like" behaviour "(*Anton Paar,* Yield point calculation*, 2021, 05.12).*

The yield point value is important for cement jobs in sections potentially exposed to shallow gas because it gives an indication on how much stress the slurry can withstand before it stops behaving like a solid when displaced.

4 Experimental setup and method

To achieve the objective of this thesis I am going to need a broad range of tools and equipment. The chapter is split into three sub chapters where the first one covers the equipment itself. The second chapter covers methods involving viscosity measurements. The third and last chapter covers UCS measurements.

4.1 Equipment

4.1.1 Fann 35 viscometer

For measuring the viscosity of the cement slurries, I used the Fann 35 viscometer. This tool can be used to measure the viscosity of several drilling fluids and other types of fluids. The machine has an outer cylinder which rotates. On the inside of the cylinder there is a spring-loaded bob. When the cylinder rotates it creates a drag on the fluid between the cylinder and the internal bob. This fluid then creates a torque on the spring-loaded bob. The torque deflection is read on a dial.

FIGURE 3 FANN35 VISCOMETER PRIVATE PHOTO

4.1.2 SE378 Temperature logger

To verify that the cooling bath was able to keep my slurry samples curing at stable conditions I used the SE378 for two days. This device has the option of 4 channels, meaning one can get four different temperature logs at once. The principle it uses is the same as a common thermometer that can be found in your home. The thermometer measures the temperature through the variance of resistance of electricity. The value varies with change in temperature.

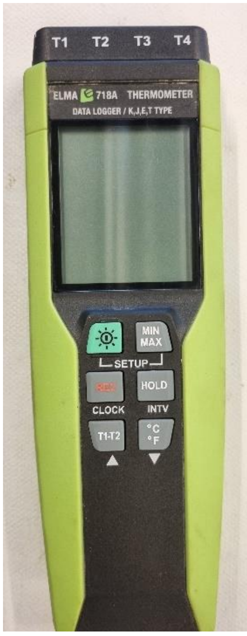


FIGURE 3. SE378 THERMOMETER. PRIVATE PHOTO

4.1.3 Ofite model 60 Atmospheric consistometer

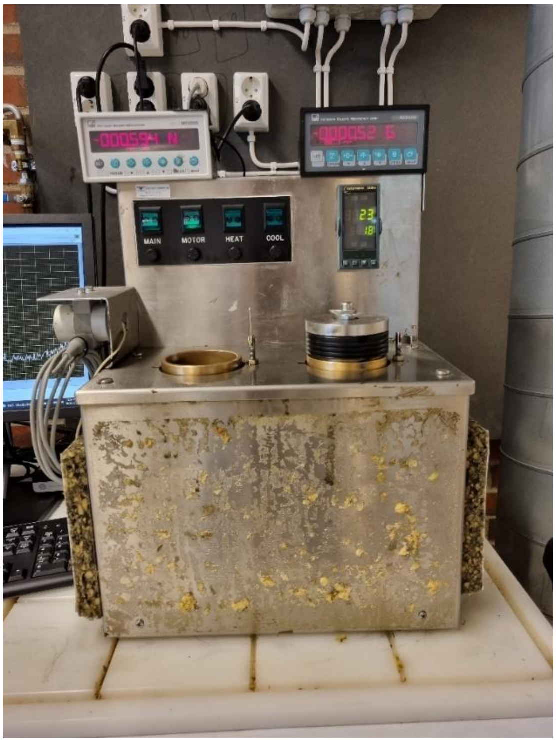


FIGURE 4 ATMOSPHERIC CONSISTOMETER PRIVATE PHOTO

Determinating rheological properties of slurries are ideally done after being pre-conditioned by an atmospheric consistometer (Nelson-Guillot, Well cementing, p. 101).

This helps making sure that the cement particles are wet and therefore the fluid will show properties more like the state it will be in during cement jobs. For the room temperature sample, I conditioned the slurries at room temperature which was a steady 23 degrees Celsius during the period. The conditioning was done for 20 minutes per slurry prior to measuring the viscosity.

For the cold temperature sample, I had a Julobo F34 refrigerated / heating circulator connected to the consistometer. While running this I managed to get the temperature of the oil bath down to 4 degrees Celsius. When this was achieved and proved stable over time, I conditioned the CTS for 20 minutes per slurry prior to measuring the viscosity.

4.1.4 Waring commercial blender

For mixing the cement slurry, a Waring commercial blender was used. This fits within the criteria set in API 10RB regarding what type of blenders can be used for this purpose. The blender has room for one litre of fluid, bottom drive and is a blade type blender. The blender runs on a mixing sequence where it goes for 15 seconds at 4000rpm then it increases to 12000rpm for 35 seconds. This is a standard sequence decided to make reproducibility of results possible. The water is placed first then followed by the solids. When the ingredients are in the cup and the cup is correctly installed, the sequence can start.

FIGURE 5 WARING BLENDER. PRIVATE PHOTO

4.1.5 Julabo F34 Refrigerated/heating circulator

For curing the cement and cooling down the atmospheric consistometer I used two Julabo F34 units were used. The circulator has a water bath that can be connected to the Ofite atmospheric consistometer. By doing this one can pump cold liquid into elements fitted in the oil bath. The elements will cool down the oil which will then cool down or hold the temperature of the slurry during the conditioning.

For curing cement at low temperatures, the samples were put into the cooling bath. As previously recorded this had enough cooling effect on cement samples to act as a stable environment during curing.

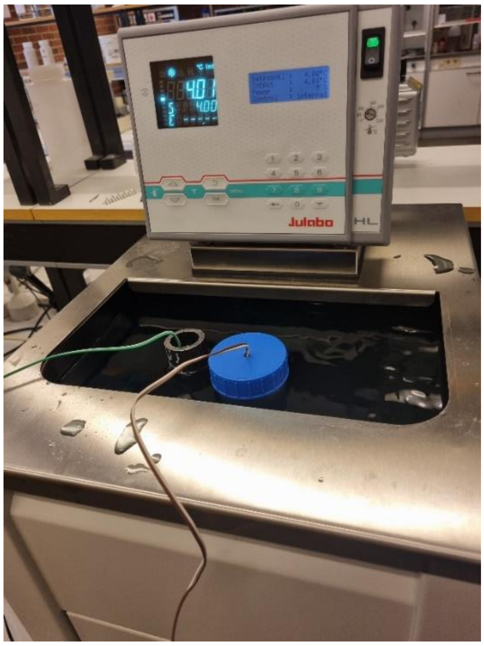


FIGURE 6 JOLABO F34 COOLER. PRIVATE PHOTO

4.1.6 Mudbalance weight – density

To verify the density of the slurries, a mud weight balance was used to measure what specific gravity the slurries had after they had been mixed. This is done by filling up the cup before putting the lid on. After the lid is put in place the syringe is used to fill and pressure up the cylinder After the cylinder is filled with fluid, the counterweight is used to balance out the weight. When the cylinder is in balance the specific gravity of the fluid can be read from a scale going along the x axis.

FIGURE 7 MUD BALANCE (HTTPS://HAMDON.NET/PRODUCTS/TRU-WATE-MUD-BALANCE-MODEL-141)

4.1.7 MTS Criterion M45

To measure the strength of the hardened slurries previously run in the Fann 35, an MTS Criterion M45 with TW Elite software was used. The machine measures the unconfined compressive strength of the cement samples. This result gives information about how much force the sample can resist before it reaches its breaking point.

Since the curing conditions for the samples have varied with temperature and time, a tool to measure and document the different properties between them was needed. From the raw data gathered after a test, the UCS and Youngs modulus could be calculated.

FIGURE 8 UCS MACHINE PRIVATE PHOTO

4.2 Viscosity measurements

When circulating the cement, some type of friction is needed. This is necessary to get a good placement of the cement in the annular. While pumping through the casing shoe and into the annulus one need to be able to place the cement without the slurry fingering, At the same time one also needs to make sure the wellbore doesn't get washed out, and that the equivalent circulation density value is too high due to greater pumping to displace the slurry.

The room temperature samples were conditioned for 20 minutes at 23 degrees Celsius prior to viscosity testing as per API 10RB regulations. The RTS were mixed with room temperature deonitized water. The cold temperature samples were conditioned for 20 minutes at 4 degrees Celsius, and the slurry was mixed with deonitized water with a temperature between 2,5 and 4 degrees Celsius. This was done to get a better understanding of how the properties of the cement behave during cold conditions. Cold temperatures are often the case in shallow gas sections.

To keep the liquid cool, a precooled glass bottle filled with deonitized water in a rigid cooler box. On the inside of the box together with the glass some ice cubes and frozen cooling elements were put to maintain a cool temperature for hours during my mixing and conditioning. This proved to be very efficient.

During conditioning the atmospheric consistometer was cooled down prior to, and kept cool during, by a Jolabo F34 cooling bath connected in a loop. This was done to constantly circulate cooling liquid through the cooling elements of the oil bath of the consistometer. The consistometer is equipped with a thermometer reading the temperature of the oil bath, this was controlled with an extra thermometer to see that readings were correct.

Prior to measuring the cement slurry viscosity, the slurry has to be conditioned. Nelson Guillot has standard approach to how this is done.

"Immediately after mixing, the slurry is poured into the slurry container of an atmospheric or pressurized consistometer for preconditioning. The container temperature must be initially ambient to avoid thermally shocking temperature-sensitive additives. The slurry is then heated to the test temperature and stirred for a period of 20 min. If preconditioning was performed in a pressurized consistometer" (Nelson Guillot, Well cementing, p640*)*

The slurries in this thesis were conditioned in an atmospheric consistometer and conditioned for 20 minutes straight at the temperature they held after mixing. This was done at 4 degrees Celsius for the cold batches, and 23 degrees Celsius for the warm batches.

For measuring the viscosity of the slurries, the Fann 35 rotational viscometer with R1-B1 configuration was used. The measurements were performed following the API 10B-2 Recommended Practise *(American Petroleum Institute, 2013).*

Recommended practise for testing well cements.

"Record the temperature of the slurry in the viscometer cup before taking the first reading. Take the initial instrument dial reading 10 s after continuous rotation at the lowest speed. Take all the remaining readings first in ascending order, and then in descending order, after continuous rotation of 10 s at each speed. Shifting to the next speed shall be done immediately after taking each reading. The recommended highest reading shall be taken at a shear rate (equivalent speed) of about 511 rotations per sec. Exposing cementer slurries to shear rates about 511 / sec has been reported to generate inconsistent results. "

Following this practise, the max RPM used for viscosity measurements is 300. To calculate the viscosity of the samples the average dial reading between ramp up and ramp down was calculated then converted to the shear stress. Following this equation:

$$\tau = 0.5109 * \theta$$

Where the shear stress is described as τ and viscosity as θ

The shear stress is described by the following equation:

$$\gamma = 1.705 * \Omega$$

Where the shear rate is decribed as γ and the RPM value of the viscometer is noted as Ω. The following formulas are mentioned in Nelson Guillot's Well cementing book.

4.3 Cement curing conditions

In this thesis I will be looking for cement properties for use in shallow sections. While cement jobs occur on and offshore, I decided that I would run tests at both room temperature and 4 degrees Celsius. 4 degrees Celsius is the same temperature you experience at the bottom of the sea. To achieve this temperature a cooling bath with glycogen and a thermostat is used for cooling down the atmospheric consistometer. This is done to keep the cement temperature as low as possible during conditioning. The water used for mixing the slurries is cooled down beforehand to below 4 degrees before it is added to the solids and mixed to slurry.

The samples ran for 20 minutes in the cold consistometer before the viscosity of the slurry was measured in the Fann 35 viscometer. The temperature was recorded before and after the viscosity tests. The slurry was then placed in a sample cup and set to cure in a water bath for the planned interval. When mixing cement with water you get an exothermic reaction during the hardening process. At room temperature the only thing working against this effect is the room temperature itself, but at cold conditions (in this case 4 degrees Celsius is used due to it being the same temperature as the seabed) the exothermic reaction is held back in this case from the cold liquids circulating. To prove this, I mixed three samples of Norcem Class G according to previously decided recipe and placed it in three containers

- One sample was placed in a steel tube in the water bath
- One sample was placed in a sample cup made of plastic and put in the cooling bath
- One sample was placed in a sample cup made of plastic and left at room temperature

The samples were left curing for a 48-hour period with wire placed in the sample connected to the SE378 thermometer to record the potential change of temperature in the slurries. The results from the SE378 log were exported from the software to Microsoft Excel. In Excel then raw data was organised and a graph was made up showing the change in temperature during the time interval. The results show that the exothermic reaction proven in the RTS, was withstood in the CTS. The plastic container reached 4 degrees Celsius after 13 minutes while the steel tubing needed 37 minutes to achieve a core temperature of 4. This proved to make no difference to the cooling of the cement during the hardening process. The maximum measured temperature of the RTS was after 10 hours, whilst the CTS held it core temperature stable throughout the whole curing.

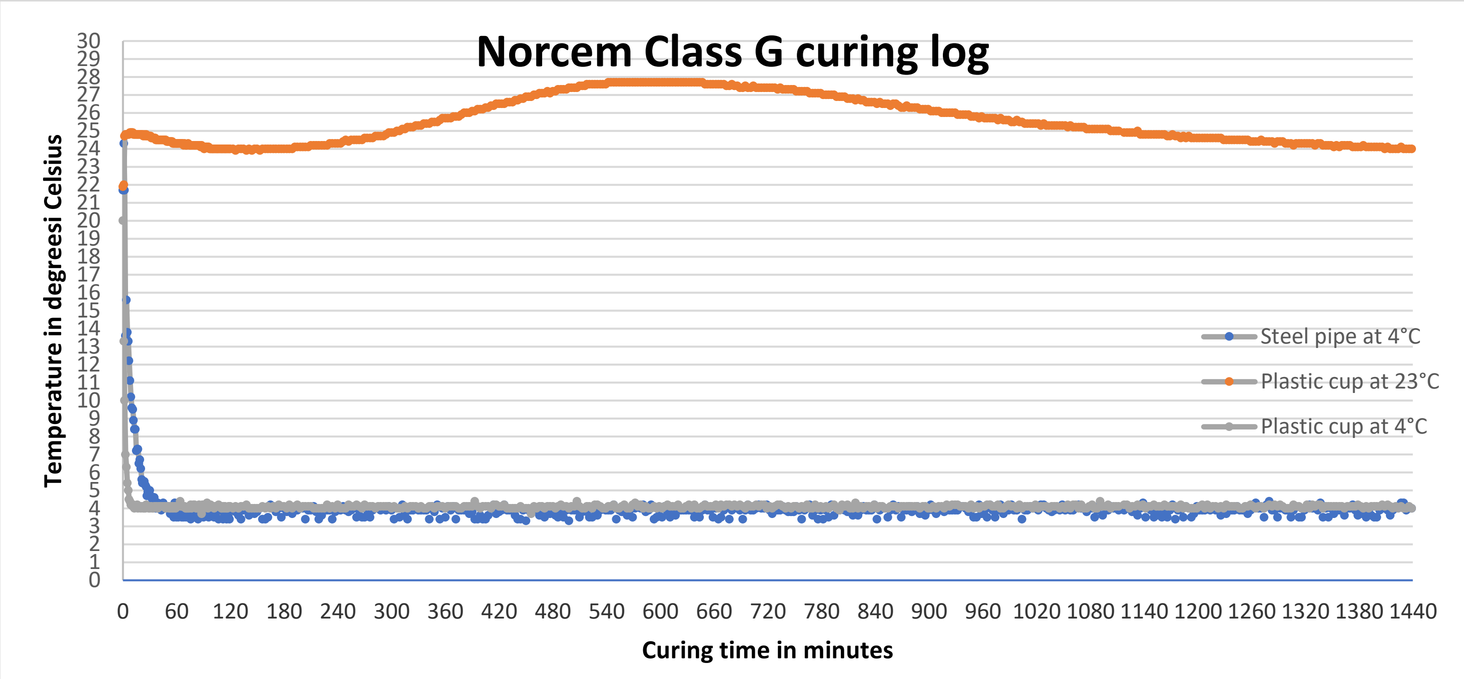


FIGURE 9 TEMPERATURE VS MINUTES. FROM SE378 LOGGING RUN

The results on display in this graph are from the raw data gathered by the SE 378 and exported into Microsoft Excel.

- The orange graph shows the core temperature from the room temperatured plastic sample cup.
- The grey graph shows the core temperature from the plastic sample cup placed in the cooling bath.
- The blue graph shows the core temperature from the steel pipe sample placed in the cooling bath.

For the cold temperature logging it shows variations in measurements from +- 0,5 degrees Celsius. This can potentially be a deviation coming from the transmitter (electric cable) struggling to deliver stable results due to the cool temperature. The RTS log proved a steady increase in core temperature before coming down again, both the CTS showed a stable trend though varying by +- 0,5 degrees Celsius. All samples in this thesis are cured under atmospheric conditions.

4.4 UCS testing

UCS is the stress at which the cement specimen fails in a compression test without confining pressure. It is determined experimentally by destructively testing the cement sample. The maximum stress recorded during the test is the UCS value. (American Petroleum Institute, 2017)

The following test matrix goes for RTS and CTS. A total of 36 UCS tests are performed. Due to the differences in materials, curing temperature and time I had to do three samples for each scenario to get a measurement system for standard deviation and variation.

TABLE 3 TEST MATRIX CURING CONDITIONS

Cement	8-day curing	16-day curing
NG	3 samples	3 samples
NA	3 samples	3 samples
DG	3 samples	3 samples

The following samples have been UCS tested with 7kN increase per minute. This is within the recommended limits from American Petroleum institute API TR 10TRY7 chapter 7.2.3

*"For load control, the force may be applied in a rate such that a constant stress rate in the range of 3.5MPa/min to 14MPa/min is produced in the specimen" (*American Petroleum Institute).

The unit for 1 Pascal = a pressure of one newton per square metre.

The formula for stress = $\frac{Force}{Area}$

In this event it will be $\frac{7000N}{0{,}00200296m^2}$ = 3,5 MPa

Proving that 7kN per minute for UCS testing of these samples is according to API guidelines.

4.5 Curing and correction of UCS test values

After doing viscosity measurements on the different samples, they were placed for curing at different conditions. In this thesis all curing is done at atmospheric conditions, but at different temperatures and for different periods. The intervals were planned to be 7 and 14 days but due to logistical circumstances the tests ended up taking 8 and 16 days.

Prior to testing, the CTS have been removed from the cooling bath 45 min before UCS testing (American Petroleum Institute, 2017). After the moulds have been removed from the cooling bath, the sample is carefully separated from the mould. The sample is then put in a jig to smoothen up the edges. This ends up with shortening the sample so it ends up smaller than 2*D.
Because of this I must use a correction factor.

TABLE 4 CORRECTION FACTOR OF UNIAXIAL COMPRESSIVE STRENGTH FROM API TR7

Correction factor of uniaxial compressive strength for specimens that have slenderness ratio below 2.

l/d	2	1.75	1.5	1.25	1
Correction factor	1	0.98	0.96	0.93	0.87

The samples in this thesis are measured to a width of 50,6mm and length of 75,7mm. When dividing the length by the width, the slenderness ratio = 1,5. “For samples with slenderness < 2, API has referred to American Society for Testing and Materials, ASTM (2014) and correction factors can be either interpolating the range provided by Table 2, or using the polynomial equation in Figure 12” (Kamali, 2021, p.5).

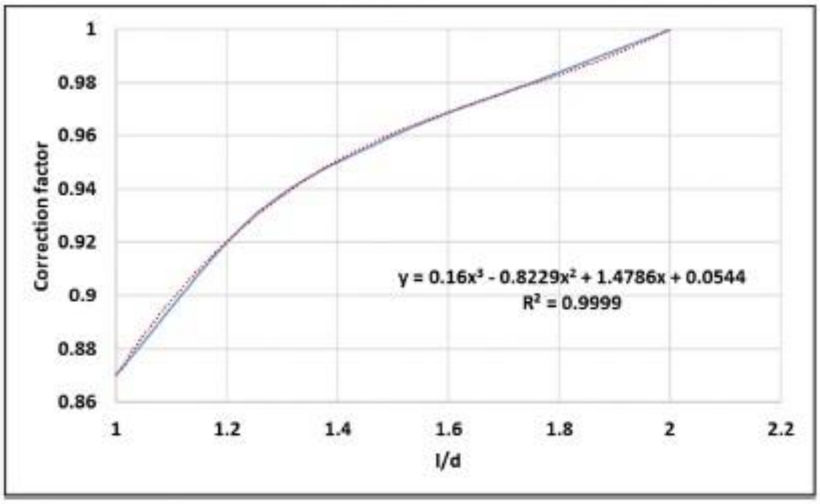


FIGURE 10 FROM KAMALI 2021

5 Evaluation of measured results

5.1 Viscosity measurements from Fann 35 testing

With all the measurements I have made I needed to verify that they are reproduceable. To do this I mixed four batches of Norcem class G cement at room temperature and then did viscosity measurements on these slurries. The results were recorded and compared for deviation. I calculated the standard deviation, average value and variation for the different speeds the cements were being tested at.

TABLE 5 VARIATION BETWEEN MEASUREMENTS PER SPEED

Variation between measurements per speed						
3RPM	6RPM	30RPM	60RPM	100RPM	200RPM	300RPM
0,05	0,13	1,36	3,25	5,17	7,13	2,5

TABLE 6 AVERAGE MEASUREMENTS

RPM	Average measurements for the 4 tests
3	10,88
6	15,5
30	35,75
60	43,5
100	51,88
200	66,63
300	79

After these calculations for the Norcem G standard deviation I assume that the same % of deviation will be the same for the two remaining slurries as the system stays the same.

Within +/- 10 % of the average measurements all tests were well inside the confidence interval. For +/- 5% of the average measurements 3 out of 4 slurries were within on all shear rates. The slurry batch that deviated outside the 5% was within limits on 3rpm,6rpm and 300rpm. For cement circulation in the conductor and surface casing the 5,11/s^-1 and 10,2s^-1 measurements are the most important ones.

Due to the recommended limits on cement share rate (API 10RB) your drill pipe circulation rate is the bottleneck for your cement job. With an internal diameter between 3 to 4,8" in the drill pipe you will end up with a very low shear rate in the big annulars. Due to this I would argue that the 4th batch measurements will still be acceptable.

For further comparisons the measured value is calculated to shear stress. Here are two tables made up of the average of results made up from measurements on cold and warm slurries. The bold digits from 5,1 to 510 is the Shear rate. The shear rate = rpm from the Fann35 viscometer x 1,7 conversion factors.

TABLE 7 MEASURED SHEER STRESS AT SHEAR RATE FOR WARM SAMPLES

Cement type	Measured shear stress at shear rate for warm samples						
	Shear rate 1/s						
	5,1	**10,2**	**51**	**102**	**170**	**340**	**510**
Norcem G	6,05	8,43	19,33	23,93	28,79	37,90	45,82
Norcem A	5,03	7,49	15,59	19,50	23,34	31,09	38,16
Dyckerhoff G	7,41	10,82	22,74	27,76	33,13	42,07	48,72

TABLE 8 MEASURED SHEAR STRESS AT SHEAR RATE FOR COLD SAMPLES

Cement type	Measured shear stress at shear rate for cold samples						
	Shear rate 1/s						
	5,1	**10,2**	**51**	**102**	**170**	**340**	**510**
Norcem G	5,62	6,98	13,88	18,65	23,16	33,13	42,41
Norcem A	4,94	6,73	13,63	17,72	21,97	31,51	38,83
Dyckerhoff G	7,92	12,01	22,74	27,00	32,02	40,54	47,52

TABLE 9 POSITIVE AND NEGATIVE INCREASE IN SHEAR STRESS FROM COLD TO WARM MEASUREMENTS IN %

Cement type	Positive and negative increase in shear stress from cold to warm measurements in %						
	Shear rate 1/s						
	5,1	**10,2**	**51**	**102**	**170**	**340**	**510**
Norcem G	7,58	20,72	39,25	28,31	24,27	14,40	8,03
Norcem A	1,7	11,37	14,37	10,09	6,20	-1,36	-1,75
Dyckerhoff G	-6,45	-9,93	0	2,85	3,45	3,78	2,51

Comparing the measured sheer stress between the three slurries and the two different temperature conditions they have been through there are a few observations:

- The Norcem A slurries measures the lowest sheared stress across both conditions. Meaning the Norcem A cement has the lowest viscosity and will flow easier. This has also got the lowest SG of the samples.
- Dyckerhoff Class G is the only slurry out of the three that experiences an increase in viscosity when being at cold temperature compared to warm temperature.
- Norcem Class G has the largest increase in shear stress/viscosity when comparing cold to hot values. At a shear rate of 51/s^-1 it measures 39,25% higher at room temperature compared to cold. Comparing the measurements, the Norcem Class G experienced an increase at an average of 23,76% of viscosity at warm conditions compared to cold conditions. This can be assumed to come from quicker hydration of the Norcem G at room temperature than at cold., proving how temperature severely affects hydration.
- Dyckerhoff class G and Norcem A are proving a lot more consistent regardless of temperature. Dyckerhoff Class G had an average deviation of -0,5% in difference between the measurements. Norcem A with an average of 5,8% increase in viscosity from cold to hot.
- Looking at the difference between cold and warm performance tells us that Norcem A is the best and most consistent option for a base slurry cold temperature if judged by viscosity alone.

The low shear yield stress (LSYS) for the slurries was calculated using the following equation:

$$\theta 0 = (2 * \ \theta 3 - \theta 6)$$

Equation source ((Jafr, 2018,p.132).

Based on this equation the following yield strengths were calculated

TABLE 10 YIELD STRESS

Cement type	Norcem class G		Norcem class A		Dyckerhoff class G	
Temperature	**Cold**	**Warm**	**Cold**	**Warm**	**Cold**	**Warm**
Yield strength	4,26	3,66	3,15	2,56	3,83	4,00

These numbers tell us that in terms of resisting gas migration at the point the cement is placed in the annular that Norcem Class G is the best option for this matter alone, while Dyckerhoff proving to be the stronger option at room temperature conditions. In practical use based on yield point value alone you would use Norcem Class G for your conductor cement job and Dyckerhoff Class G for your surface casing. In real life conditions you will not have the luxury to have two different G cements stored on the rig, simply down to limitations and logistics. Due to this important factor and the little difference in yield strength value, selection of either one would come down to cost and availability more than the yield strength value itself.

Norcem class G viscosity comparison

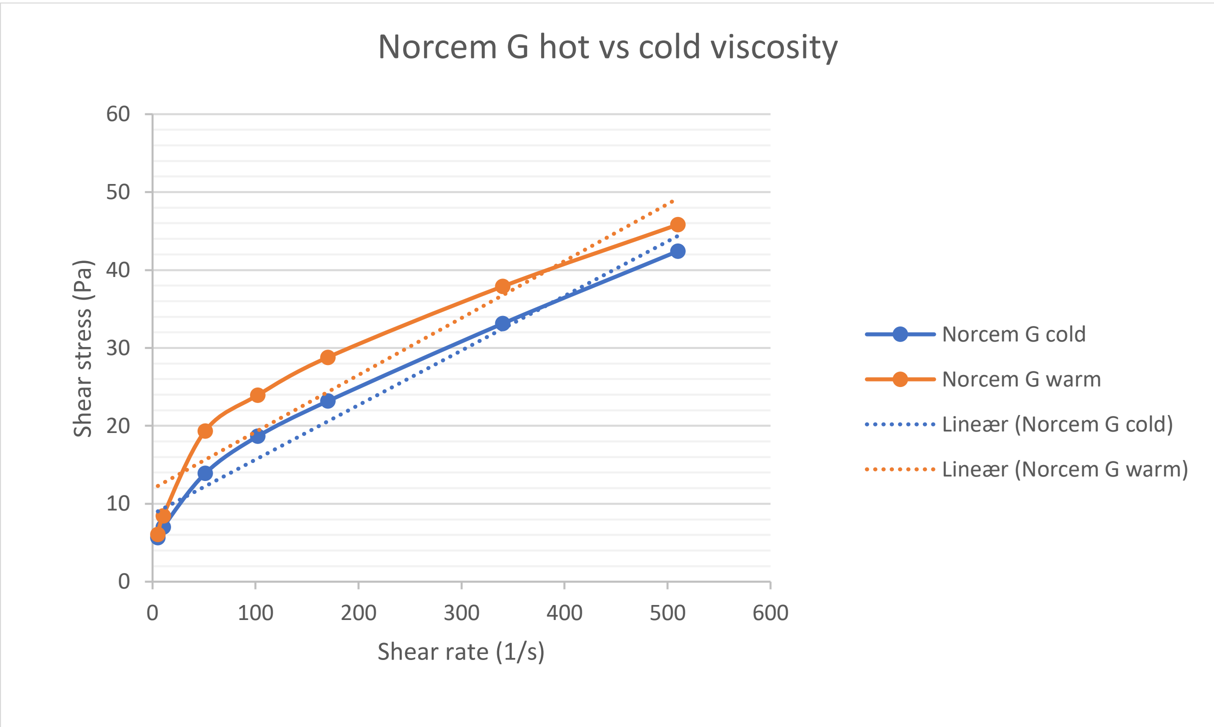


FIGURE 11 NORCEM CLASS G HOT VS COLD AVERAGE VISCOSITY

Norcem class A viscosity comparison

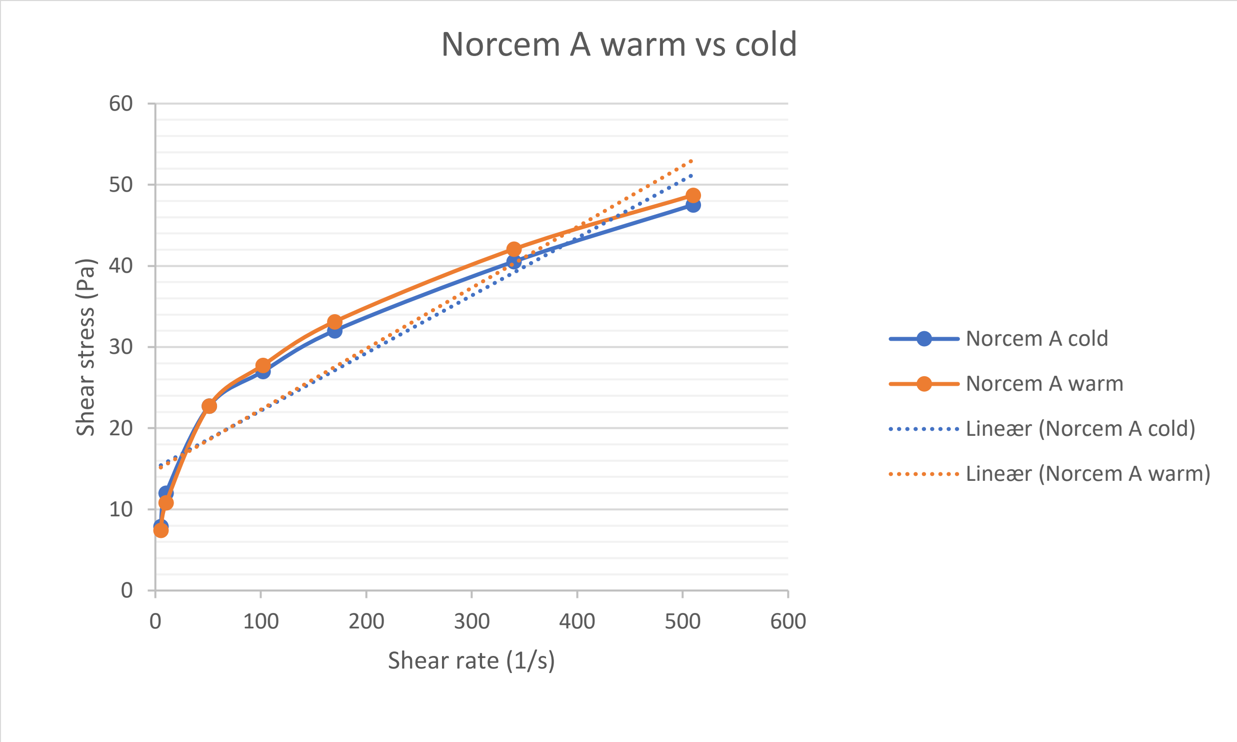


FIGURE 12 NORCEM CLASS A HOT VS COLD AVERAGE VISCOSITY

Dyckerhoff class G viscosity comparison

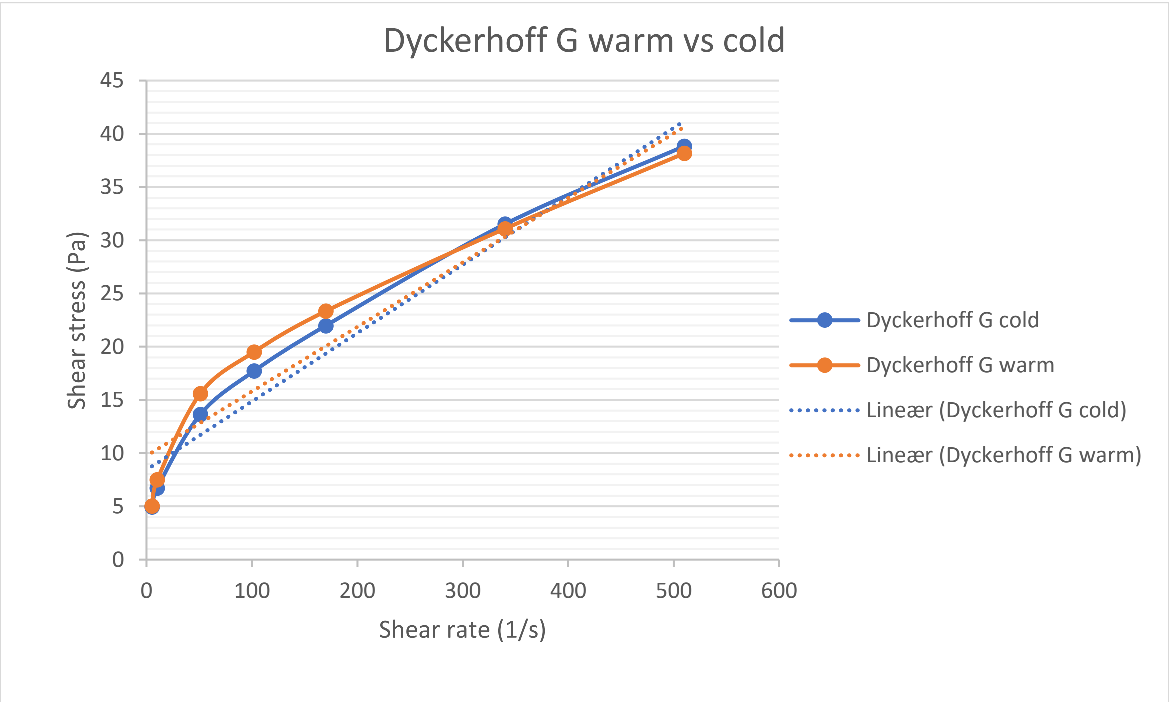


FIGURE 13 DYCKERHOFF CLASS G AVERAGE VISCOSITY MEASUREMENTS

5.2 Unconfined Compressive Strength results

5.2.1 Observations

During preparations for UCS testing I noticed that while sawing the samples: the 8-day cold samples proved weaker than the 8-day RTS. If I sawed off too big of a piece the force from the saw would make chippings in the CTS while the 8-day RTS was more resistant to force from the saw.

During UCS the 8-day CTS also had a lower UCS value than the RTS. After the UCS test you could also notice that the CTS had left a small trace on the surface of the test area. The room temperature samples left less or no trace on the same surface even if they were exposed to a force almost twice of what the cold samples experienced. This can be seen as a proof of much of a difference the hydration is slowed down at cold temperatures.

5.2.2 Norcem class G UCS comparison

TABLE 11 NORCEM CLASS G UCS COMPARISON

Temperature in °C	Days curing	UCS (MPa)	Standard deviation (MPa)	E (GPa)	UCS / E (10^-3)
4	8	19,54	0,33	1,92	10,18
23	8	33,94	4,54	1,92	17,87
4	16	26,23	4,58	1,92	13,66
23	16	35,70	4,97	1,92	18,59

5.2.3 Norcem class A UCS comparison

TABLE 12 NORCEM CLASS A UCS COMPARISON

Temperature in °C	Days curing	UCS (MPa)	Standard deviation (MPa)	E (GPa)	UCS / E (10^-3)
4	8	18,51	2,4	1,92	9,64*10^-3
23	8	18,71	8,35	3,84	4,87*10*-3
4	16	21,45	3,41	1,6	13,41*10*-3
23	16	19,68	0,59	1,6	12,30*10*-3

5.2.4 Dyckerhoff class G UCS comparisons

TABLE 13 DYCKERHOFF CLASS G UCS COMPARISON

Temperature in °C	Days curing	UCS (MPa)	Standard deviation (MPa)	E (GPa)	UCS / E (10^-3)
4	8	14,83	1,46	0,96	15,45
23	8	27,73	2,04	1,47	18,84
4	16	25,97	6,84	1,92	13,53
23	16	36,55	3,52	1,92	19,04

All data from the UCS testing is available in appendix b. The data from table 9, 10 and 11 are the calculated average values based on the testing of 3 samples per condition.

The big difference in E value for Norcem class came unexpectedly from one sample measuring a much higher value than the same sample in the two different batches did.

Dyckerhoff 16 days cold batch two got damaged too much during preparation. Due to the damage and with not enough time left for preparations of a new one, this was left as NA in the data sampling.

A sample from the Dyckerhoff 8-day curing at room temperature cracked at 8kN. Which is a lot earlier than expected. The reason for this could be some air trapped in the sample causing a weakness in the sample.

By looking at the graph in Figure 14, one can argue that for 8-day at cold conditions results the Norcem class A cement can compete with the commonly used Class G cement. The Portland cements clearly cure better at warmer conditions but with time they surpass the measured strength of class A cement at the same conditions.

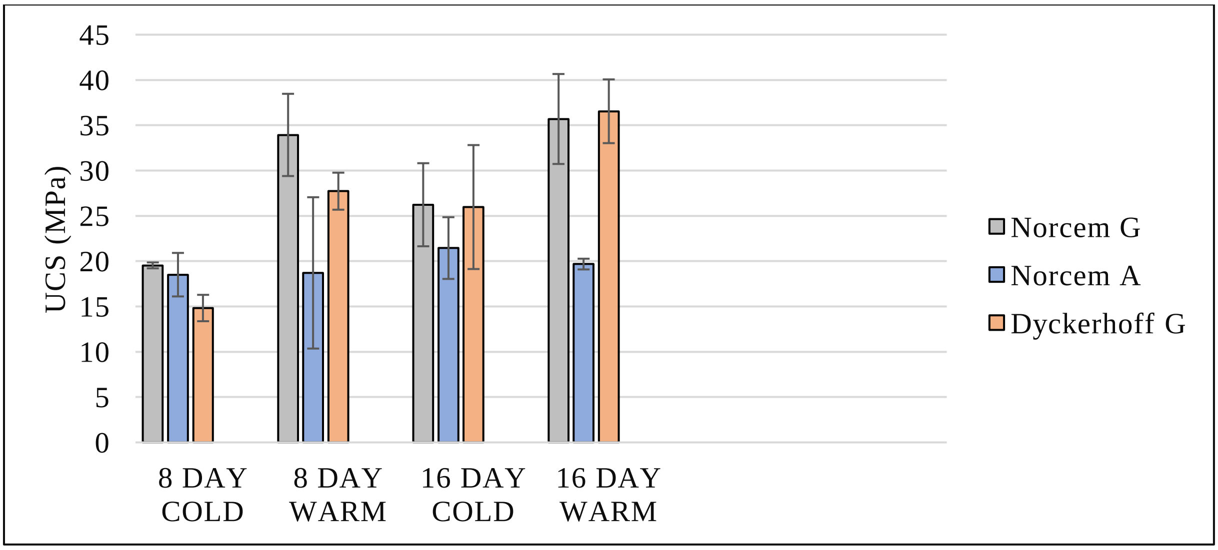


FIGURE 14 UCS

6 Conclusion

When looking into the difference in measured values for shear stress against shear rate for the different slurries, available in appendix e. There is very little difference going from cold to hot for Norcem class A and Dyckerhoff class G. The big difference in measured shear stress for Norcem class G at low shear rates can possibly be a result of a chemical reaction from a difference in content you find in Norcem class G and not in Dyckerhoff class G, since both are Portland cements.

Looking into the calculated yield stress there was little difference between the slurries. Due to a lack of accessible data there was no opportunity to compare these values with other slurries. By not having a scale or data to compare with there is nothing to compare to and evaluate if the yield strength of the slurries are strong enough.

Based on the reported UCS results one can argue that Norcem class A can compete with class G cements at cold conditions. It would be interesting to see how strong the Norcem class A would be compared to the class G cements over a longer period. The Class G cements experienced a 70%+ higher measured UCS during room temperature curing, compared to cold curing. Based on an evaluation of the UCS results it can be assumed that the well conditions dictate the strength development

8-day and 16-day intervals for curing, does not provide sufficient enough evidence for a difference in properties between class A and class G slurries, to determine if use of class A cement can reduce the leakage of shallow gas from cemented wells. The results in terms of viscosity, yield stress and UCS gives us an indication that Norcem A can be, and possibly of better use for primary cementing in cold conditions than the typical Portland cements like Norcem class G and Dyckerhoff class G. To go further into overcoming shallow gas leaks, the gel strength of the cement slurries has to be examined, together with research on fluid loss during curing.

7 Suggestions for future work

From my own operational experience when it comes to cement jobs on offshore wells and during the writing of this thesis, I have gained a few ideas on parts this study should look further into. Hopefully this can be looked at for future work, as I strongly believe that there is a gap able to be closed between the research we do as students in this manner, and how cement jobs are performed in the real world. Even though attention to detail is important to recreate results in the lab, it isn't always that much attention put into it at the worksite. Therefore, we need more data and wellsite intel. With that in place we can reduce the deviation between experimental and operational results.

Data sampling from actual rig conditions while mixing cement.

- What is the temperature the cement is mixed under?
- What is the actual content of this water in terms of minerals and additives? Some samples of drill water would be very helpful. Or even some IBC-containers with DW for this purpose.
- If, how and for how long is the cement conditioned prior to pumping DH?
- Some data on the deviation between API standards for mixing slurries and rig site mixing properties.

Data sampling from down hole conditions

To start with, data should be collected and made available from one field initially. Then at least there is something to compare with while doing the research and working towards recreating conditions. Preferably a field with a lot of previous drilled wells.

- What kind of pressure is the cement curing at?
- What kind of temperature is the cement curing at?
- To make this as realistic as possible there should also be rheological measurements of the cement after it has been circulated through the rig system down to placement. The slurry has travelled through different sizing of pipe at different rates and so on. To recreate this will be very demanding, but sometimes big jobs are needed for big results. If we can not find out more about how the cement is conditioned during placement, we can perhaps recreate the system in a lab with tools we already have in place.

There is also some equipment available at the University of Stavanger already that can be of use. A pressurized consistometer and equipment for curing cement under pressure and temperature. This is definitely something I would recommend being used if someone was to build on my work. Pressured conditions will make data even more similar to "the real thing". I am not sure if there is one of these at the university, but there are coaxial cylinder viscometers on the market who can produce measurements at different pressures and temperatures. This would give us better accuracy in terms of sheer strength for the cement at DHC.

Moving on based on the experience I have gathered during this thesis, I would recommend that studying early strength development at perhaps 6, 9 and 12 hours of curing at cold conditions are looked deeper into. This is based on the conclusion that 8-day curing time is not sufficient to tell us if there is time to save on waiting for cement to cure.

Looking into Class G cement with a lower specific gravity than 1.9 could be beneficial due to the risk of weak formation in shallow sections. Especially for the conductor section.

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BALDER FUTURE DEVELOPMENT DRILLING PROGRAM PL001 BALDER PHASE IV
WELL: 25/11-GT-3 H (M11INJ2MS)

Appendix A Fann 35 measurements

16 days room temperature curing batch 1

Norcem Class G#1

RPM	Up	Down	Avg	Shear rate	Shear stress	
3	11	13	12	5,1	6,132	
6	15	18	16,5	10,2	8,4315	
30	40	44	42	51	21,462	
60	50	53	51,5	102	26,3165	
100	61	63	62	170	31,682	
200	80	82	81	340	41,391	
300	97	97	97	510	49,567	
Weight of solids in gram		348,03	**Temperature before measurements**			22,4°C
Weight of liquid in gram		792,28	**Temperature after measurements**			23°C

Norcem Class A#1

RPM	Up	Down	Avg	Shear rate	Shear stress	
3	13	14	13,5	5,1	6,8985	
6	22	20	21	10,2	10,731	
30	42	45	43,5	51	22,2285	
60	52	54	53	102	27,083	
100	63	64	63,5	170	32,4485	
200	82	81	81,5	340	41,6465	
300	95	95	95	510	48,545	
Weight of solids in gram		475	**Temperature before measurements**			23,2°C
Weight of liquid in gram		792,06	**Temperature after measurements**			23,6°C

Dyckerhoff Class G#1

RPM	Up	Down	Avg	Shear rate	Shear stress	
3	7	9	8	5,1	4,088	
6	12	14	13	10,2	6,643	
30	28	33	30,5	51	15,5855	
60	36	41	38,5	102	19,6735	
100	42	49	45,5	170	23,2505	
200	57	65	61	340	31,171	
300	76	76	76	510	38,836	
Weight of solids in gram		347,89	**Temperature before measurements**			24,5°C
Weight of liquid in gram		792	**Temperature after measurements**			24,7°C

16 days room temperature curing batch 2

Norcem Class G#2

RPM	Up	Down	Avg	Shear rate	Shear stress	
3	11	12	11,5	5,1	5,8765	
6	15	18	16,5	10,2	8,4315	
30	31	37	34	51	17,374	
60	39	47	43	102	21,973	
100	48	55	51,5	170	26,3165	
200	64	73	68,5	340	35,0035	
300	84	84	84	510	42,924	
Weight of solids in gram		348,03	**Temperature before measurements**			23°C
Weight of liquid in gram		792,01	**Temperature after measurements**			23,7°C

Norcem Class A#2

RPM	Up	Down	Avg	Shear rate	Shear stress	
3	13	15	14	5,1	7,154	
6	18	21	19,5	10,2	9,9645	
30	40	45	42,5	51	21,7175	
60	50	54	52	102	26,572	
100	62	64	63	170	32,193	
200	80	82	81	340	41,391	
300	95	95	95	510	48,545	
Weight of solids in gram		474,8	**Temperature before measurements**			23,2°C
Weight of liquid in gram		792,06	**Temperature after measurements**			23,6°C

Dyckerhoff Class G#2

RPM	Up	Down	Avg	Shear rate	Shear stress	
3	9	12	10,5	5,1	5,3655	
6	13	17	15	10,2	7,665	
30	29	33	31	51	15,841	
60	36	42	39	102	19,929	
100	45	50	47,5	170	24,2725	
200	60	65	62,5	340	31,9375	
300	76	76	76	510	38,836	
Weight of solids in gram		348,08	**Temperature before measurements**			21,4°C
Weight of liquid in gram		792,02	**Temperature after measurements**			22°C

Slurries for 16 days room temperature curing batch 3

Norcem Class G #3

RPM	Up	Down	Avg	Shear rate	Shear stress	
3	10	14	12	5,1	6,132	
6	14	19	16,5	10,2	8,4315	
30	35	40	37,5	51	19,1625	
60	44	48	46	102	23,506	
100	54	57	55,5	170	28,3605	
200	72	74	73	340	37,303	
300	88	88	88	510	44,968	
Weight of solids in gram		348,08	**Temperature before measurements**			21,4°C
Weight of liquid in gram		792,02	**Temperature after measurements**			22°C

Norcem Class A #3

RPM	Up	Down	Avg	Shear rate	Shear stress	
3	15	17	16	5,1	8,176	
6	22	24	23	10,2	11,753	
30	46	49	47,5	51	24,2725	
60	57	59	58	102	29,638	
100	67	69	68	170	34,748	
200	84	85	84,5	340	43,1795	
300	96	96	96	510	49,056	
Weight of solids in gram		348,08	**Temperature before measurements**			21,4°C
Weight of liquid in gram		792,02	**Temperature after measurements**			22°C

Dyckerhoff Class G #3

RPM	Up	Down	Avg	Shear rate	Shear stress	
3	10	12	11	5,1	5,621	
6	15	17	16	10,2	8,176	
30	28	32	30	51	15,33	
60	35	39	37	102	18,907	
100	42	46	44	170	22,484	
200	57	61	59	340	30,149	
300	72	72	72	510	36,792	
Weight of solids in gram		348	**Temperature before measurements**			22,8 °C
Weight of liquid in gram		792,03	**Temperature after measurements**			23,3 °C

Slurries for 8 days room temperature curing batch 1

Norcem Class G#1

RPM	Up	Down	Avg	Shear rate	Shear stress	
3	11	15	13	5,1	6,643	
6	18	20	19	10,2	9,709	
30	45	47	46	51	23,506	
60	55	57	56	102	28,616	
100	66	67	66,5	170	33,9815	
200	85	87	86	340	43,946	
300	101	101	101	510	51,611	
Weight of solids in gram		348,02	**Temperature before measurements**			23°C
Weight of liquid in gram		791,6	**Temperature after measurements**			23,2°C

Norcem Class A#1

RPM	Up	Down	Avg	Shear rate	Shear stress	
3	13	15	14	5,1	7,154	
6	20	21	20,5	10,2	10,4755	
30	40	43	41,5	51	21,2065	
60	49	52	50,5	102	25,8055	
100	58	60	59	170	30,149	
200	75	76	75,5	340	38,5805	
300	89	89	89	510	45,479	
Weight of solids in gram		475,01	**Temperature before measurements**			23,9°C
Weight of liquid in gram		792,06	**Temperature after measurements**			23,6°C

Dyckerhoff Class G#1

RPM	Up	Down	Avg	Shear rate	Shear stress	
3	8	10	9	5,1	4,599	
6	12	16	14	10,2	7,154	
30	25	32	28,5	51	14,5635	
60	30	38	34	102	17,374	
100	36	45	40,5	170	20,6955	
200	49	57	53	340	27,083	
300	65	65	65	510	33,215	
Weight of solids in gram		347,96	**Temperature before measurements**			23,4°C
Weight of liquid in gram		792,03	**Temperature after measurements**			23°C

Slurries for 8 days room temperature curing batch 2

Norcem Class G#2

RPM	Up	Down	Avg	Shear rate	Shear stress	
3	10	10	10	5,1	5,11	
6	14	15	14,5	10,2	7,4095	
30	31	30	30,5	51	15,5855	
60	39	39	39	102	19,929	
100	46	45	45,5	170	23,2505	
200	61	60	60,5	340	30,9155	
300	73	73	73	510	37,303	
Weight of solids in gram		348,02	**Temperature before measurements**			23°C
Weight of liquid in gram		792,2	**Temperature after measurements**			23,4°C

Norcem Class A#2

RPM	Up	Down	Avg	Shear rate	Shear stress	
3	15	18	16,5	5,1	8,4315	
6	23	25	24	10,2	12,264	
30	45	50	47,5	51	24,2725	
60	55	59	57	102	29,127	
100	66	67	66,5	170	33,9815	
200	86	86	86	340	43,946	
300	100	100	100	510	51,1	
Weight of solids in gram		475,01	**Temperature before measurements**			25°C
Weight of liquid in gram		791,97	**Temperature after measurements**			24,8°C

Dyckerhoff Class G#2

RPM	Up	Down	Avg	Shear rate	Shear stress	
3	9	12	10,5	5,1	5,3655	
6	13	18	15,5	10,2	7,9205	
30	34	41	37,5	51	19,1625	
60	43	49	46	102	23,506	
100	51	58	54,5	170	27,8495	
200	67	73	70	340	35,77	
300	84	84	84	510	42,924	
Weight of solids in gram		348,01	**Temperature before measurements**			25,5°C
Weight of liquid in gram		792,2	**Temperature after measurements**			24,7°C

Slurries for 8 days room temperature curing batch 3

Norcem Class G#3

RPM	Up	Down	Avg	Shear rate	Shear stress	
3	13	15	14	5,1	7,154	
6	19	21	20	10,2	10,22	
30	39	42	40,5	51	20,6955	
60	47	50	48,5	102	24,7835	
100	57	58	57,5	170	29,3825	
200	72	73	72,5	340	37,0475	
300	85	85	85	510	43,435	
Weight of solids in gram		348	**Temperature before measurements**			24,5
Weight of liquid in gram		792	**Temperature after measurements**			24,7

Norcem Class A #3

RPM	Up	Down	Avg	Shear rate	Shear stress	
3	13	15	14	5,1	7,154	
6	20	21	20,5	10,2	10,4755	
30	40	43	41,5	51	21,2065	
60	49	52	50,5	102	25,8055	
100	58	60	59	170	30,149	
200	75	76	75,5	340	38,5805	
300	89	89	89	510	45,479	
Weight of solids in gram		475,01	**Temperature before measurements**			23,9
Weight of liquid in gram		792,06	**Temperature after measurements**			23,6

Dyckerhoff Class G #3

RPM	Up	Down	Avg	Shear rate	Shear stress	
3	9	11	10	5,1	5,11	
6	13	15	14	10,2	7,154	
30	30	34	32	51	16,352	
60	37	40	38,5	102	19,6735	
100	44	47	45,5	170	23,2505	
200	59	62	60,5	340	30,9155	
300	73	73	73	510	37,303	
Weight of solids in gram		348,1	**Temperature before measurements**			24,2
Weight of liquid in gram		792	**Temperature after measurements**			24,3

Slurries for 16 days cold temperature curing batch 1

Norcem Class G #1

RPM	Up	Down	Avg	Shear rate	Shear stress	
3	10	13	11,5	5,1	5,8765	
6	13	16	14,5	10,2	7,4095	
30	27	31	29	51	14,819	
60	36	40	38	102	19,418	
100	44	48	46	170	23,506	
200	61	66	63,5	340	32,4485	
300	80	80	80	510	40,88	
Weight of solids in gram		348	**Temperature before measurements**			9,7°C
Weight of liquid in gram		791,94	**Temperature after measurements**			13,3°C

Norcem Class A #1

RPM	Up	Down	Avg	Shear rate	Shear stress	
3	14	17	15,5	5,1	7,9205	
6	23	25	24	10,2	12,264	
30	40	44	42	51	21,462	
60	49	51	50	102	25,55	
100	58	59	58,5	170	29,8935	
200	73	75	74	340	37,814	
300	87	87	87	510	44,457	
Weight of solids in gram		474,88	**Temperature before measurements**			8,8°C
Weight of liquid in gram		792	**Temperature after measurements**			12,7°C

Dyckerhoff Class G #1

RPM	Up	Down	Avg	Shear rate	Shear stress	
3	8	11	9,5	5,1	4,8545	
6	13	15	14	10,2	7,154	
30	25	29	27	51	13,797	
60	32	39	35,5	102	18,1405	
100	39	47	43	170	21,973	
200	56	64	60	340	30,66	
300	72	72	72	510	36,792	
Weight of solids in gram		348	**Temperature before measurements**			8,5°C
Weight of liquid in gram		792,03	**Temperature after measurements**			12°C

Slurries for 16 days cold temperature curing batch 2

Norcem Class G #2

RPM	Up	Down	Avg	Shear rate	Shear stress	
3	9	12	10,5	5,1	5,3655	
6	12	14	13	10,2	6,643	
30	25	27	26	51	13,286	
60	34	36	35	102	17,885	
100	43	46	44,5	170	22,7395	
200	63	66	64,5	340	32,9595	
300	83	83	83	510	42,413	
Weight of solids in gram		348,12	**Temperature before measurements**			9°C
Weight of liquid in gram		792	**Temperature after measurements**			12°C

Norcem Class A #2

RPM	Up	Down	Avg	Shear rate	Shear stress	
3	13	17	15	5,1	7,665	
6	19	23	21	10,2	10,731	
30	39	42	40,5	51	20,6955	
60	48	51	49,5	102	25,2945	
100	58	60	59	170	30,149	
200	75	77	76	340	38,836	
300	90	90	90	510	45,99	
Weight of solids in gram		475	**Temperature before measurements**			8°C
Weight of liquid in gram		792,05	**Temperature after measurements**			11,8°C

Dyckerhoff Class G #2

RPM	Up	Down	Avg	Shear rate	Shear stress	
3	9	12	10,5	5,1	5,3655	
6	12	14	13	10,2	6,643	
30	25	27	26	51	13,286	
60	34	36	35	102	17,885	
100	43	46	44,5	170	22,7395	
200	63	66	64,5	340	32,9595	
300	83	83	83	510	42,413	
Weight of solids in gram		348,12	**Temperature before measurements**			9°C
Weight of liquid in gram		792	**Temperature after measurements**			12°C

Slurries for 16 days cold temperature curing batch 3

Norcem Class G#3

RPM	Up	Down	Avg	Shear rate	Shear stress	
3	10	12	11	5,1	5,621	
6	13	14	13,5	10,2	6,8985	
30	25	28	26,5	51	13,5415	
60	34	39	36,5	102	18,6515	
100	43	48	45,5	170	23,2505	
200	63	70	66,5	340	33,9815	
300	86	86	86	510	43,946	
Weight of solids in gram		348	**Temperature before measurements**			9,7°C
Weight of liquid in gram		791,94	**Temperature after measurements**			13,3°C

Norcem Class A#3

RPM	Up	Down	Avg	Shear rate	Shear stress	
3	14	18	16	5,1	8,176	
6	24	27	25,5	10,2	13,0305	
30	49	53	51	51	26,061	
60	58	60	59	102	30,149	
100	70	71	70,5	170	36,0255	
200	87	89	88	340	44,968	
300	102	102	102	510	52,122	
Weight of solids in gram		474,97	**Temperature before measurements**			8,4°C
Weight of liquid in gram		792,12	**Temperature after measurements**			9,9°C

Dyckerhoff Class G#3

RPM	Up	Down	Avg	Shear rate	Shear stress	
3	8	11	9,5	5,1	4,8545	
6	12	15	13,5	10,2	6,8985	
30	25	30	27,5	51	14,0525	
60	33	37	35	102	17,885	
100	41	46	43,5	170	22,2285	
200	60	65	62,5	340	31,9375	
300	77	77	77	510	39,347	
Weight of solids in gram		348,01	**Temperature before measurements**			8,5°C
Weight of liquid in gram		792,03	**Temperature after measurements**			9,7°C

Slurries for 8 days cold temperature curing batch 1

Norcem Class G#1

RPM	Up	Down	Avg	Shear rate	Shear stress	
3	8	12	10	5,1	5,11	
6	12	14	13	10,2	6,643	
30	25	28	26,5	51	13,5415	
60	32	37	34,5	102	17,6295	
100	41	47	44	170	22,484	
200	60	66	63	340	32,193	
300	80	80	80	510	40,88	
Weight of solids in gram		348	**Temperature before measurements**			8°C
Weight of liquid in gram		792,25	**Temperature after measurements**			11,8°C

Norcem Class A#1

RPM	Up	Down	Avg	Shear rate	Shear stress	
3	14	17	15,5	5,1	7,9205	
6	23	26	24,5	10,2	12,5195	
30	44	47	45,5	51	23,2505	
60	54	56	55	102	28,105	
100	64	65	64,5	170	32,9595	
200	82	83	82,5	340	42,1575	
300	97	97	97	510	49,567	
Weight of solids in gram		475,03	**Temperature before measurements**			8°C
Weight of liquid in gram		792,05	**Temperature after measurements**			11,8°C

Dyckerhoff Class G#1

RPM	Up	Down	Avg	Shear rate	Shear stress	
3	8	11	9,5	5,1	4,8545	
6	11	14	12,5	10,2	6,3875	
30	24	28	26	51	13,286	
60	32	36	34	102	17,374	
100	40	43	41,5	170	21,2065	
200	56	59	57,5	340	29,3825	
300	73	73	73	510	37,303	
Weight of solids in gram		347,94	**Temperature before measurements**			8,7°C
Weight of liquid in gram		792,18	**Temperature after measurements**			11°C

Slurries for 8 days cold temperature curing batch 2

Norcem Class G#2

RPM	Up	Down	Avg	Shear rate	Shear stress	
3	8	12	10	5,1	5,11	
6	11	14	12,5	10,2	6,3875	
30	22	25	23,5	51	12,0085	
60	30	34	32	102	16,352	
100	37	42	39,5	170	20,1845	
200	55	59	57	340	29,127	
300	73	73	73	510	37,303	
Weight of solids in gram		348	**Temperature before measurements**			8,7°C
Weight of liquid in gram		792,22	**Temperature after measurements**			10,5°C

Norcem Class A#2

RPM	Up	Down	Avg	Shear rate	Shear stress	
3	16	19	17,5	5,1	8,9425	
6	28	30	29	10,2	14,819	
30	48	52	50	51	25,55	
60	59	61	60	102	30,66	
100	69	68	68,5	170	35,0035	
200	86	86	86	340	43,946	
300	99	99	99	510	50,589	
Weight of solids in gram		475	**Temperature before measurements**			7,9°C
Weight of liquid in gram		792,05	**Temperature after measurements**			11,8°C

Dyckerhoff Class G#2

RPM	Up	Down	Avg	Shear rate	Shear stress	
3	8	11	9,5	5,1	4,8545	
6	12	15	13,5	10,2	6,8985	
30	26	30	28	51	14,308	
60	34	38	36	102	18,396	
100	42	47	44,5	170	22,7395	
200	60	65	62,5	340	31,9375	
300	79	79	79	510	40,369	
Weight of solids in gram		348	**Temperature before measurements**			8,2°C
Weight of liquid in gram		791,89	**Temperature after measurements**			10,9°C

Slurries for 8 days cold temperature curing batch 3

Norcem Class G#3

RPM	Up	Down	Avg	Shear rate	Shear stress	
3	9	12	10,5	5,1	5,3655	
6	11	14	12,5	10,2	6,3875	
30	24	27	25,5	51	13,0305	
60	32	36	34	102	17,374	
100	40	43	41,5	170	21,2065	
200	56	60	58	340	29,638	
300	73	73	73	510	37,303	
Weight of solids in gram		348	Temperature before measurements			8,5°C
Weight of liquid in gram		791,98	Temperature after measurements			9,1°C

Norcem Class A#3

RPM	Up	Down	Avg	Shear rate	Shear stress	
3	14	19	16,5	5,1	8,4315	
6	26	30	28	10,2	14,308	
30	46	50	48	51	24,528	
60	56	58	57	102	29,127	
100	65	65	65	170	33,215	
200	80	80	80	340	40,88	
300	91	91	91	510	46,501	
Weight of solids in gram		475	Temperature before measurements			9°C
Weight of liquid in gram		792,24	Temperature after measurements			11°C

Dyckerhoff Class G#3

RPM	Up	Down	Avg	Shear rate	Shear stress	
3	9	11	10	5,1	5,11	
6	13	15	14	10,2	7,154	
30	26	30	28	51	14,308	
60	34	37	35,5	102	18,1405	
100	41	45	43	170	21,973	
200	57	62	59,5	340	30,4045	
300	75	75	75	510	38,325	
Weight of solids in gram		348	Temperature before measurements			8,5°C
Weight of liquid in gram		791,89	Temperature after measurements			10,9°C

Appendix B UCS measurements

16 days room temperature curing batch 1

Norcem Class G#1

UCS	85,05 kN
σu	85000/0.002010902 = 42,26mPa
E	2 Gpa
R2	99,85

Norcem Class A#1

UCS	41.635 kN
σu	41635/0.002010902 = 20,7 mPa
E	1 Gpa
R2	99,95

Dyckerhoff Class G#1

UCS	70,893kN
σu	70893/0.002010902 = 35,25mPa
E	2 Gpa
R2	99,96

16 days room temperature curing batch 2

Norcem Class G#2

UCS	74,20 kN
σu	74200/0.002010902 = 36,90mPa
E	2 Gpa
R2	99,99

Norcem Class A#2

UCS	39,89 kN
σu	39889/0.002010902 = 19,84mPa
E	2 Gpa
R2	99,99

Dyckerhoff Class G#2

UCS	74,305 kN
σu	74305/0.002010902 = 36,95mPa
E	2 Gpa
R2	99,98

16 days room temperature curing batch 3

Norcem Class G#3

UCS	65,098 kN
σu	65098/0.002010902 = 32,37mPa
E	2 Gpa
R2	99,97

Norcem Class A#3

UCS	42,17 kN
σu	42170/0.002010902 = 20,97mPa
E	2 Gpa
R2	99,97

Dyckerhoff Class G#3

UCS	84,492 kN
σu	84492/0.002010902 = 42,01mPa
E	2 Gpa
R2	99,92

8 days room temperature curing batch 1

Norcem Class G#1

UCS	44,688 kN
σu	44468/0.002010902 = 22,22mPa
E	2 Gpa
R2	99,95

Norcem Class A#1

UCS	31,047 kN
σu	31047/0.002010902 = 15,44mPa
E	1 Gpa
R2	99,85

Dyckerhoff Class G#1

UCS	60,99 kN
σu	60990/0.002010902 = 30,32mPa
E	2 Gpa
R2	99,85

8 days room temperature curing batch 2

Norcem Class G#2

UCS	73,317 kN
σu	73317/0.002010902 = 36,46mPa
E	2 Gpa
R2	99,98

Norcem Class A#2

UCS	26,314 kN
σu	26314/0.002010902 = 13,08mPa
E	9 Gpa
R2	99,98

Dyckerhoff Class G#2

UCS	8,155 kN
σu	8155/0.002010902 = 4,055mPa
E	0,6 Gpa
R2	99,65

8 days room temperature curing batch 3

Norcem Class G#3

UCS	61,05 kN
σu	61050/0.002010902 = 30,36mPa
E	2 Gpa
R2	99,98

Norcem Class A#3

UCS	33,079 kN
σu	33079/0.002010902 = 16,45mPa
E	1 Gpa
R2	99,82

Dyckerhoff Class G#3

UCS	55,18 kN
σu	55180/0.002010902 = 27,44mPa
E	2 Gpa
R2	99,89

16 days cold temperature curing batch 1

Norcem Class G#1

UCS	49.51 kN
σu	49510/0.002010902 = 24,62 mPa
E	2 Gpa
R2	99,86

Norcem Class A#1

UCS	44,415 kN
σu	44415/0.002010902 = 22,08mPa
E	2 Gpa
R2	99,97

Dyckerhoff Class G#1

UCS	64.141 kN
σu	64141/0.002010902 = 31,89 mPa
E	2 Gpa
R2	99,9

16 days cold temperature curing batch 2

Norcem Class G#2

UCS	49,749 kN
σu	49748/0.002010902 = 24,74mPa
E	2 Gpa
R2	99,84

Norcem Class A#2

UCS	52,031 kN
σu	52031/0.002010902 = 25,87mPa
E	2 Gpa
R2	99,98

Dyckerhoff Class G#2

UCS	NA
σu	NA
E	NA
R2	NA

16 cold temperature curing batch 3

Norcem Class G#3

UCS	65,594 kN
σu	65594/0.002010902 = 32,62mPa
E	2 Gpa
R2	99,97

Norcem Class A#3

UCS	38,358 kN
σu	38358/0.002010902 = 19,07mPa
E	1 Gpa
R2	99,74

Dyckerhoff Class G#3

UCS	44,688 kN
σu	44468/0.002010902 = 22,22mPa
E	2 Gpa
R2	99,95

8 days cold temperature curing batch 1

Norcem Class G#1

UCS	40,193 kN
σu	40193/0.002010902 = 19,99mPa
E	1 Gpa
R2	99,7

Norcem Class A#1

UCS	38,242 kN
σu	38242/0.002010902 = 19,02 mPa
E	2 Gpa
R2	99,98

Dyckerhoff Class G#1

UCS	33,652 kN
σu	33652/0.002010902 = 16,73mPa
E	1 Gpa
R2	1

8 days cold temperature curing batch 2

Norcem Class G#1

UCS	41,451 kN
σu	41451/0.002010902 = 20,61mPa
E	2 Gpa
R2	1

Norcem Class A#1

UCS	47,176 kN
σu	47176/0.002010902 = 23,46mPa
E	2 Gpa
R2	99,97

Dyckerhoff Class G#1

UCS	31,662 kN
σu	31662/0.002010902 = 15,74mPa
E	1 Gpa
R2	99,93

8 **days cold temperature curing batch 3**

Norcem Class G#2

UCS	41,138 kN
σu	41138/0.002010902 = 20,46mPa
E	2 Gpa
R2	99,98

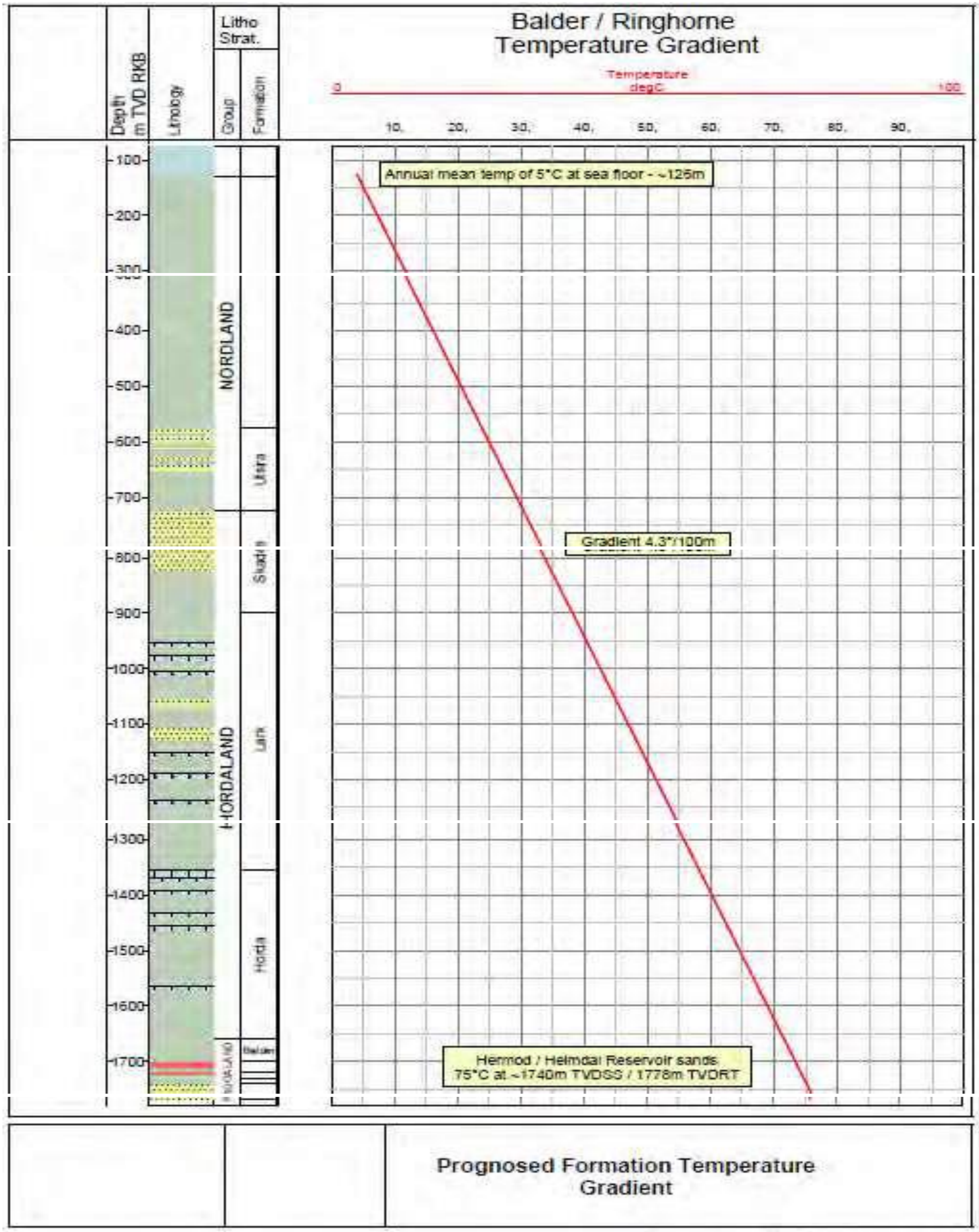
Norcem Class A#2

UCS	43,852 kN
σu	43852/0.002010902 = 21,67mPa
E	2 Gpa
R2	99,98

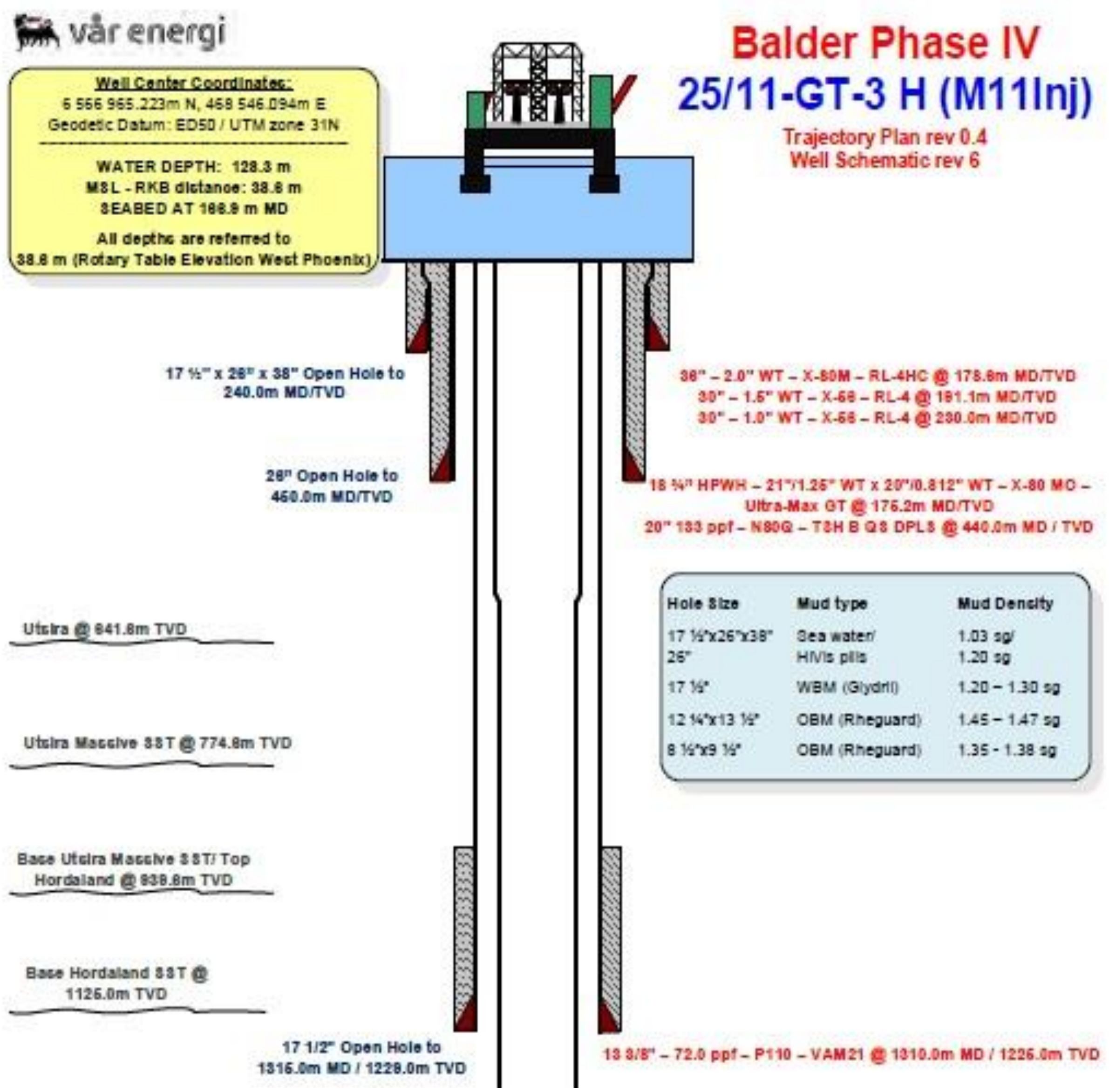
Dyckerhoff Class G#2

UCS	27,89 kN
σu	27888/0.002010902 = 13,86mPa
E	1 Gpa
R2	99,97

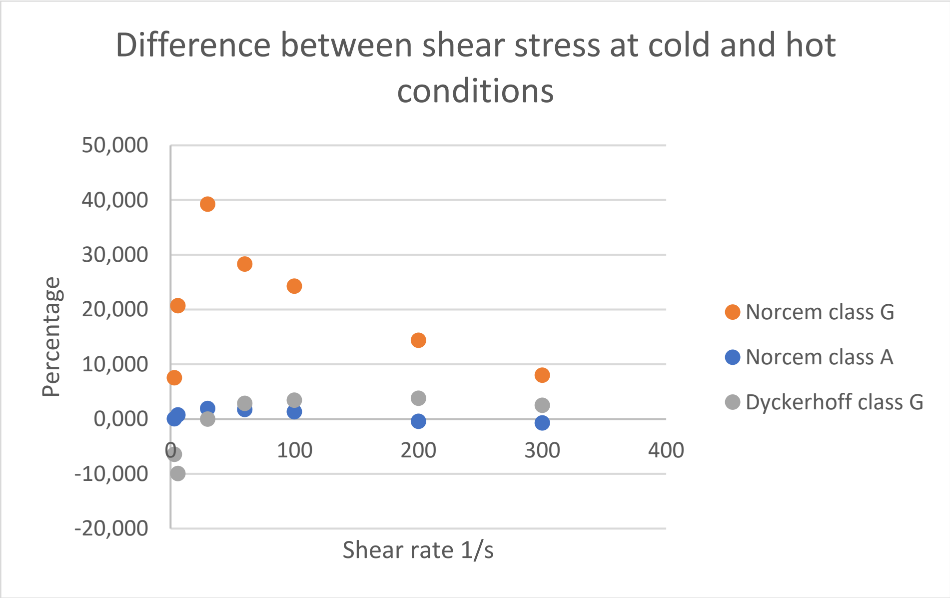
Appendix C Temperature gradient Balder field



Appendix D Well schematics



Appendix E Difference in viscosity graph



Difference in calculated shear stress going from cold to hot conditions.

Based on measurements from appendix a.