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Evaluation of Bentonite as an Alternative Sealing Material in Oil and Gas Wells

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HOVEDOPPGAVE/DIPLOMA THESIS/MASTER OF SCIENCE THESIS

Kandidatens navn/The candidate's name:	*Hans Erik Tveit*
Oppgavens tittel, norsk/Title of Thesis, Norwegian:	*Evaluering av bentonitt som et alternativt tetningsmaterial i olje- og gassbrønner*
Oppgavens tittel, engelsk/Title of Thesis, English	*Evaluation of bentonite as an alternative sealing material in oil and gas wells*

Utfyllende tekst/Extended text:

Background:
Cement has always been the most used sealing material, both for primary cementing and for plug and abandonment of oil and gas wells. However, cement can have problems related to shrinking, micro annuli and cracking due to subsurface movements. Bentonite which swells and hydrates in contact with water has the ability to reshape itself and heal cracks after subsurface movements. This could be an alternative material to cement for plug and abandonment operations.

Task:

1) Make an overview of current plug and abandonment regulations.
2) Review performed studies and research including experiences using bentonite/bentonite pellets as sealing material for plug and abandonment operations.
3) Perform laboratory experiments and evaluate pressure limitation using bentonite plugs. Compare results with earlier models and experiments.

Supervisor	*Sigbjørn Sangesland*
Studieretning/Area of specialization:	*Petroleum Engineering, Drilling Technology*
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…………………………………
Sigbjørn Sangesland

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Summary

A growing number of wells will have to be plugged and abandoned in the future. On the Norwegian continental shelf, 2000 wells will have to be abandoned from 2011-2040. The costs of plugging a well are high and can contribute with up to 25% of the total cost of the well.

In this thesis bentonite was evaluated as an alternative sealing material to cement for plug and abandonment of wells. Bentonite shows superior sealing ability due to the fact that it will swell and expand during hydration compared to cement which has the tendency to shrink. A hydrated bentonite plug also has a lower permeability than cement, and it has the ability to reshape itself and heal any cracks which may occur during subsurface movements.

A literature study was performed to review previous work, and tests using bentonite as a sealing material was conducted in the lab.

In the lab experiments, 9 fullbore plugs and 6 annulus plugs of different lengths made of bentonite pellets were tested. In addition, 7 fullbore plugs and 5 annulus plugs made of dry powdered bentonite were tested. Fullbore plugs were tested in an 8,97cm ID plastic pipe while annulus plugs were tested between the same plastic pipe and a 5,00cm OD plastic pipe. The total length of the test pipe was 1m.

In all the experiments, bentonite created a hydraulically solid plug, both for fullbore plugs and annulus plugs. The pressure needed to dislodge the plugs varied from 20kPa to 101kPa with plug lengths from 23cm to 91cm.

The pressure was found to increase linearly with the length of the plug for both fullbore plugs and annulus plugs, whether bentonite pellets or dry powdered bentonite were used to create the plugs. This leads to the shear strength τ being independent of plug length.

The shear strength τ between the hydrated plugs made of bentonite pellets and the plastic pipes was found to be 1,33 kPa for fullbore plugs and 1,02 kPa for annulus plugs. For plugs prepared by powdered bentonite the shear strength was found to be 1,40 kPa for fullbore plugs and 0,89 kPa for annulus plugs.

The density of the hydrated bentonite pellets plugs was found to be 1,533 g/cm^3. The expansion from dry volume of pellets to hydrated plug volume was in the range of 92%-120%. The dry density of the pellets before hydration was measured to 2,025 g/cm^3.

The density of plugs made of powdered bentonite was found to be 1,102 g/cm^3. The expansion from dry volume of powdered bentonite to hydrated plug volume was in the range of 283-332%. The dry density of the powdered bentonite was measured to 1,09 g/cm^3.

Theory and experiments from soil plugs in driven piles predict that a relatively short sand plug can resist very large forces. By placing a suitable sand plug on top of a bentonite plug, the result could be a short total plug length which is impermeable due to bentonite and can resist large forces due to the sand plug.

Plug height needed to achieve a plug capacity of 200 bar in a 5 ½” casing is 352m for bentonite pellets using the shear strength found for plastic pipes. By taking the increased roughness of a steel pipe into account the height needed is estimated to 89m. The same pressure rating can be achieved using a combination of a 2m long sand plug placed on top of a 10m long bentonite plug.

Further work is suggested to be carried out on combining a bentonite plug with a sand plug located on top. Improved methods for placement of bentonite and sand in the wellbore should also be investigated.

Sammendrag

Et økende antall brønner vil bli plugget og forlatt (Plug & Abandoment) i fremtiden. På den norske kontinentalsokkelen er det estimert at rundt 2000 brønner kommer til å bli plugget og forlatt fra 2011 til 2040. Kostnadene ved plugging av brønner er svært høye og kan utgjøre opp til 25% av total brønnkostnad.

I denne oppgaven ble bentonitt evaluert som et alternativt tetningsmaterial til sement for plugging og forlating av brønner. Bentonitt viser overlegen tettingsevne fordi den sveller og utvider seg under hydrering, i motsetning til sement som har en tendens til å krympe. En hydrert bentonittplugg har også en lavere permeabilitet enn sement, og kan forme seg og tette eventuelle sprekker som kan oppstå som følge av bevegelser i undergrunnen.

Et litteraturstudium ble utført for å gjennomgå tidligere arbeid, etterfulgt av eksperimenter med bentonitt som tetningsmaterial.

I laboratorieforsøkene ble 9 sylinderplugger og 6 ringroms-plugger laget av bentonitt pellets testet. I tillegg ble det testet 7 sylinderplugger og 5 ringroms-plugger laget av bentonitt i pulverform. Sylinderpluggene ble testet i et plastrør med en indre diameter på 8,97cm og en lengde på 1m, mens ringroms-pluggene ble testet mellom plastrøret på 8,97cm og et indre plastrør med en ytre diameter på 5,00cm.

I alle forsøkene ble resultatet en tett bentonittplugg som kunne motstå trykk. Trykket som var nødvendig for å forskyve pluggen oppover i plastrøret varierte fra 20kPa til 101kPa med plugglengder fra 23cm til 91cm.

Trykket for å løsne pluggene ble funnet til å øke lineært med lengden av pluggene, både for plugger laget av bentonitt pellets og bentonitt i pulverform. Dette viser at skjærstyrken τ mellom bentonittpluggen og plastrøret er uavhengig av lengden til pluggen.

Skjærstyrken τ mellom plastrøret og bentonittplugger laget av pellets ble målt til 1,33 kPa for sylinderplugger og 1,02 kPa for ringroms-plugger. For plugger laget av bentonitt i pulverform ble skjærstyrken målt til 1,40 kPa for sylinderplugger og 0,89 kPa for ringroms-plugger.

Tettheten til de hydrerte pluggene laget av bentonitt pellets ble målt til 1,533 g/cm^3, ekspansjon fra tørt volum av pellets til volum av hydrert plugg varierte fra 92% til 120%. Tettheten til pellets før hydrering ble målt til 2,025 g/cm^3.

Tettheten til de hydrerte pluggene laget av bentonitt i pulverform ble målt til 1,102 g/cm^3, ekspansjon fra tørt volum av pulver til volum av hydrert plugg varierte fra 282% til 332%. Tettheten til bentonitt pulveret før hydrering ble målt til 1,09 g/cm^3.

Teori og eksperimenter som omhandler peling (for fundamentering) viser at relativt korte sandplugger som bygger seg opp inni pelene under installasjon kan motstå svært store krefter. Ved å plassere en passende sandplugg over en bentonittplugg kan resultatet bli en kort total plugglengde som er ugjennomtrengelig på grunn av bentonitten, og som kan motstå store krefter på grunn av sandpluggen.

Eksempelvis vil nødvendig plugglengde for å motstå ett trykk på 200 bar i et 5 ½" fôringsrør være 352m ved å bruke skjærstyrken funnet for bentonitt pellets i plastrør. Ved å ta hensyn til ruheten til stål er nødvendig plugglengde anslått til 89m. En tilsvarende trykkdifferanse kan oppnås ved å plassere en 2m lang sandplugg på toppen av en 10m lang bentonittplugg.

Forslag til videre arbeid er å undersøke kombinasjonen av bentonittplugg og sandplugg plassert over. I tillegg må det undersøkes metoder for effektiv plassering av bentonitt og sand i borehullet.

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Nomenclature

HSE	-	Health, safety and environment
ID	-	Inner diameter
MD	-	Measured depth
OD	-	Outer diameter
P&A	-	Plug and Abandonment
TVD	-	True vertical depth
WBS	-	Well Barrier Schematics

1 Introduction

Many wells on the Norwegian Continental shelf are in the end stages of their lifetime and will need to be plugged and abandoned in the near future. From 2011-2040 it is estimated that around 2000 wells need to be abandoned, while 150 new wells will be drilled each year (Ringøen, 2011). On world basis the numbers are much larger. Plug and abandonment (P&A) operations are expensive and can contribute for up to 25% of the total drilling costs of exploration wells (Sørheim et al. 2011). Because of this, more research should be done to reduce the costs and at the same time increase the safety and integrity of plugged and abandoned wells.

The choice of sealing material for the plug and abandonment operations is important, it shall seal the wellbore for eternity and ensure that well integrity is maintained for any foreseeable event.

Traditionally has cement always been the sealing material of choice, both for primary cementing of casing and when the well needs to be permanently plugged and abandoned at the end of the lifetime. But cement has problems related to shrinking while setting, creation of micro annuli and channeling. Cement is also brittle and can crack and make pathways for hydrocarbons to escape in events of subsurface movements such as earthquakes, salt migration or compaction/subsidence. If a plastic material such as bentonite was used, which swell and expands during hydration, it will have the ability to reshape itself to the surroundings and heal any cracks which may occur.

Bentonite has been used as a plugging material in monitoring wells, mining shafts, seismic shot holes and water wells, it has also been suggested to plug high level nuclear waste deposits (Englehardt et al. 2001).

The main objective of this thesis is to evaluate if bentonite is a viable sealing material for oil and gas wells. Lab experiments will be carried out to evaluate how much differential pressure a bentonite plug can withstand before being dislodged, and how the pressure varies with increasing plug length.

2 Literature study

2.1 Norsok and requirements

Guidelines and requirements for plug and abandonment operations on the Norwegian continental shelf are found in the NORSOK standard D-010. This standard is developed by the Norwegian petroleum industry to ensure safety, cost effectiveness and value adding in the industry. In addition NORSOK standards are trying to replace oil company specifications and to be a reference for the authorities (Norsk Standard, 2004).

Chapter 9 of the NORSOK standard D-010 deals with requirements and guidelines for permanent and temporary plug and abandonment of wells. Permanent abandonment is defined as a “well status, where the well or part of the well will be plugged and abandoned permanently, and with the intentions to never being used or re-entered again”. While temporary abandonment is defined as a “well status, where the well is abandoned and/or the well control equipment is removed, with the intention that the operation will be resumed within a specified time frame (from days up to several years)” (Norsk Standard, 2004).

Table 2.1 lists the individual well barriers that shall be included in plug and abandonment activities (Norsk Standard, 2004).

Name	Function	Purpose
Primary well barrier	First well barrier against flow of formation fluids to surface	To isolate a potential source of inflow from surface
Secondary well barrier	Backup to the primary well barrier	Same purpose as the primary well barrier, and applies where the potential source of inflow is a reservoir with flow potential, or contains hydrocarbons
Well barrier between reservoirs	To isolate reservoirs from each other	To reduce potential for crossflow between reservoirs
Open hole to surface barrier	To isolate an open hole from surface	Fail-safe well barrier

Table 2.1: List of well barriers to be included in plugging activities (Norsk Standard, 2004).

2.1.1 Permanent abandonment

According to Norsok should permanent plug and abandonment of a well be done for an eternal perspective, the purpose of this is to evaluate the effect on the well barriers after any foreseeable geological and chemical process has taken place. For a well with a reservoir with hydrocarbons or flow potential, two permanent well barriers are required downhole, one primary well barrier and one secondary well barrier. In addition a permanent open hole to surface plug is needed on top, regardless of pressure or flow potential (Norsk Standard, 2004).

All permanent well barriers are required to extend over the full cross section of the wellbore and seal completely both vertical and horizontally, see Figure 2.1. This means that if a plug is set inside the casing, it must be set at a depth interval where there is a verified well barrier in the annulus outside the casing (Norsk Standard, 2004).

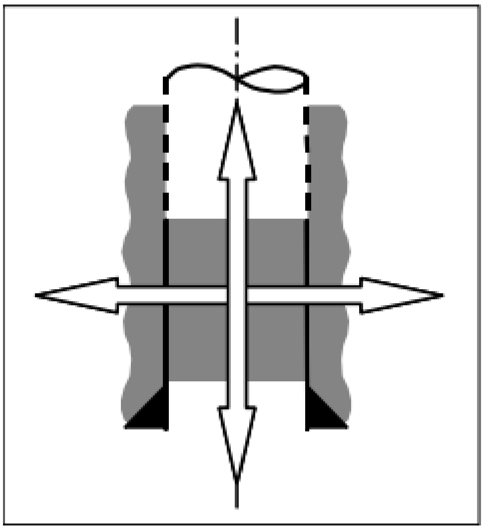


Figure 2.1: A permanent well barrier shall extend across the full wellbore (Norsk Standard, 2004).

The required properties of a permanent well barrier are the following (Norsk Standard, 2004):

- Impermeable
- Long term integrity
- Non shrinking
- Non brittle
- Ductile, able to withstand mechanical loads
- Resistance to substances like H_2S, CO_2 and hydrocarbons
- Wetting, to ensure bonding to steel

Materials used in well barriers should have the properties listed above, and be able to withstand the loads and environmental conditions it will be exposed to. Tests should be carried out to prove long term integrity of plugging materials.

Steel tubulars are not accepted as a permanent well barrier element, unless it is supported both inside and outside by cement or an alternative plugging material with properties similar to those listed above (Norsk Standard, 2004).

Well barriers should generally be installed as close as possible to the potential source of inflow, while covering all possible leak paths. Primary and secondary well barriers shall be set at place where the estimated formation fracture pressure is higher than the maximum potential internal pressure below the plug. The length of a cement plug should generally be at least 100m MD, and should extend at least 50m MD above any source of inflow. A plug set in the transition from open hole to casing should extend at least 50m MD below the casing shoe. If a cement plug is set inside the casing on a mechanical plug minimum length is 50m MD. After placing the final position of a plug should be verified by tagging (Norsk Standard, 2004).

As long as the integrity of the well barrier is ensured, it is not required to remove downhole equipment, but control cables and lines can create vertical leak paths and must be removed from areas where permanent well barriers are set. If well completion tubulars are left in hole and permanent plugs are installed around and inside the tubulars, reliable methods to install and verify position of the plugs should be used (Norsk Standard, 2004).

After permanent abandonment of a well the wellhead, conductor and casings should be cut and retrieved such that no parts of the well will ever stick up of the seabed. The cutting depth should be at least 5m below the seabed (Norsk Standard, 2004).

2.1.2 Temporary abandonment

Requirements for isolation of pressure, formations and fluids are the same for temporary abandonment as for permanent abandonment. But choice of well barrier elements may vary due to abandonment time and ability to re-enter the well at a later time.

For temporary well abandonment two barriers are also required, one primary and one secondary, but an open hole to surface barrier is not needed. As the primary and secondary well barrier, mechanical plugs can be used as long as they are designed to last for the planned temporary abandonment period times two. Mechanical plugs are not allowed as well barriers for permanent plug and abandonment (Norsk Standard, 2004).

2.1.3 Plug and abandonment design

Generally all elements of the well barrier shall withstand the pressure differential across the well barrier at time of installation and as long as the well will be abandoned.

As a basis of the abandonment plan and well barrier design the following information should be gathered (Norsk Standard, 2004):

- Well configuration including depths and specifications of permeable formations, casing strings, primary casing cement status, well bores and side tracks.
- Location of reservoirs and information about their current and future production potential, including pressure (initial, current and in an eternal perspective).
- Logs from primary cementing operations.
- Estimated formation fracture gradient.

Design of well barriers made of cement should account for uncertainties related to the following (Norsk Standard, 2004):

- Downhole placement techniques
- Minimum volumes required to mix a homogenous slurry
- Surface volume control
- Pump efficiency and parameters
- Contamination of fluids
- Shrinkage of cement

Functional and environmental loads shall be combined in the most unfavorable way. For permanently abandoned wells the maximum specific gravity of well fluids shall be set to seawater gradient (Norsk Standard, 2004).

2.1.4 Well barrier schematics

It is recommended that well barrier schematics are made and used to illustrate the presence of the primary and secondary well barriers in the well, Figure 2.2 and Figure 2.3 shows typical well barrier schematics for plug and abandonment operations following the NORSOK standard D-010.

Figure 2.2 is a WBS for permanent plug and abandonment of an open hole completion. The right half of the figure is for a well with no reservoir connected, and thus only a primary well barrier is necessarily. The primary well barrier consist of verified cement behind casing and a cement plug set in transition across the casing shoe, it should be minimum 100m MD long and extend at least 50m MD below the casing shoe. The left half of the figure is for a well with a reservoir, here the primary well barrier is a cement plug in open hole which shall extend at least 50m MD above any source of inflow. The secondary well barrier is a 50m MD cement plug on top of a mechanical plug with verified cement behind casing. For both cases an open hole to surface cement plug is set on top (green color), to ensure verified cement behind casing for this plug, the two inner casings needs to be cut/milled over the plug length.

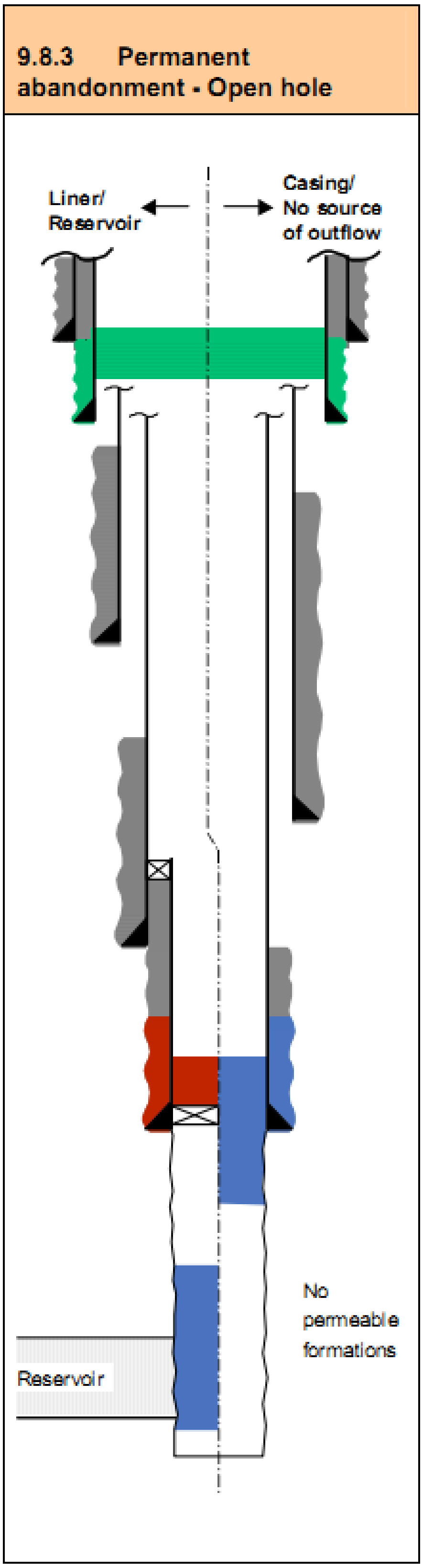


Figure 2.2: Well barrier schematic, permanent abandonment of open hole solution (Norsk Standard, 2004).

Figure 2.3 is a WBS for permanent plug and abandonment for a cased and perforated hole. To the left the production tubing has been removed and the secondary well barrier (red) consists of a cement plug across the liner top with verified cement behind casing. For both cases the primary well barrier is a cement plug across the perforations with verified cement behind the liner. In the right half of Figure 2.3 the production tubing has been left in hole, because of this the secondary well barrier consist of a cement plug both inside and outside of the production tubing in addition to verified cement behind casing. The final open hole to surface plug is identical for both cases, surface casings and tubing need to be cut and retrieved to ensure verified cement behind casing.

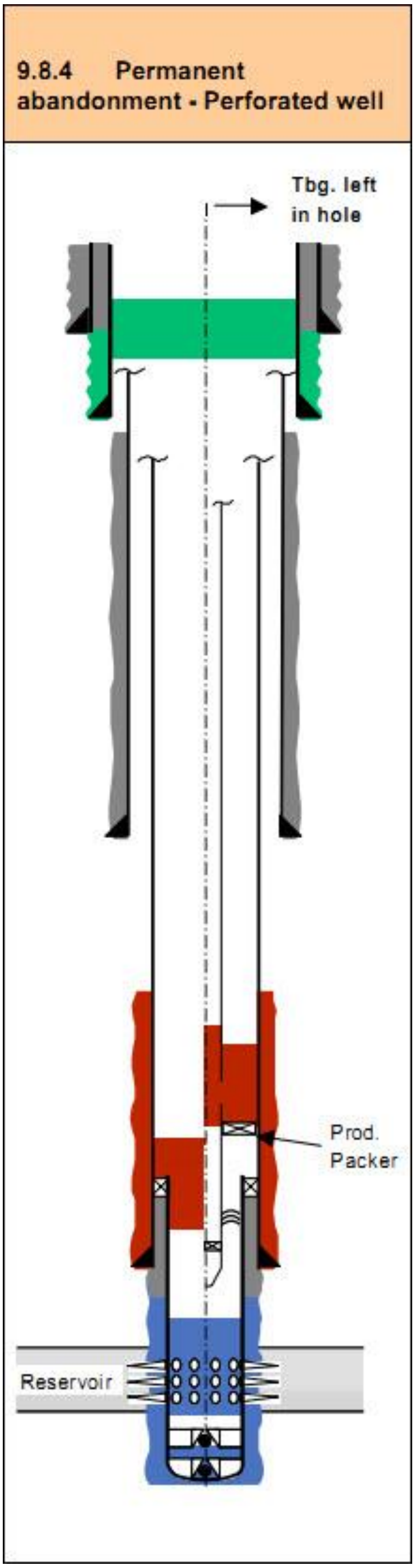


Figure 2.3: Well barrier schematic for permanent abandonment of perforated well (Norsk Standard, 2004).

2.2 Cement

Cement has always been the most used sealing material in the oil and gas industry, both for sealing around casing and for setting of plugs for abandonment operations.

Portland cement is produced by fusing powdered blends of limestone ($CaCO_3$) with materials such as clays, shales, siliceous sand, iron ores, blast furnace slag and pyrite cinders at a temperature of about 1450°C. These blends can be seen as a mixture of the oxides of calcium (CaO), silicon (SiO_2), aluminium (Al_2O_3), iron (Fe_2O_3), magnesium (MgO), potassium (K_2O) and sodium (NaO_2). During heating these oxides combine to create calcium silicates ($(CaO)_3 \cdot SiO_2$ and $(CaO)_2 \cdot SiO_2$) and aluminates ($(CaO)_3 \cdot Al_2O_3$) which will react with water and form a hydrated product with cement properties (Calvert and Smith, 1990).

Because the mix of Portland cement and water can harden both in air and under water it is called hydraulic cement. The process where hydraulic cement set and hardens by reaction with water is called hydration and it creates a stonelike mass. The hydration process start as soon as cement is in contact with water and each cement particle grows until it is in contact and link up with other growing cement particles (Calvert and Smith, 1990).

2.3 Sandaband

Sandaband is an alternative plugging material to cement, and it is described by the following properties on Sandaband Well Plugging AS homepage (2012):

- Incompressible, everlasting, gas-tight material
- Liquid as pumped, solid at rest (Bingham-plastic)
- Yields if stress exceed strength
- Non-shrinking, non-fracturing, non-segregating
- Thermodynamically stable and chemically inert
- Needs a solid floor, will sink if placed on a fluid

Sandaband has been used in both temporary and permanent plug and abandonment. In 2004 a well in the Kristin field was temporarily abandoned using this concentrated sand slurry (Saasen et al. 2004). The well was to be temporarily abandoned after just being finished drilled to wait for later completion. Normally this is done by setting a cement plug across the reservoir which later needs to be drilled out by the completion rig (Saasen et al. 2004). A cement plug set in the reservoir will take up to one week of extra rig time to remove compared to a sand slurry, it will also cause more damage to the reservoir (Saasen et al. 2004). Due to this a sand slurry plug was placed in the well from 4917m MD to 5150m MD in 35° deviation, see Figure 2.4.

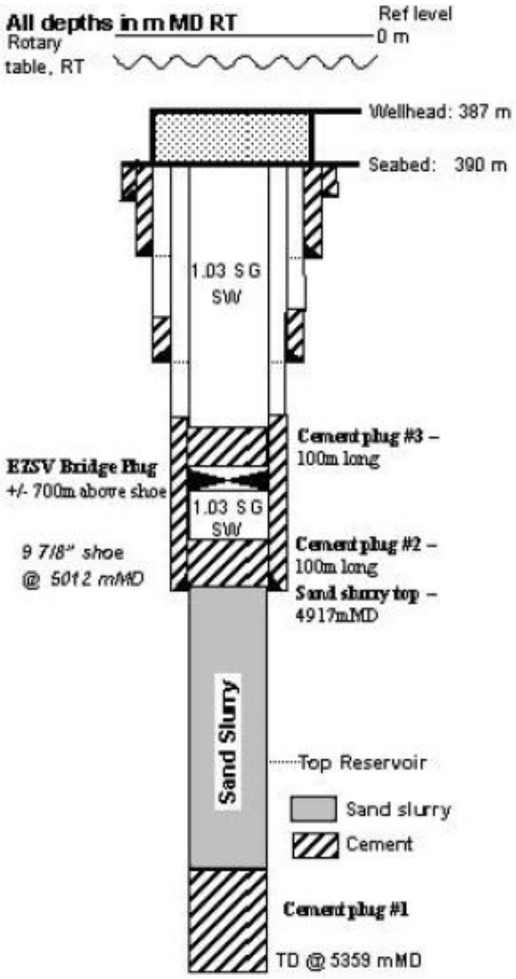
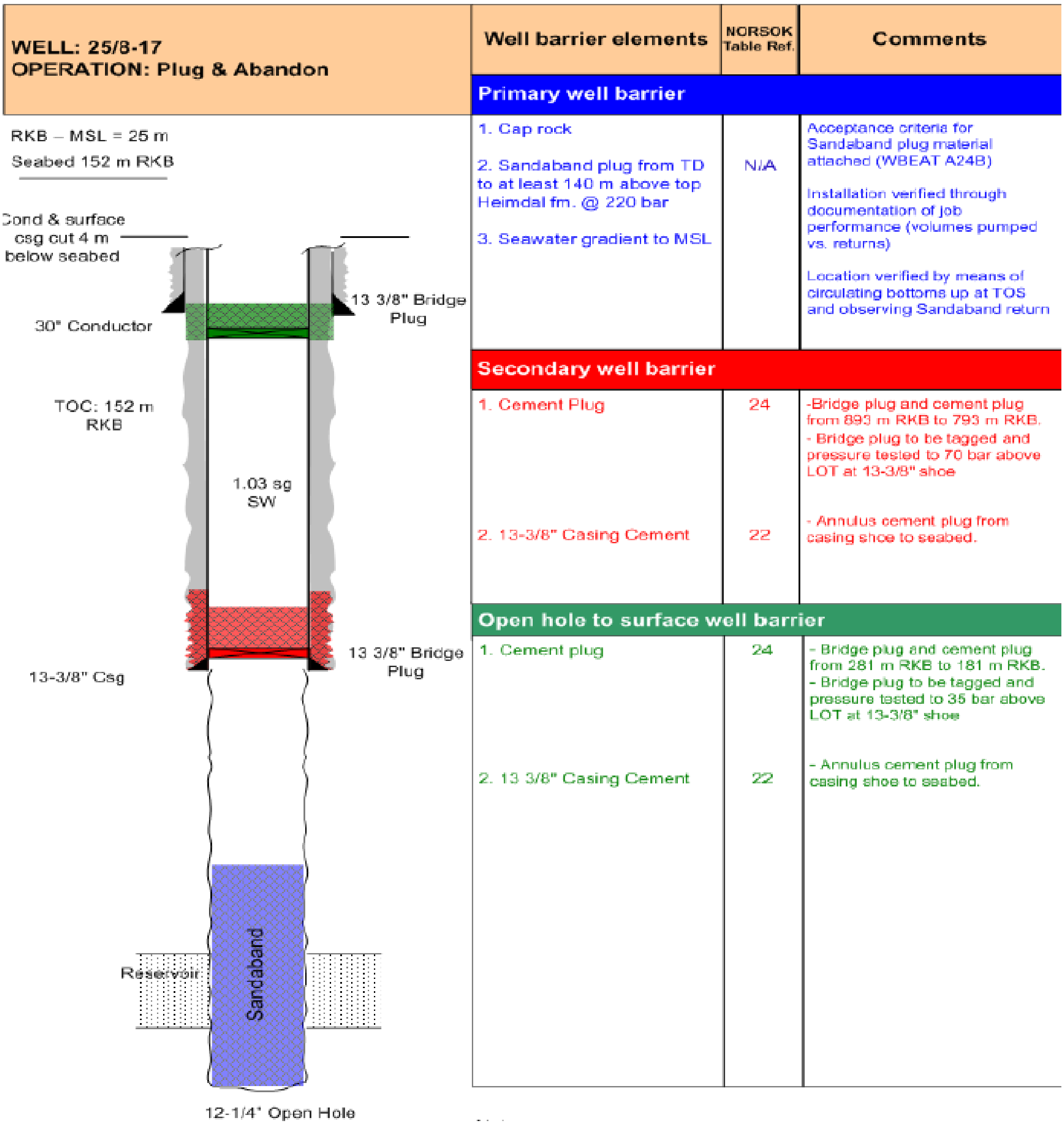


Figure 2.4: Temporary plug and abandonment scheme for well at the Kristin field (Saasen et al. 2004).

In February 2006 the Sandaband plug was completely washed out with an open ended drill pipe saving several days of rig time due to no need to mill out a cement plug, the well was completed successfully with no formation damage and is now the best producer in the Kristin field (Grannes, 2011).

In 2010 exploration well 25/8-17 was permanently plugged with Sandaband, this was done by setting a 290m long concentrated sand slurry plug as the permanent primary plug in the reservoir, see Figure 2.5 (Saasen et al. 2010).



Well barrier elements	NORSOK Table Ref.	Comments
Primary well barrier		
1. Cap rock 2. Sandaband plug from TD to at least 140 m above top Heimdal fm. @ 220 bar 3. Seawater gradient to MSL	N/A	Acceptance criteria for Sandaband plug material attached (WBEAT A24B) Installation verified through documentation of job performance (volumes pumped vs. returns) Location verified by means of circulating bottoms up at TOS and observing Sandaband return
Secondary well barrier		
1. Cement Plug	24	-Bridge plug and cement plug from 893 m RKB to 793 m RKB. - Bridge plug to be tagged and pressure tested to 70 bar above LOT at 13-3/8" shoe
2. 13-3/8" Casing Cement	22	- Annulus cement plug from casing shoe to seabed.
Open hole to surface well barrier		
1. Cement plug	24	- Bridge plug and cement plug from 281 m RKB to 181 m RKB. - Bridge plug to be tagged and pressure tested to 35 bar above LOT at 13-3/8" shoe
2. 13 3/8" Casing Cement	22	- Annulus cement plug from casing shoe to seabed.

Figure 2.5: Well abandonment schematics and WBE (Grannes, 2011).

The procedure was to tag bottom with a 5" open ended drill pipe, pull up 1 meter and pump 30,5m^3 Sandaband at a rate of 550 lpm. Operational risks associated with cement, like temperature effects, contamination, losses to formation and premature curing are avoided by using Sandaband. This is because the properties of the sand slurry comes from the physical and mechanical properties of the material, being mostly quartz sand (75%) and water, it is stable to downhole fluids like H_2S, CO_2 and hydrocarbons. Only a small amount of non-hazardous viscosifiers and dispersant are included to keep the material pumpable (Saasen et al. 2010). It remains stable and impermeable forever and compared to cement the material is also non-shrinking, non-fracturing and able to self-heal and reshape resulting in no leakages in microannuli or similar (Saasen et al. 2010).

2.4 Bentonite and clay mineralogy

Bentonite as a term was first used in 1898 to describe a highly colloidal and plastic clay found in Wyoming, this clay had the unique characteristic of creating thixotropic gels when small amounts was mixed with water, and the clay swelled to several times its original volume when placed in water. Later bentonite has been used to describe clays with similar properties as the clay found in Wyoming. The dominant clay-mineral found in bentonite is montmorillonite, it is from montmorillonite bentonite get its characteristic swelling and thixotropic properties. Other clay-minerals such as illite and kaolinite are often found in bentonite, in addition the nonclay mineral content of bentonite is rarely less than 10% (Grim, 1953).

With regards to exchangeable cations, most bentonites carry Ca^{2+} as the most abundant cation, while bentonites with Na^{+} cations, as the one found in Wyoming, are more seldom (Grim, 1953).

2.4.1 Definition of clay

Clay is used both as a rock term and as a particle-size term. As a rock term, clay generally implies a natural earthy material which is fine-grained and when mixed with a small amount of water it will behave plastic. The moistened material will deform when pressure is applied, and when the pressure is removed the clay will keep the deformed shape. Chemical analysis of clays reveals that they consist mostly of silicon (Si), aluminium (Al) and water (H_2O). Often with substantial amounts of iron (Fe), alkali metals (Na) and alkaline earth metals (Mg). The term clay has also no genetic significance, it is used for materials that have been deposited as sediments, are products of weathering or are formed by hydrothermal action (Grim, 1953).

As a particle-size term, clay is categorized as the fraction of particles with the smallest size. The maximum size of a clay grade size particle varies in different disciplines, in geology it is defined as particles smaller than about 4 micron ($4*10^{-6}$m) while in soil investigations the upper size of 2 micron is used for clay grade size particles (Grim, 1953).

Clay contains varying amounts of clay grade particles, and in result varying amounts of nonclay minerals. In all clays there exist nonclay minerals with a size larger than the clay grade, in some hydrothermal clays the amount of nonclay minerals can be as low as 5%. But many other materials are called clays even when the clay-minerals and the clay-grade particles makes up less than half of the rock, but in these cases the nonclay particles are normally close to the maximum size of the clay grade. In general materials have been called clay if they behave plastic while moistened and are fine grained and do not contain enough coarse material to be placed in the silt or sand category (Grim, 1953).

2.4.2 Structure of clay minerals

The structures of the different clay minerals are based on two structural units, an octahedral layer and a tetrahedral layer.

2.4.2.1 Octahedral layer

This layer consists of two parallel planes packed with oxygen or hydroxyl. In the middle, with exactly the same distance to all the oxygen (or hydroxyl) a cation is located, this makes a octahedral structure as seen in Figure 2.6. The cation can be aluminium (Al^{3+}), magnesium (Mg^{2+}) or iron (Fe), when Al^{3+} is in the center, only 2/3 of the positions are filled and the structure is called gibbsite with formula $Al_2(OH)_6$. With Mg^{2+} in the center all the positions are filled and the structure is called brucite with formula $Mg_3(OH)_6$ (Grim, 1953).

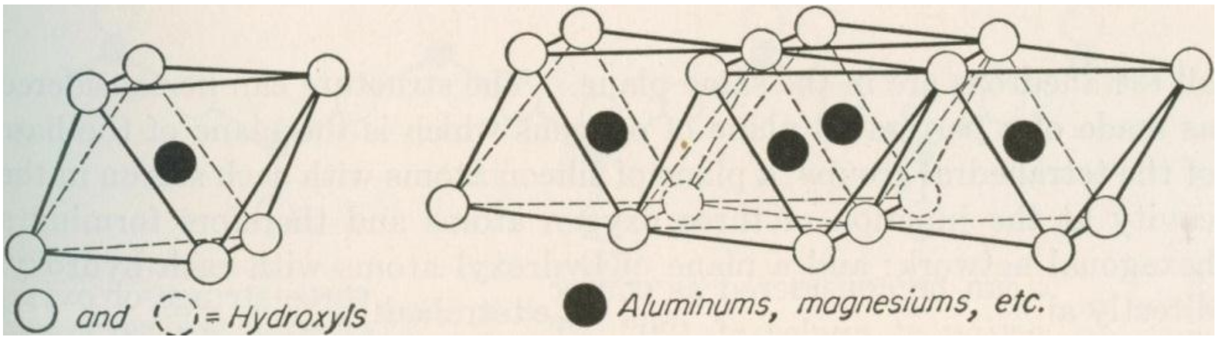


Figure 2.6: Single octahedral unit to the left, layer structure of octahedral units to the right (Grim, 1953).

2.4.2.2 Tetrahedral layer

This layer consists of tetrahedrons with oxygen or hydroxyl in all four corners and a silicon (Si) atom in the center, see Figure 2.7. By sharing corner oxygen (or hydroxyl) several silicon tetrahedra can combine and make larger structures, like the hexagonal structure seen to the right in Figure 2.7.

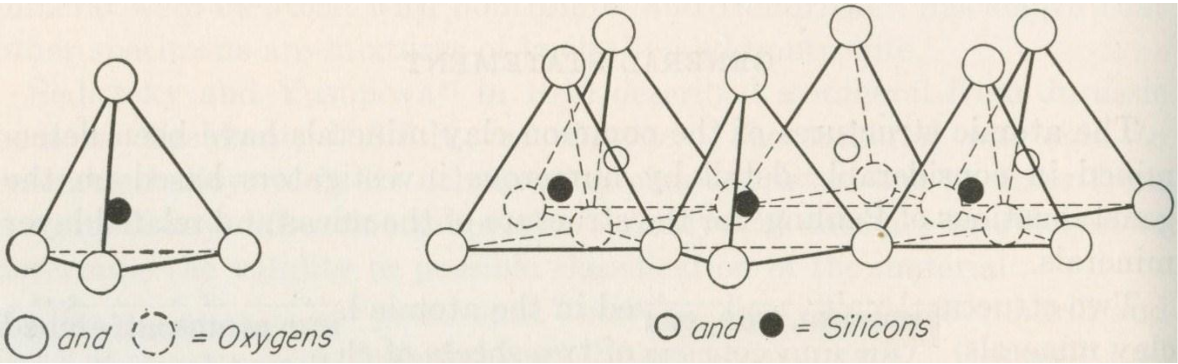


Figure 2.7: Single tetrahedron to the left, hexagonal layer structure to the right (Grim, 1953)

The tetrahedrons are arranged such as they all face the same direction, and the base for all of them are in the same plane. The octahedral layer and the tetrahedral layer can combine by sharing oxygen or hydroxyl, and different compositions of these two layers create the various clay minerals (Grim, 1953).

2.4.3 Montmorillonite

Montmorillonite is composed of two sheets of silica tetrahedral with an octahedral sheet in the center, the tips of the tetrahedrons point in the same direction towards the center of the structure, as seen in Figure 2.8. The structures are stacked as seen in Figure 2.8 with the O layer of one tetrahedron-octahedron-tetrahedron unit facing the O layer of another unit. This result in a very weak bond and a separation between the units, the main feature of the montmorillonite structure is that water or other polar molecules can enter between the unit layers and cause the montmorillonite to expand in the vertical direction (Grim, 1953).

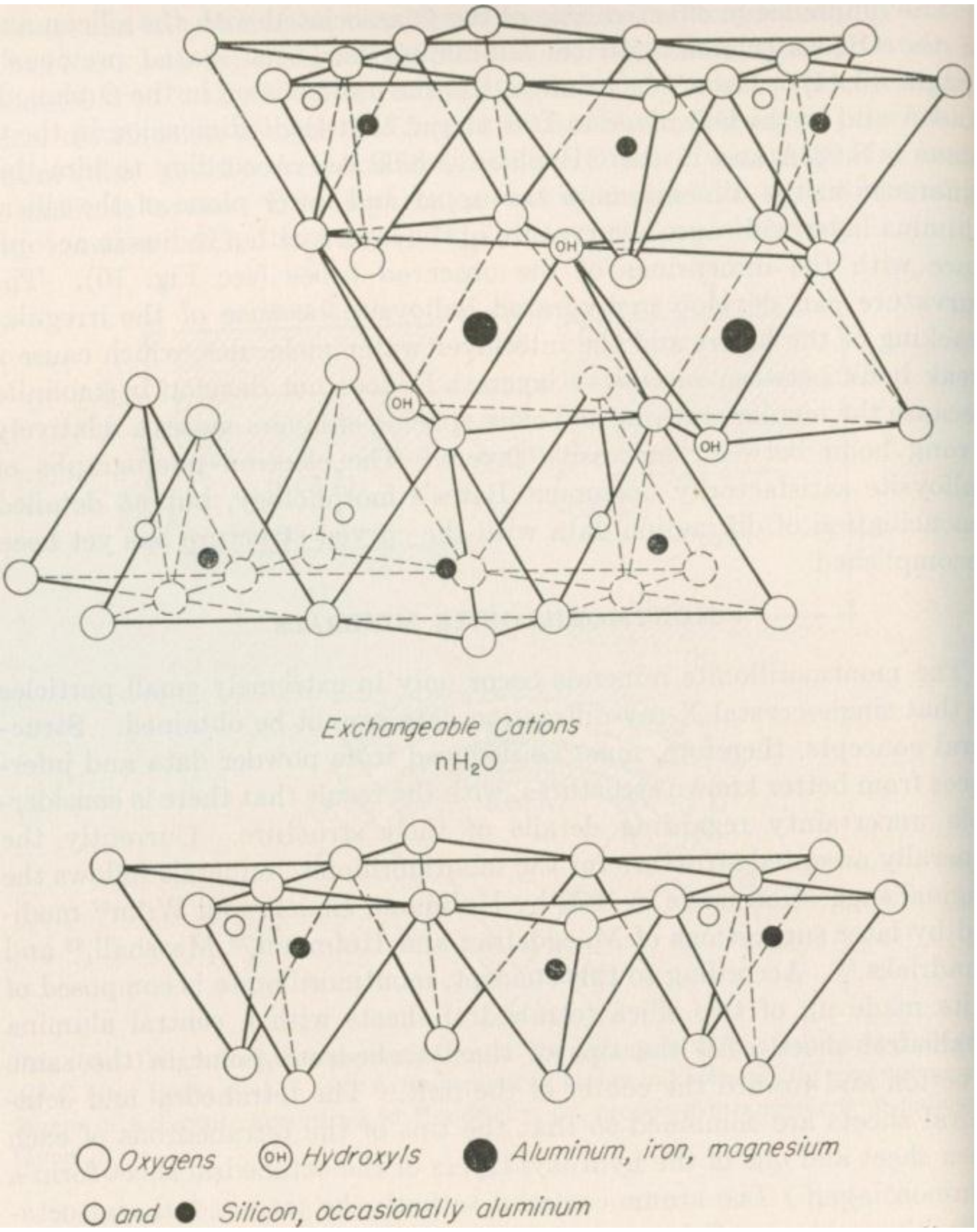


Figure 2.8: Sketch of the structure of montmorillonite (Grim, 1953)

The theoretical composition of montmorillonite without considering substitution of atoms and interlayer material is 66,7% SiO_2, 28,3% Al_2O_3 and 5% H_2O. Because of substitution of Al^{3+} for Si^{4+} in the tetrahedron and substitution of Mg^{2+} for Al^{3+} in the octahedron, montmorillonite always differ from the theoretical composition. The substitution result in an average negative net charge of 0,66 per unit cell. This negative charge is balanced by exchangeable cations (Na^+ or Ca^{2+}) absorbed between the unit layers as seen in Figure 2.8 (Grim, 1953).

2.4.4 Swelling of clay

Bentonite can swell up to several times its original volume, caused by the clay mineral montmorillonite. In particular sodium montmorillonite where the cation that balance the negatively charged units are sodium experience this swelling effect. With calcium as the exchangeable cation the swelling will only reach 10-20% of what is possible with sodium as the exchangeable cation. This can be explained by sodium neutralizing the negative charges on one montmorillonite unit while calcium connects two different montmorillonite units to neutralize the charges and thus leave less space for water to absorb to the unit surface (Skjeggestad, 1989).

2.5 Earlier experiments with bentonite

Some experiments have been conducted earlier to evaluate bentonite as a possible sealing material in wells, mainly by Towler and Ehlers in 1997, Towler et al. in 2008, Englehardt et al. in 2001 and Ogden and Ruff in 1991.

2.5.1 Towler and Ehlers

In a paper from 1997 Towler and Ehlers investigated the possibility to use hydrated bentonite to plug oil and gas wells. At that time bentonite was already widely used to plug seismic shot holes in US (Towler and Ehlers, 1997). Bentonite can be placed into the wellbore by setting a bridge plug and then drop bentonite on top of the bridge plug. If water is not present to hydrate and swell the plug this can be added (Towler and Ehlers, 1997). They also point out that a bentonite plug has the ability to swell and heal cracks that may form after shifting wellbore due to events like earthquakes or salt migration, this is a major advantage over solid cement plugs which can crack and loose the integrity.

An equation for calculating the pressure a cylindrical bentonite plug can withstand was derived by Towler and Ehlers in the following steps:

The hydrated plug is deformable and pushed against the wall by the weight of material above (water), to dislodge the plug one must overcome the friction between the plug and the wall in addition to the total weight of the plug and material above. For a cylindrical differential element of the bentonite plug with height dh, the area in contact with the wall is $\pi D \cdot dh$ and the friction force is:

$$dF = K_b[\rho_w L_w + \rho_b h]\pi D \cdot dh$$

Integrated from 0 to H this gives:

$$F = K_b\left[\rho_w L_w H + \frac{1}{2}\rho_b H^2\right]\pi D$$

The total force to dislodge the plug is then the friction force plus the weight:

$$F_T = K_b\left[\rho_w L_w H + \frac{1}{2}\rho_b H^2\right]\pi D + [\rho_w L_w + \rho_b H]\cdot\frac{1}{4}\pi D^2$$

The pressure needed to dislodge the plug is the total force divided by the area where pressure is applied: $P = \frac{F_T}{\frac{1}{4}\pi D^2}$ and this gives the final equation (Towler and Ehlers, 1997):

$$P = K_b\cdot\rho_w\left(\frac{4L_w H}{D} + \frac{2\gamma_b H^2}{D}\right) + \rho_w\cdot(L_w + \gamma_b H) \qquad \text{(Eq. 2.1)}$$

The first term of the equation is the friction part which normally is the most important, while the last part is from the weight of the bentonite plug and the water column above. Where K_b is the friction factor between the bentonite plug and the casing, $\rho_w$is the density of water, L_w is the height of water above the plug, H is the height of the bentonite plug, D is the internal diameter of the casing and γ_b is the specific gravity of the hydrated bentonite. According to this equation the pressure the bentonite plug can withstand is proportional to the square of the height of the plug (Towler and Ehlers, 1997).

To calculate how much pressure different lengths of bentonite plugs can withstand the friction factor K_b between the plug and the casing need to be determined. The goal of the experiments done by Towler and Ehlers was to verify the equation and to find a value for K_b to be able to calculate plug strength for longer plug lengths.

Towler and Ehlers did experiments with plug lengths of 3, 4, 5, 7.5, 10 and 15 feet in casing sizes of 4, 5 and 6 inches schedule 40 steel casing. The bentonite plugs were made of 3/8" granular dry sodium bentonite from Wyoming mines with a hydration time of 72 hours to one week. After hydration pressure was applied under the plug until water flow was observed (Towler and Ehlers, 1997). To determine K_b a plot of $[P - \rho_w\cdot(L_w + \gamma_b H)]$ versus $[(4L_w H + 2\gamma_b H^2)/D]$ was made where the slope should be equal to $K_b\cdot\rho_w$, this resulting plot can be seen in Figure 2.9 (Towler and Ehlers, 1997).

A slope of 0.3478 psi/ft gives a friction factor K_b of 0.8026. The linearity of the plot in Figure 2.9 would be a good indication of the validity of Equation 2.1 but the data is too scattered to be a conclusive proof (Towler and Ehlers, 1997).

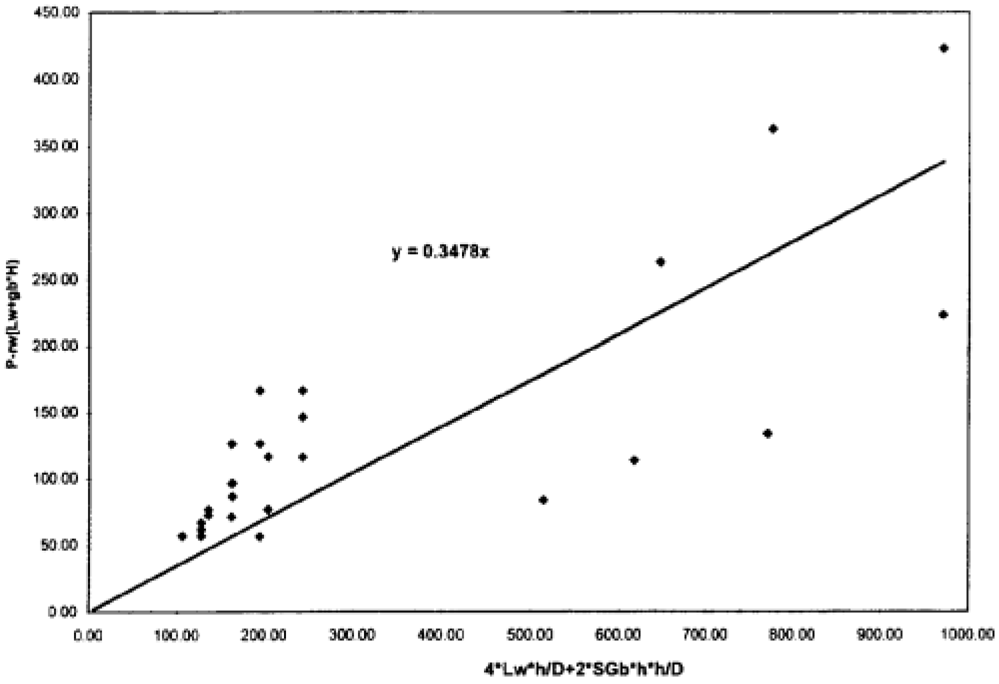


Figure 2.9: Determination of K_b (Towler and Ehlers, 1997).

Towler and Ehlers report that according to Equation 2.1 a 100 foot bentonite plug in a 5 ½" steel casing would be estimated to withstand 24500 psi, which should be more than enough for most plugging purposes. By utilizing Equation 2.1 and a K_b of 0.80 Figure 2.10 show estimated plug strength of different lengths of bentonite plugs in different casing sizes (Towler and Ehlers, 1997).

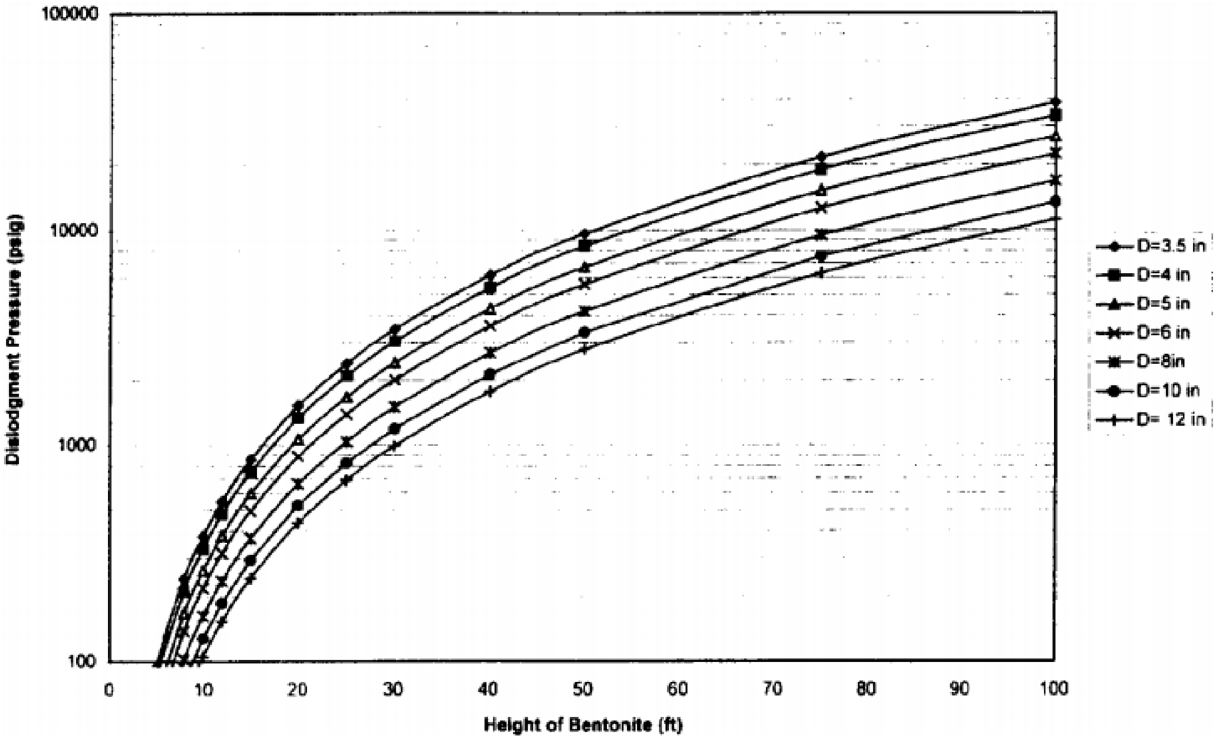
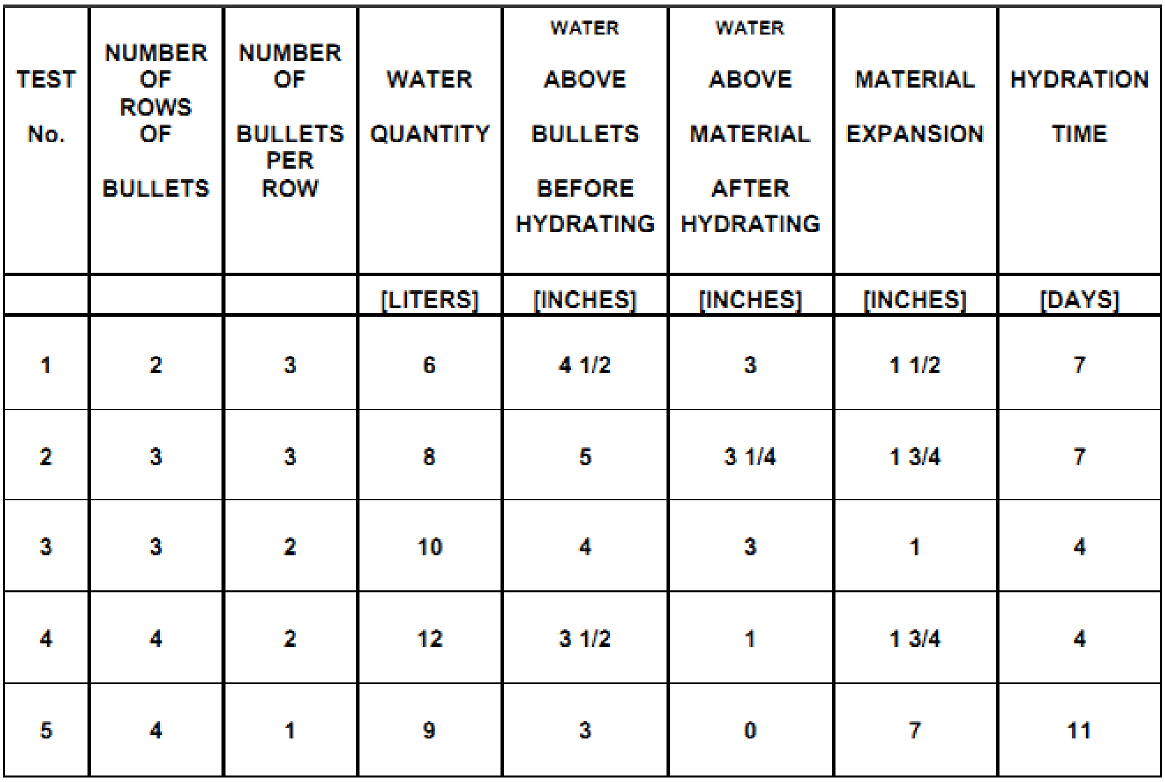


Figure 2.10: Plug strength calculated by Equation 2.1 (Towler and Ehlers, 1997).

2.5.2 Towler et al.

In some later work Towler et al. (2008) do further experiments with bentonite as a plugging material, this time bentonite pellets which were compressed into a bullet shape were tested. One of the problems with plugging wells with bentonite is that simply pouring bentonite granulates into the well will tend to swelling and bridging of bentonite before it reach the designated place for plugging (Towler et al. 2008). This can be solved by compressing the bentonite into solid bullet shaped bars with a suitable binder, this will hinder early swelling and hydration of bentonite before it reaches the area to be plugged (Towler et al. 2008).

The experiments conducted by Towler et al. (2008) are presented in Figure 2.11, 4 tests were done in a 6 ¼” steel pipe while the last test was in a 5” plastic pipe. The size of the bentonite bars used was 8 ½” long with a diameter of 2 ¾”. Different configurations with up to 3 rows of bars and 3 bars per row were tested as seen in Figure 2.11 (Towler et al. 2008).



TEST No.	NUMBER OF ROWS OF BULLETS	NUMBER OF BULLETS PER ROW	WATER QUANTITY	WATER ABOVE BULLETS BEFORE HYDRATING	WATER ABOVE MATERIAL AFTER HYDRATING	MATERIAL EXPANSION	HYDRATION TIME
			[LITERS]	[INCHES]	[INCHES]	[INCHES]	[DAYS]
1	2	3	6	4 1/2	3	1 1/2	7
2	3	3	8	5	3 1/4	1 3/4	7
3	3	2	10	4	3	1	4
4	4	2	12	3 1/2	1	1 3/4	4
5	4	1	9	3	0	7	11

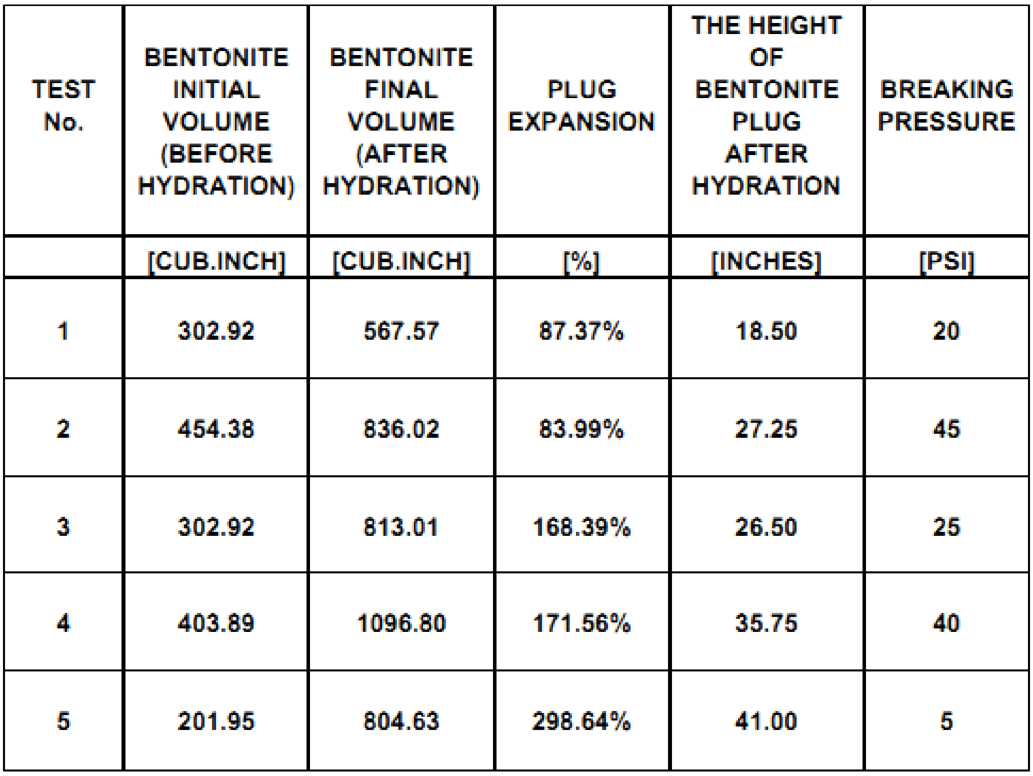
Figure 2.11: Overview of experiments conducted (Towler et al. 2008).

After allowing the plugs to hydrate for 4-7 days (long time needed due to large bars) air pressure was injected at the bottom until the plugs were displaced. The pressure needed to dislodge the plugs can be seen in Figure 2.12 in addition to the volume expansion due to hydration of the plugs (Towler et al. 2008).

To find the friction factor K_b a plot of $[P - \rho_w \cdot (L_w + \gamma_b H)]$ versus $[\rho_w(4L_w H + 2\gamma_b H^2)/D]$ according to Eq. 2.1 was made and this is shown in Figure 2.13 (Towler et al. 2008).

From the plot in Figure 2.13 the friction factor K_b for bentonite bars/bullets was found to be 1,85. This is a bit higher than the K_b of 0,8 found in earlier work by Towler and Ehlers (1997).

For the plastic pipe only one measurement was done and that gave a K_b of 0,083 (Towler et al. 2008).



TEST No.	BENTONITE INITIAL VOLUME (BEFORE HYDRATION)	BENTONITE FINAL VOLUME (AFTER HYDRATION)	PLUG EXPANSION	THE HEIGHT OF BENTONITE PLUG AFTER HYDRATION	BREAKING PRESSURE
	[CUB.INCH]	[CUB.INCH]	[%]	[INCHES]	[PSI]
1	302.92	567.57	87.37%	18.50	20
2	454.38	836.02	83.99%	27.25	45
3	302.92	813.01	168.39%	26.50	25
4	403.89	1096.80	171.56%	35.75	40
5	201.95	804.63	298.64%	41.00	5

Figure 2.12: Results from the experiment performed by Towler et al. (Towler et al. 2008).

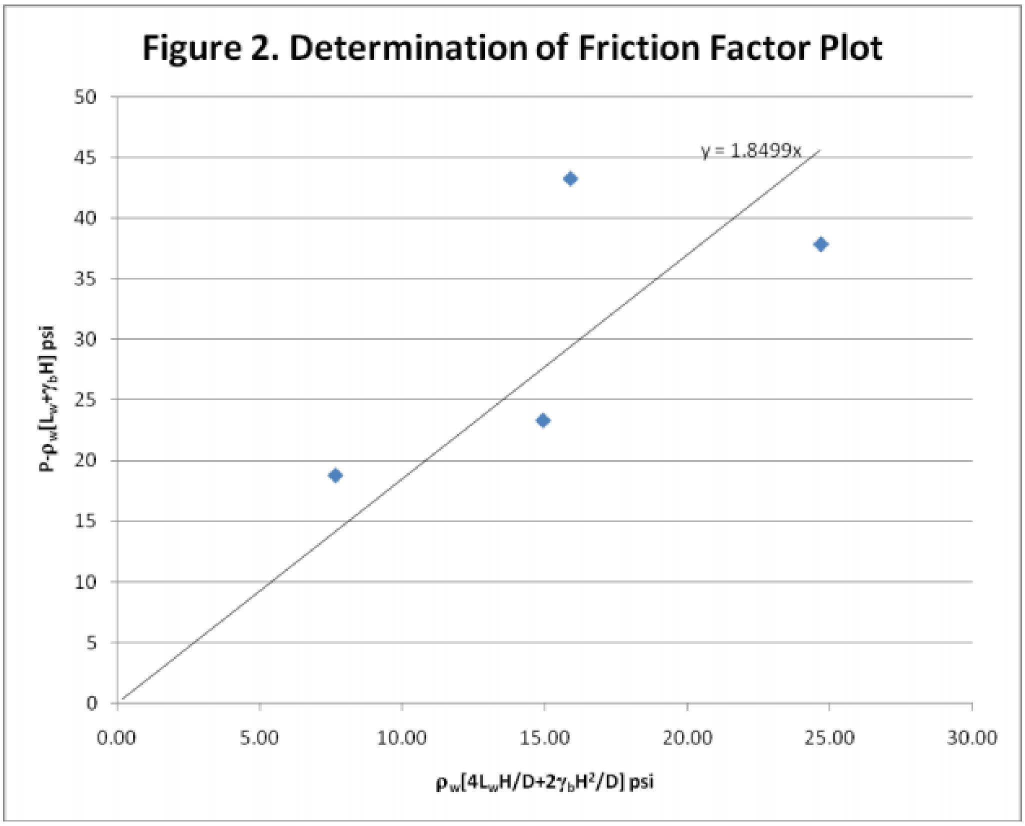


Figure 2.13: Plot to determine Kb (Towler et al. 2008).

2.5.3 Ogden and Ruff

In a paper from 1991 Ogden and Ruff report results from experiments done on bentonite as a sealing material in water wells. Four different commercially available granular bentonite products were tested. Plug lengths of 30-90cm were tested in an outer steel pipe with a 10,19cm inner diameter, the outer steel pipe was roughened to simulate borehole roughness by machining 3,1mm deep grooves spaced at 9,3mm along the length of the test pipe, see Figure 2.14 (Ogden and Ruff, 1991).

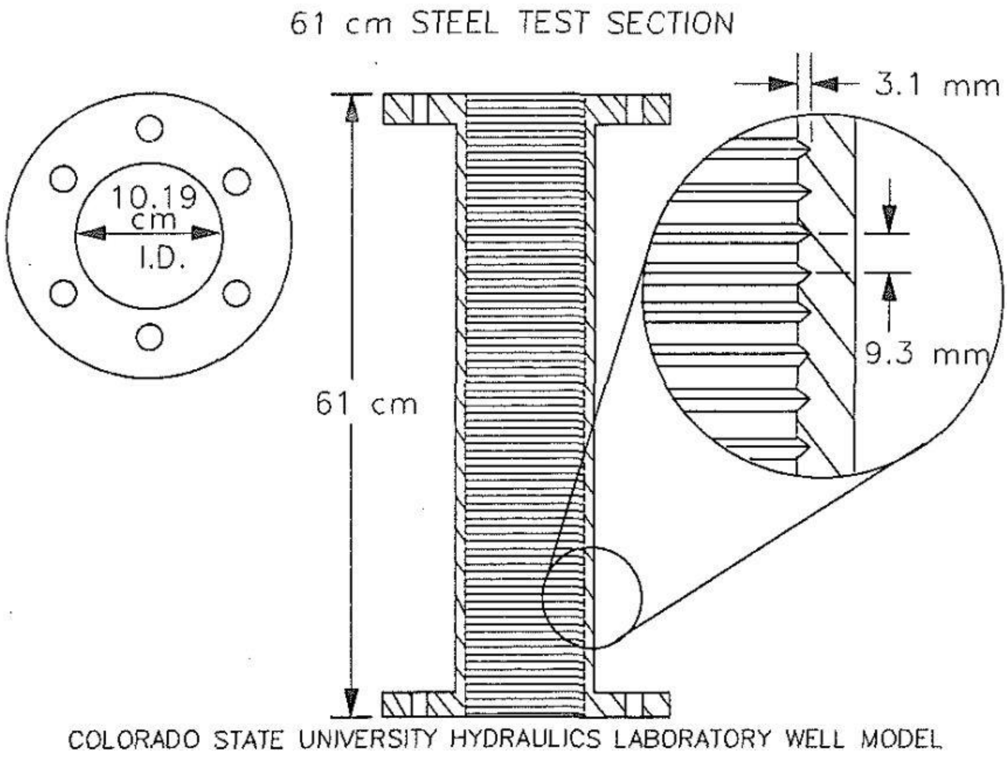


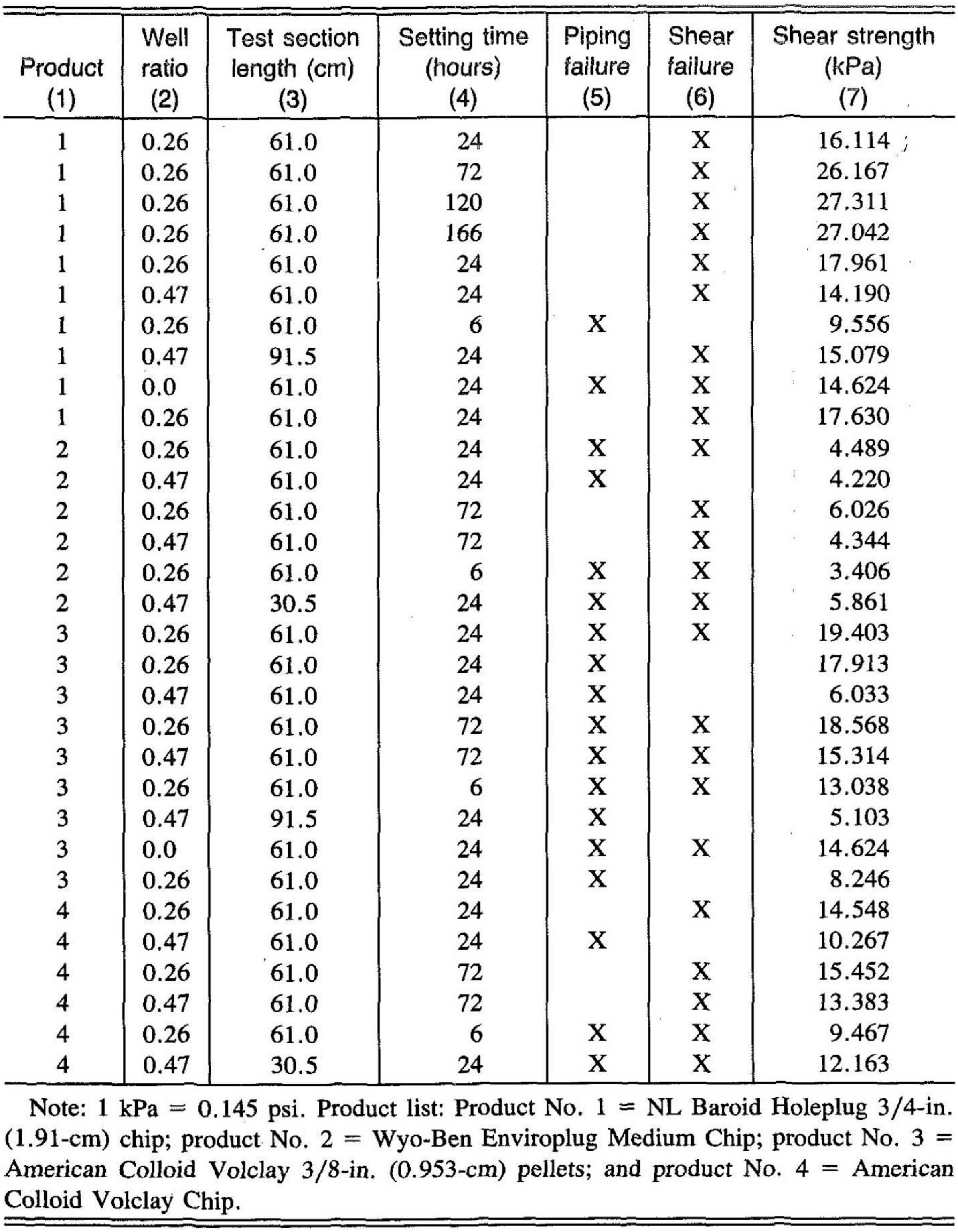
Figure 2.14: Cross section of outer test pipe (Ogden and Ruff, 1991).

Two different casings of 2,67cm and 4,83cm outer diameter were installed in the 10,19cm ID steel pipe to create annulus plugs. By dividing the outer diameter of the inner casing with the inner diameter of the outer pipe the two casings creates annuli with a well ratio of 0,26 and 0,47, it was also possible to test plugs with no inner casing installed (Ogden and Ruff, 1991). Results from the experiments can be seen in Figure 2.15.

The shear strengths in Figure 2.15 were calculated from Equation 2.2. The force causing plug motion is the pressure difference across the plug while the force resisting plug motion is the average shear stress per unit surface area between the outer and inner test pipe, the gravitational forces acting on the plug itself was neglected as being small compared to the other forces (Ogden and Ruff, 1991).

$$\tau_A = \frac{P \cdot A}{A_t} \qquad \text{(Eq. 2.2)}$$

Where P is the pressure across the plug in kPa at failure, A is the axial annular cross-sectional area and A_t is the total surface area of the outer and inner test pipe in contact with the plug (Ogden and Ruff, 1991).



Product (1)	Well ratio (2)	Test section length (cm) (3)	Setting time (hours) (4)	Piping failure (5)	Shear failure (6)	Shear strength (kPa) (7)
1	0.26	61.0	24		X	16.114
1	0.26	61.0	72		X	26.167
1	0.26	61.0	120		X	27.311
1	0.26	61.0	166		X	27.042
1	0.26	61.0	24		X	17.961
1	0.47	61.0	24		X	14.190
1	0.26	61.0	6	X		9.556
1	0.47	91.5	24		X	15.079
1	0.0	61.0	24	X	X	14.624
1	0.26	61.0	24		X	17.630
2	0.26	61.0	24	X	X	4.489
2	0.47	61.0	24	X		4.220
2	0.26	61.0	72		X	6.026
2	0.47	61.0	72		X	4.344
2	0.26	61.0	6	X	X	3.406
2	0.47	30.5	24	X	X	5.861
3	0.26	61.0	24	X	X	19.403
3	0.26	61.0	24	X		17.913
3	0.47	61.0	24	X		6.033
3	0.26	61.0	72	X	X	18.568
3	0.47	61.0	72	X	X	15.314
3	0.26	61.0	6	X	X	13.038
3	0.47	91.5	24	X		5.103
3	0.0	61.0	24	X	X	14.624
3	0.26	61.0	24	X		8.246
4	0.26	61.0	24		X	14.548
4	0.47	61.0	24	X		10.267
4	0.26	61.0	72		X	15.452
4	0.47	61.0	72		X	13.383
4	0.26	61.0	6	X	X	9.467
4	0.47	30.5	24	X	X	12.163

Note: 1 kPa = 0.145 psi. Product list: Product No. 1 = NL Baroid Holeplug 3/4-in. (1.91-cm) chip; product No. 2 = Wyo-Ben Enviroplug Medium Chip; product No. 3 = American Colloid Volclay 3/8-in. (0.953-cm) pellets; and product No. 4 = American Colloid Volclay Chip.

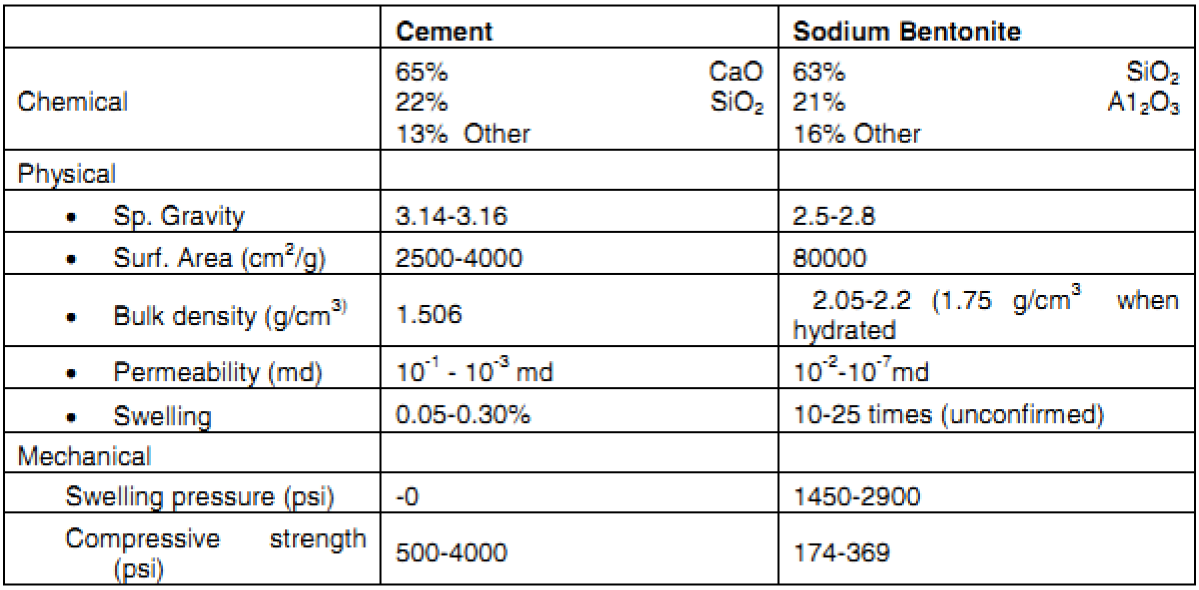
Figure 2.15: Results from experiments conducted by Ogden and Ruff (Ogden and Ruff, 1991).

The shear strengths found varied from 3,4 kPa to 27,3 kPa according to product type and setting time, but the shear strengths were found to be independent of plug length. Shear strengths increased with setting time up to a certain point, for product number 1 the maximum shear strength was achieved after 72 hours. With increasing well ratio (smaller annulus area) the shear strength was found to decrease. At 6 hours setting time all products failed by piping (channeling) but after 72 hours of setting time only one product failed by piping (Ogden and Ruff, 1991).

2.6 Field experience with bentonite

In a paper from 2001 John Englehardt et al. report results from several studies on using bentonite as a plugging material in addition to results from a field test where 19 wells were permanently plugged and abandoned with bentonite by Chevron Environmental Management Company (Englehardt et al. 2001).

The ideal alternative plugging material to cement was defined as compressed sodium bentonite nodules (marketed as Zonite), due to its ability to form an impermeable barrier by hydration and the plastic behavior, which make the material able to shape itself in an active environment. Sodium bentonite has been used to plug monitoring wells, mining shafts, seismic shot holes, water wells and it has been suggested to plug high-level nuclear waste deposits. The properties of compressed sodium bentonite compared to cement can be seen in Figure 2.16 (Englehardt et al. 2001).



	Cement	**Sodium Bentonite**
Chemical	65% CaO 22% SiO_2 13% Other	63% SiO_2 21% $A1_2O_3$ 16% Other
Physical		
• Sp. Gravity	3.14-3.16	2.5-2.8
• Surf. Area (cm^2/g)	2500-4000	80000
• Bulk density (g/cm^3)	1.506	2.05-2.2 (1.75 g/cm^3 when hydrated
• Permeability (md)	10^{-1} - 10^{-3} md	10^{-2}-10^{-7}md
• Swelling	0.05-0.30%	10-25 times (unconfirmed)
Mechanical		
Swelling pressure (psi)	-0	1450-2900
Compressive strength (psi)	500-4000	174-369

Figure 2.16: Comparison of properties of compressed sodium bentonite and cement (Englehardt et al. 2001).

Even though sodium bentonite is superior to cement as a confining material due to the extremely low permeability it has not been widely used to plug oil and gas wells. The main problems reported are issues related to placement of material due to bridging of bentonite before reaching the designated spot. Bentonite has been placed by several methods, pumping as a viscous pill, in combination with cement, dropped with a cardboard tube, placed with dump bailer, gravity fed and pumped in a diesel plug (Englehardt et al. 2001).

To solve the bridging issue bentonite was compressed into bentonite nodules, this would slow down the hydration process and allow the bentonite to reach designated depth (Englehardt et al. 2001). Picture of compressed sodium bentonite nodules can be seen in Figure 2.17, placed in a 6” plastic tube and allowed to hydrate for 24 hours. The actual compressed sodium bentonite nodules used in Figure 2.17, in the experiments and in the 19 well field test is marketed as Zonite.

Figure 2.17: Hydration of compressed sodium bentonite nodules (Zonite) (Carl, 2004).

A series of experiments was conducted on the compressed sodium bentonite nodules to find the boundary limits (Englehardt et al. 2001):

- Nodules were placed in a glass container and covered with freshwater, seawater (20 000mg/l) or saturated sodium chloride brine (189 000mg/l). In all cases the nodules had formed a hydraulically solid plug after 12 hours, some flaking was observed in seawater and brine.
- Nodules were hydrated in freshwater and afterwards submerged in saturated seawater for 60 days, no deterioration or shrinkage of the plug was observed.
- Nodules were placed in a plastic container with holes in the bottom, water was run continuously through the container, after 3 hours the bentonite had hydrated sufficiently to stop the flow of water.

- Nodules were dropped into a glass container with oily produced water with a free oil layer thicker than one nodule, 12 hours later the nodules had formed a hydraulically solid plug.
- A glass container with nodules was heated to boiling, after two hours the flow paths for steam had been sealed due to hydration.
- Nodules were submerged in saturated hydrogen sulfide water and hydrated to 70% of what was seen in freshwater.
- At a different location a 100 feet bentonite plug was pressure tested to 1500psi, long term stability was also confirmed over a 9 month period.

For the field test the 19 wells to be abandoned in Coalinga California was divided in three categories depending on freshwater zones and if there was cement behind the casing, see Figure 2.18 (Englehardt et al. 2001):

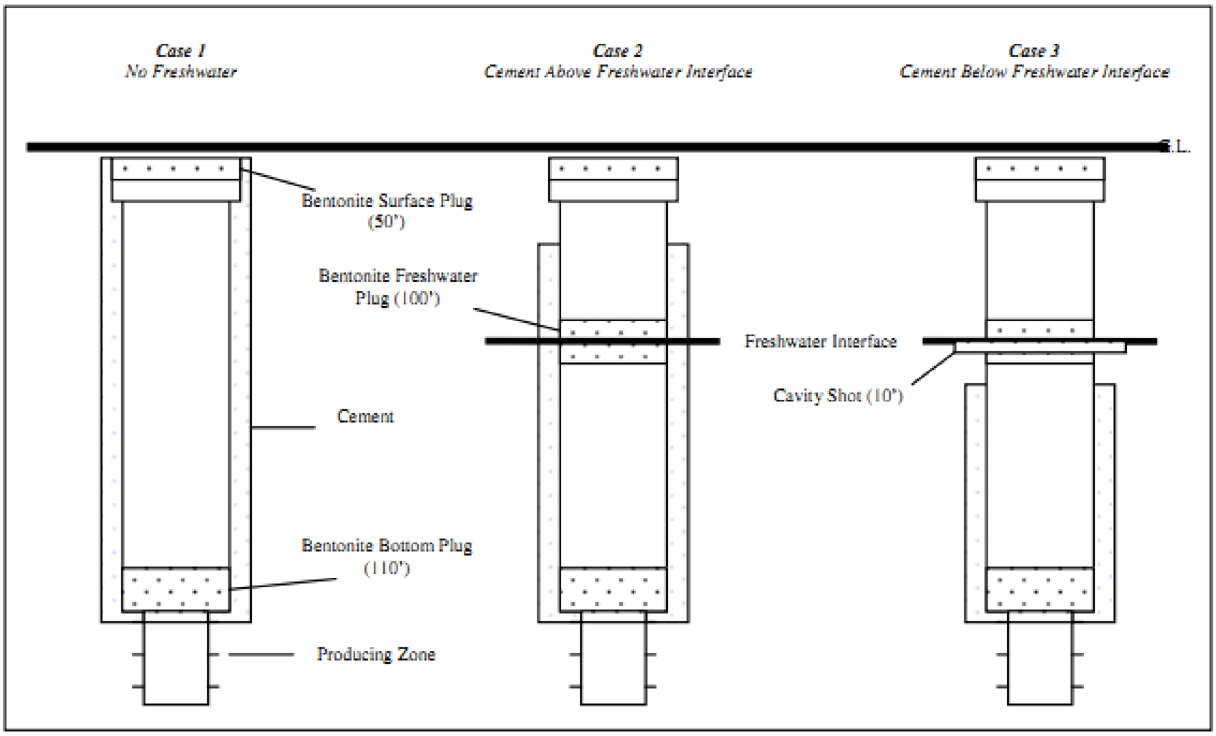


Figure 2.18: Abandonment case schematics for the 19 well field test (Englehardt et al. 2001).

- Eleven of the 19 wells were of case 1, in these a 110ft plug was set at the top of the perforations to isolate the producing zone, in combination with a 50ft surface plug.
- Four of the wells were of case 2, in addition to the two plugs set for case 1, these had a freshwater zone which needed to be isolated by a 100ft plug across the interface.
- The last four wells were of case 3, these are identical to case 2 except that there is no cement behind the casing at the freshwater zone. This normally requires a cavity shot and using cement, but the Department of Conservation's Division of Oil, Gas and Geothermal Resources (DOGGR) in California approved to use bentonite to fill the cavity and wellbore after firing a cavity shot.

In all the wells gravel were used to fill the wellbore between the bentonite plugs to create a base for the plugs, but instead of gravel a bridge plug could have been used. Bentonite plugs were verified by a slickline tag after pouring (Englehardt et al. 2001).

The equipment needed to run this operation was a dump truck with a hydraulic conveyer connected to the tailgate, which delivered bentonite nodules and gravel at specified rates, see Figure 2.19. In addition to the dump truck a vacuum truck was used to supply water and a conventional slickline unit was used for tagging of plugs (Englehardt et al. 2001).

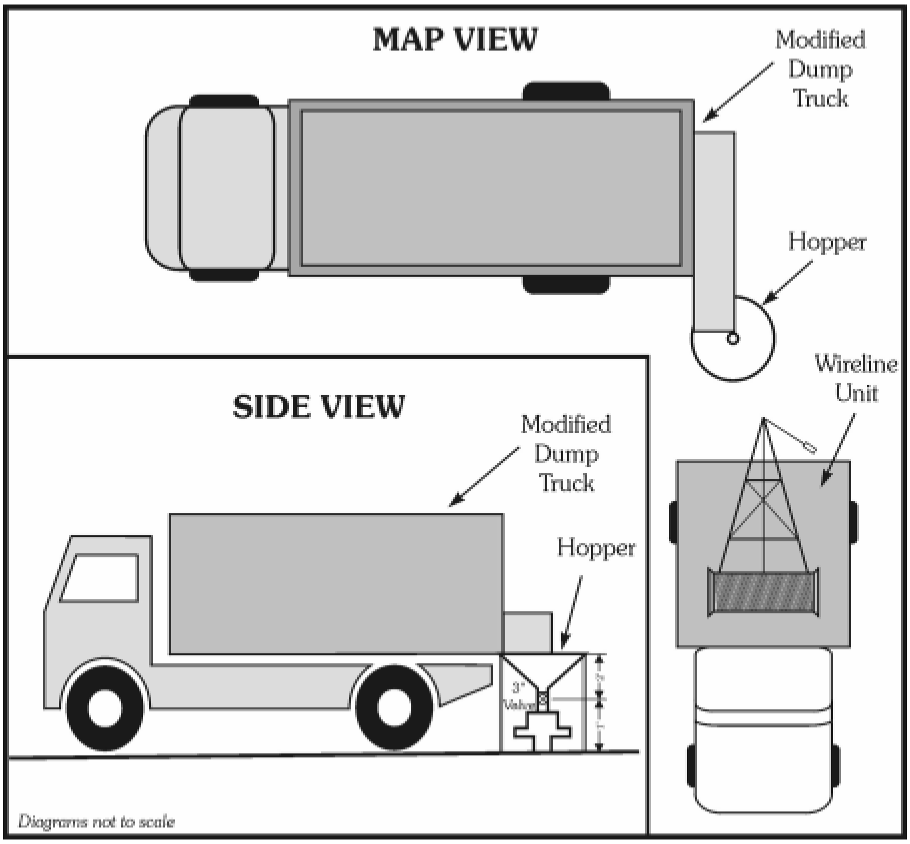
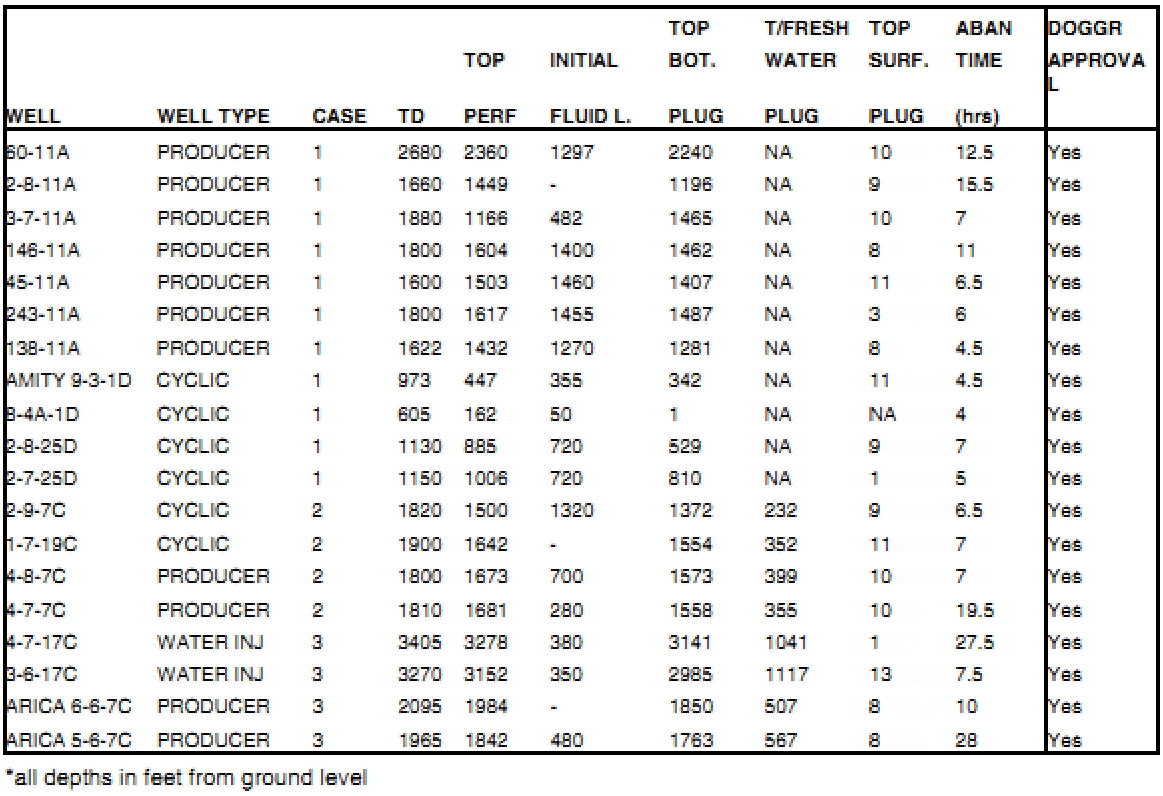


Figure 2.19: Field process schematic (Englehardt et al. 2001).

Several procedures related to filling the well with water or even hot water before adding gravel and bentonite were tried, the air/liquid interface was typically 1000feet down into the well. Bentonite nodules performed good when poured dry and penetrated the air/liquid interface without bridging, and fell through the liquid column to wanted depth. But the gravel used (pea gravel and ¾"-minus gravel) tended to bridge while free-falling down to the air/liquid interface, therefore it was decided to fill up the wellbore with hot water before adding the gravel and this eliminated the problems with gravel bridging (Englehardt et al. 2001).

Unfortunately when they for the first time filled the well with hot water before adding bentonite to plug the producing zone, the bentonite bridged too early, this happened in three wells, and the conclusion was to modify the method again. Hot water was needed to reduce the viscosity for gravel not to bridge, but bentonite needed cool water to avoid early hydration and bridge off. The solution was to let the bentonite free-fall as much as possible to ensure that it reached the designated place before hydrating, when it was in place and verified by a slickline tag, hot water was gradually added to the well while pouring gravel. To reduce the risk of bentonite bridging in the second bentonite plug, adding of hot water was stopped before the end of the gravel stage, this let the water cool down before bentonite was added again. This modified method proved to be efficient and as a result the abandonment time was reduced (Englehardt et al. 2001).

A list over the wells plugged in the Coalinga field test can be seen in Figure 2.20, with TD, plug locations, water levels and time used for all wells. Costs savings by using sodium bentonite compared to cement was estimated to 20-40%, due to no need for pump trucks, coiled tubing and bulk units (Englehardt et al. 2001).



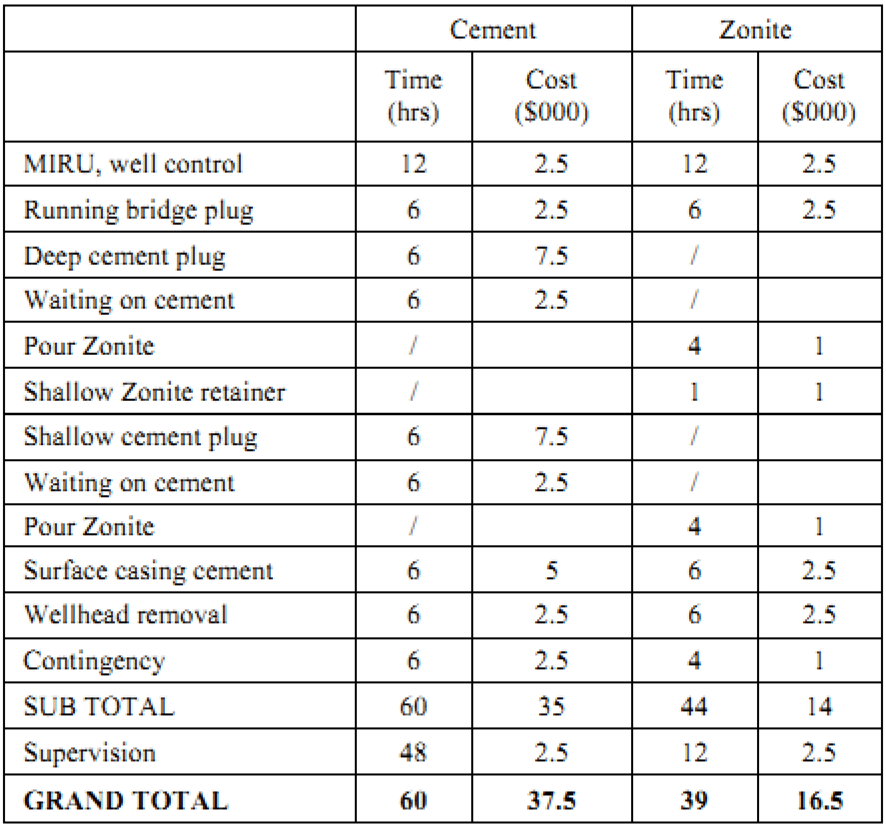
WELL	WELL TYPE	CASE	TD	TOP PERF	INITIAL FLUID L.	TOP BOT. PLUG	T/FRESH WATER PLUG	TOP SURF. PLUG	ABAN TIME (hrs)	DOGGR APPROVAL
60-11A	PRODUCER	1	2680	2360	1297	2240	NA	10	12.5	Yes
2-8-11A	PRODUCER	1	1660	1449	-	1196	NA	9	15.5	Yes
3-7-11A	PRODUCER	1	1880	1166	482	1465	NA	10	7	Yes
146-11A	PRODUCER	1	1800	1604	1400	1462	NA	8	11	Yes
45-11A	PRODUCER	1	1600	1503	1460	1407	NA	11	6.5	Yes
243-11A	PRODUCER	1	1800	1617	1455	1487	NA	3	6	Yes
138-11A	PRODUCER	1	1622	1432	1270	1281	NA	8	4.5	Yes
AMITY 9-3-1D	CYCLIC	1	973	447	355	342	NA	11	4.5	Yes
8-4A-1D	CYCLIC	1	605	162	50	1	NA	NA	4	Yes
2-8-25D	CYCLIC	1	1130	885	720	529	NA	9	7	Yes
2-7-25D	CYCLIC	1	1150	1006	720	810	NA	1	5	Yes
2-9-7C	CYCLIC	2	1820	1500	1320	1372	232	9	6.5	Yes
1-7-19C	CYCLIC	2	1900	1642	-	1554	352	11	7	Yes
4-8-7C	PRODUCER	2	1800	1673	700	1573	399	10	7	Yes
4-7-7C	PRODUCER	2	1810	1681	280	1558	355	10	19.5	Yes
4-7-17C	WATER INJ	3	3405	3278	380	3141	1041	1	27.5	Yes
3-6-17C	WATER INJ	3	3270	3152	350	2985	1117	13	7.5	Yes
ARICA 6-6-7C	PRODUCER	3	2095	1984	-	1850	507	8	10	Yes
ARICA 5-6-7C	PRODUCER	3	1965	1842	480	1763	567	8	28	Yes

*all depths in feet from ground level

Figure 2.20: Coalinga pilot abandonment results, from Table 3 in (Englehardt et al. 2001).

In October 2002 ChevronTexaco Australia plugged the first well outside USA with compressed bentonite nodules (marketed as Zonite), after over 500 wells plugged with Zonite in USA. This was at the Barrow Island Oil field in Australia which is classified as a nature reserve, and environmental factors are therefore very important. The goal was to reduce the abandonment cost with 50% compared to using cement, how to achieve this is illustrated in Figure 2.21 (Clark and Salsbury, 2003).

To avoid swelling problems the selected well was circulated to freshwater before plugging started, a bridge plug was set 10m below the perforations to act as a fundament for the plug. A 210 foot long compressed sodium bentonite plug was set at 2800 foot TVD in about 5 hours by surface pouring. Plug was tagged and allowed to hydrate for 28 days before it was pressure tested to 500psi. The abandonment was a success and it was decided to monitor the pressure in the well for 6 months to prove the long term stability of the plug. In addition to the cost saving benefits of using bentonite, other benefits related to HSE such as small operational footprint, no wellsite spills, no cementing chemicals/additives and better integrity due to plasticity of plug is mentioned (Clark and Salsbury, 2003).



	Cement		Zonite	
	Time (hrs)	Cost ($000)	Time (hrs)	Cost ($000)
MIRU, well control	12	2.5	12	2.5
Running bridge plug	6	2.5	6	2.5
Deep cement plug	6	7.5	/	
Waiting on cement	6	2.5	/	
Pour Zonite	/		4	1
Shallow Zonite retainer	/		1	1
Shallow cement plug	6	7.5	/	
Waiting on cement	6	2.5	/	
Pour Zonite	/		4	1
Surface casing cement	6	5	6	2.5
Wellhead removal	6	2.5	6	2.5
Contingency	6	2.5	4	1
SUB TOTAL	60	35	44	14
Supervision	48	2.5	12	2.5
GRAND TOTAL	**60**	**37.5**	**39**	**16.5**

Figure 2.21: Cement and sodium bentonite (Zonite) time and cost estimate (Clark and Salsbury, 2003).

2.7 Soil plugs in pipe piles

Open ended steel pipes are regularly used as driven piles, especially for offshore installations. When the pile is driven into the ground, a soil plug will rise inside the pile, at the beginning the height of the soil plug inside will be approximately on level with the ground outside. But in some cases, for example during driving through dense sand layers, the soil plug inside the pile can "lock-up" and move downwards with the pile movement. This is caused by arching of forces inside the soil plug which dramatically increases the friction between soil plug and the pile and results in a "lock-up" of the soil plug. This happens when the total internal friction between the soil plug and the pile becomes larger than the end bearing capacity at the base of the plug, see Figure 2.22. In such cases the open ended pile is in a plugged mode and it will act similar to a

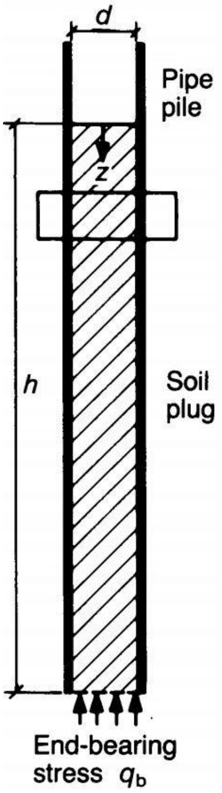


Figure 2.22: Pipe pile with soil plug (Randolph et al. 1991).

closed ended pile (Randolph et al. 1991).

For a soil plug under drained conditions, i.e. no excessive pore pressure builds up inside the plug under loading, Randolph et al. (1991) derived the following equations to describe the situation. By considering a thin slice of the soil plug in Figure 2.23, the shear stress τ around the plug is given by:

$$\tau = \beta\sigma_V'$$

Where σ_V' is the vertical effective stress in the plug at given level and β is the ratio of horizontal to vertical effective stress inside the plug. The 1 dimensional vertical equilibrium equation for the soil slice in Figure 2.23 is given by:

$$\frac{d\sigma_V'}{dz} = \gamma' + \frac{4}{D}\tau = \gamma' + \frac{4}{D}\beta\sigma_V' \qquad \text{(Eq. 2.3)}$$

Where D is the internal diameter of the pile and γ' is the effective unit weight of the soil and z is depth from top of soil plug.

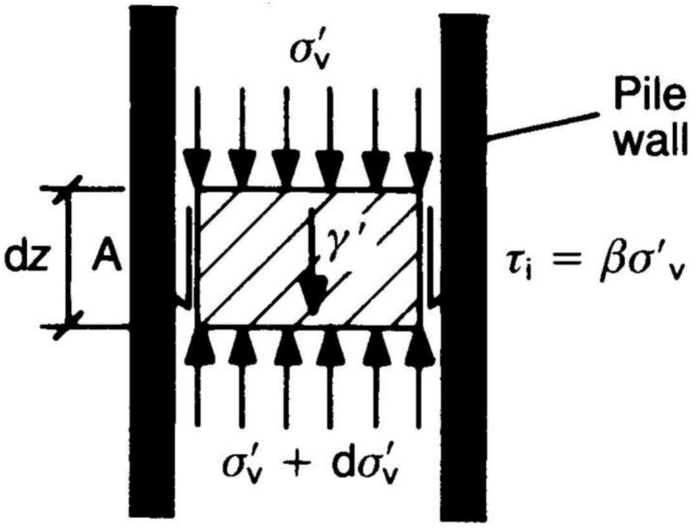


Figure 2.23: Stresses inside a horizontal slice of a soil plug (Randolph et al. 1991).

By integrating equation 2.3 the effective stress at any depth z in the soil plug is found as:

$$\sigma_V' = (e^{\frac{4\beta z}{D}} - 1)\frac{D\gamma'}{4\beta}$$

At the base of a soil plug with height h, the end bearing capacity of the soil plug under drained conditions and in excess of initial effective stress ($\gamma' h$) is given by:

$$q_b = \left(e^{\frac{4\beta h}{D}} - 1\right)\frac{D\gamma'}{4\beta} - \gamma' h \qquad \text{(Eq. 2.4)}$$

From equation 2.4 it is clear that the end bearing capacity of the soil plug increase exponentially with the ratio of length to diameter (h/D). And relatively small soil plugs under drained conditions (no pore pressure increase, water can drain out of plug) have very high end bearing capacity, in Figure 2.24 $q_b/\gamma' h$ is plotted against h/D for various β values (Randolph et al. 1991).

From Figure 2.24 it can be seen that the end bearing capacity for a plug with a β of 0,4 is 100 times the self-weight ($\gamma' h$) of the plug with a height only 4 times the diameter. If beta is kept at 0,4 and the height to diameter ratio is increased to 8, the end bearing capacity will be 28000 times the self-weight of the plug. If beta is halved, the plug height must double to achieve the same capacity.

The above equations suggested by Randolph et al. (1991) have been validated experimentally by several people, including Murff et al. (1990) and Randolph et al. (1992).

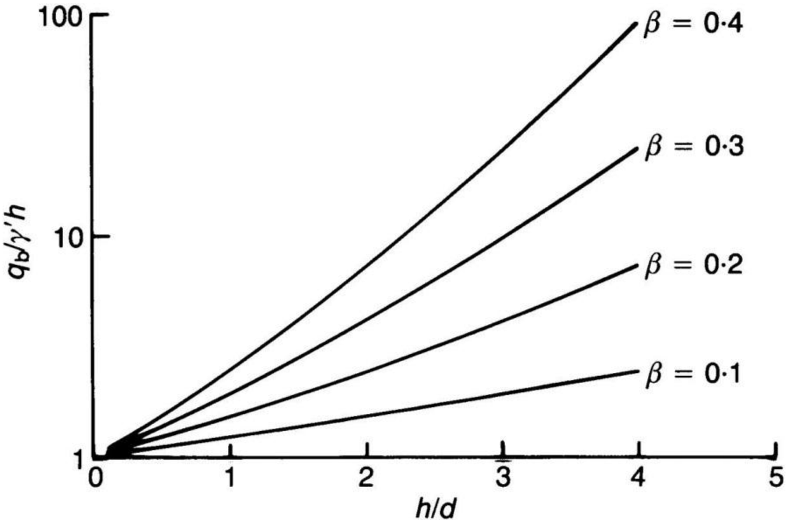


Figure 2.24: Effect of β and h/D on soil plug capacity (Randolph et al. 1991).

Randolph et al. (1992) tested soil plugs in model pipe piles with 103mm and 23mm inner diameter. For the 103mm ID pile, a soil plug with a length of 750mm (h/D ratio of 7,3) was found to take a pressure of 13,7 MPa before failure. Plugs with length of 1500mm (h/D ratio of 14,6) did not fail during static loading due to the test setup being limited to 30 MPa. For the smaller piles with 23mm inner diameter a plug with a length of 167mm (h/D ratio of 7,3) failed at a pressure of 11.3 MPa, while plugs with length of 335mm (h/D ratio of 14,6) reached the equipment limit of 33 MPa for the small scale test without failure.

Murff et al. (1990) did small scale tests on soil plugs in pipe piles with an outer diameter of 7,62cm and lengths from 23cm to 46cm (3-6 diameters). The results can be seen in Figure 2.25. The failure stress of the plugs is given in ksf (kilopounds per square foot), and 1ksf equals 47,88 kPa, which means that the the 1,5ft (46cm, h/D ratio of 6) plug in test 14 took a pressure of 57 MPa before failure. The sand was placed in both wet and dry environments, for the dry environment the sand was placed by raining through a tube fitted with a sieve. In the wet environment, the sand was allowed to seek equilibrium through a column of water independent of external influence (Murff et al. 1990).

	Test Number	Relative Density	Plug Length ft	Failure Stress ksf	Inferred β Values
Other Data:					
Pipe OD - 3.0 inches	11	.83	0.75	51	0.683
Pipe Wall Thickness - 0.15625 inches	12	.91	1.25	888	0.525
Sand Maximum Density - 107.1 lb/ft^3	13	.80	1.0	302	0.605
Sand Minimum Density - 94.9 lb/ft^3	14	.71	1.50	1190	0.444
Soil-Steel Friction Coef. - 0.61 to 0.67	15	.73	1.0	419	0.625
Grain Size - .075 mm - 4 mm, well graded	16	.85	1.25	1150	0.539

Figure 2.25: Laboratory tests conducted by Murff et al. (Murff et al. 1990).

A large scale test with a 1,5ft diameter pile and a soil plug with a length of 12ft (h/D ratio of 8) were also tested. The soil plug was loaded to the maximum jack capacity of 1000kips (a million pounds) without failing, which equals 27,1 MPa (Murff et al. 1990).

White et al. (2000) did test on soil plugs in pipe piles with a diameter of 318,5mm in test A and 162,5mm in test B. As the pile was driven and the plug length increased, 5 pressure bolts spaced at the bottom of the pile measured the plug force. These measurements are shown in Figure 2.26 together with predictions from an equation similar to Eq. 2.4 (White et al. 2000).

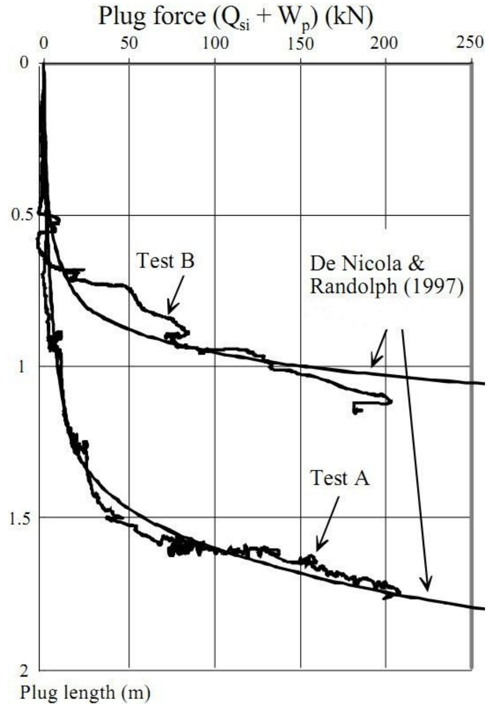


Figure 2.26: Variation of plug force vs plug length (White et al. 2000).

Hight et al. (1996) also did tests on sand plugs in pipe piles with diameters of 15cm and 30cm. The sand used was quartz sand with size between 0,6mm and 1,2mm, ratio of plug height to pile diameter from 2-10 were tested. Both dense, medium and loose packed sand were tested, the results can be seen in Figure 2.27 (Hight et al. 1996).

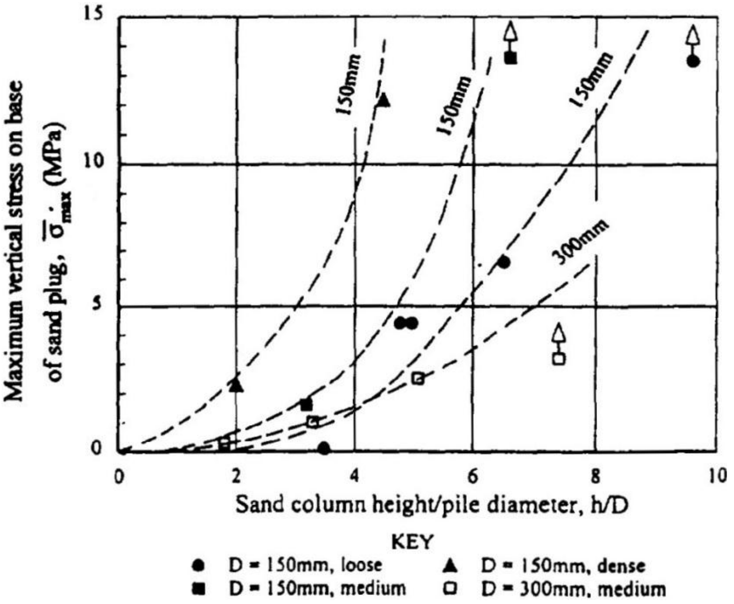


Figure 2.27: Dependency of sand plug capacity on sand density, pile diameter and h/D (Hight et al. 1996).

3 Experiments

The main goals to be achieved with the experiments are the following:

- Evaluate bentonite as a sealing material, both powdered bentonite and bentonite pellets will be tested
- Find out how much pressure different lengths of bentonite plugs can withstand, and how the pressure varies with the length of the plug.
- Compare how much pressure bentonite plugs in an annulus between two pipes can withstand with bentonite plugs in the main bore
- Find a value for the friction between the bentonite plug and the plastic pipe
- Check how much the bentonite expand while being hydrated in a pipe/annulus

In a previous project leading up to this thesis, a test pipe with a total length of 30cm and an inner diameter of 10,42cm was used to create bentonite plugs with powdered bentonite. But the short length of the test pipe restricted the plug lengths to be between 12cm - 26cm, which made it hard to make conclusions on how the pressure varied with the plug length. In addition the process of only using powdered bentonite to create the plugs resulted in a more inhomogeneous and less repeatable plug than what is achieved by using bentonite pellets.

3.1 Test equipment

To improve from the previous project a similar but a much longer test pipe was manufactured at the PTS workshop, with a length of 100cm and an inner diameter of 8,97cm. The length of the pipe allows enough space to contain the wanted bentonite plug and water for hydration, the pipe has an open top and a sealed bottom with a plug to inject air, see Figure 3.1.

For testing bentonite plugs in the annulus between two pipes a second plastic pipe with a diameter of 5,00cm was inserted into the previous 8,97cm plastic pipe. This was done by having a raised section in the bottom of the outer pipe with an o-ring for sealing against the smaller inner pipe, as seen in Figure 3.2

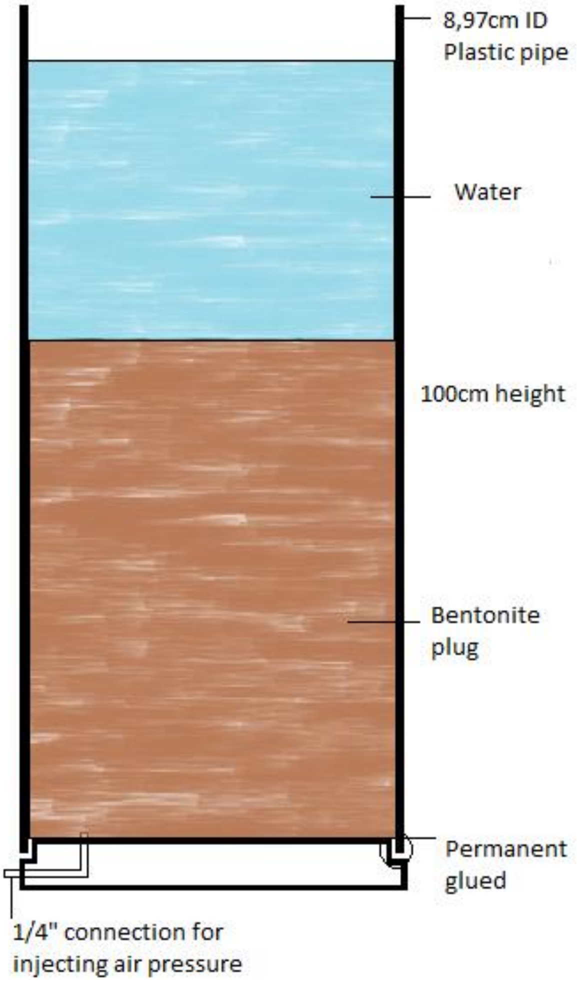


Figure 3.1: Experimental setup for fullbore plugs

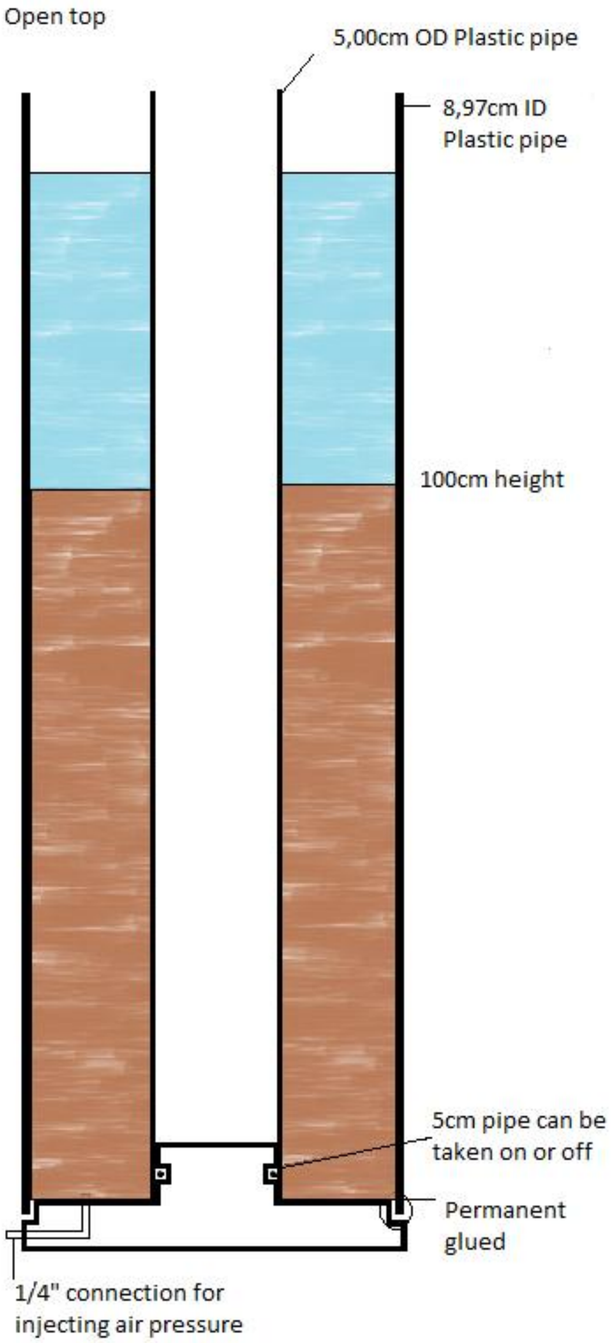


Figure 3.3: Old test pipe with a length of 30cm

Figure 3.2: Experimental setup for annulus plugs

This allowed the 5cm inner pipe to be manually removed and put in place according to what type of bentonite plug was being tested. Figure 3.3 shows the actual test pipe used in the previous project with a length of only 30cm, inside diameter of 10,42cm, and a 5cm inner pipe inserted to create an annulus.

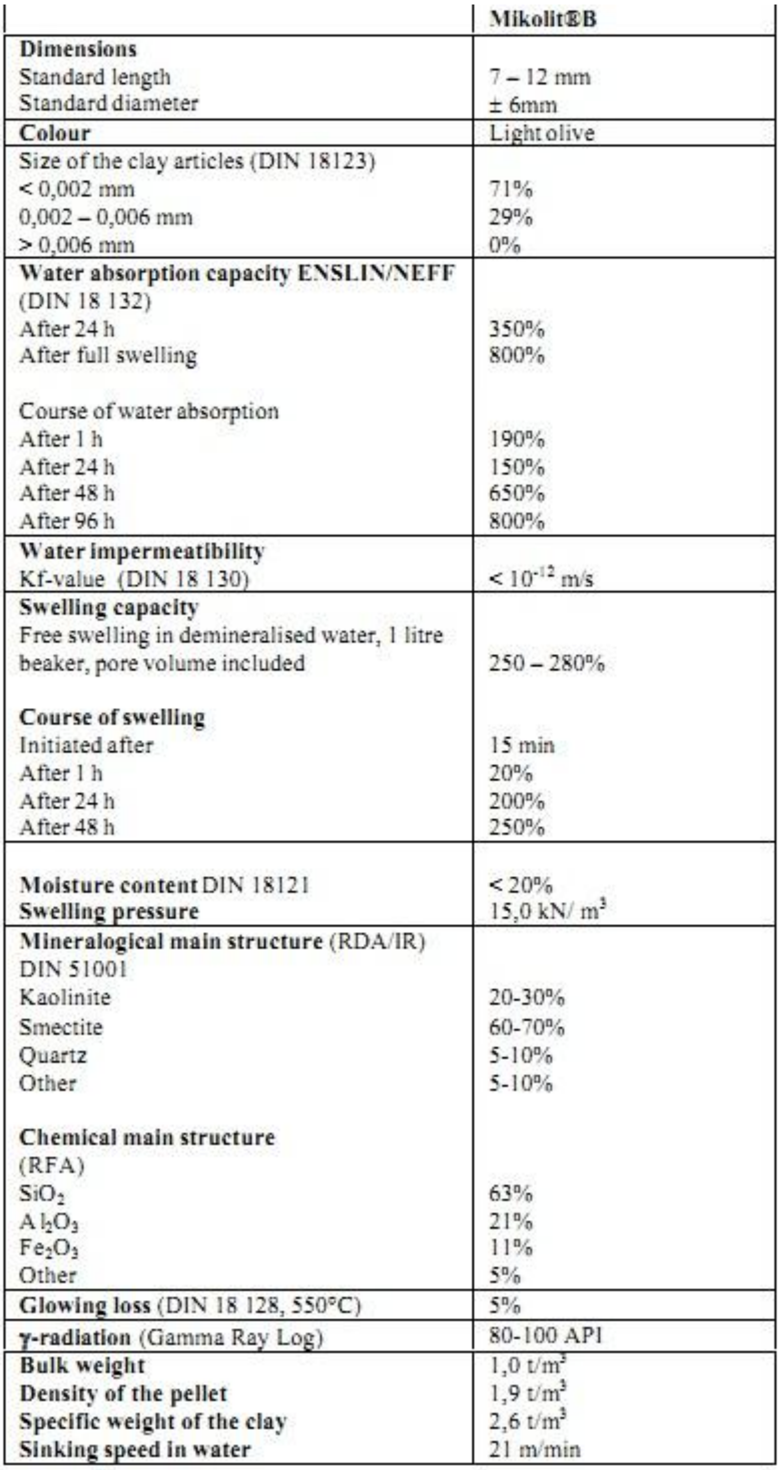
3.2 Test materials

Two types of bentonite were used to create the bentonite plugs in this experiment, bentonite pellets and dry powdered bentonite.

The bentonite pellets used were marketed as Mikolit B and supplied by Rotek, the data sheet for the Mikolit B pellets can be seen in Figure 3.4. Mikolit B pellets are made from a mix of activated calcium bentonites (it has been converted to sodium bentonite) with a very high swelling capacity.

Mikolit B pellets are made from clay found in the Dutch-German border which have been pressurized into a plastic and relatively heavy granule, the outside is then dried and the granules are sifted, cooled and packed. See Figure 3.5 for an actual photo of the pellets.

Figure 3.5: Mikolit B pellets



	Mikolit®B
Dimensions	
Standard length	7 – 12 mm
Standard diameter	± 6mm
Colour	Light olive
Size of the clay articles (DIN 18123)	
< 0,002 mm	71%
0,002 – 0,006 mm	29%
> 0,006 mm	0%
Water absorption capacity ENSLIN/NEFF (DIN 18 132)	
After 24 h	350%
After full swelling	800%
Course of water absorption	
After 1 h	190%
After 24 h	150%
After 48 h	650%
After 96 h	800%
Water impermeatibility	
Kf-value (DIN 18 130)	$< 10^{-12}$ m/s
Swelling capacity	
Free swelling in demineralised water, 1 litre beaker, pore volume included	250 – 280%
Course of swelling	
Initiated after	15 min
After 1 h	20%
After 24 h	200%
After 48 h	250%
Moisture content DIN 18121	< 20%
Swelling pressure	15,0 kN/ m^3
Mineralogical main structure (RDA/IR) DIN 51001	
Kaolinite	20-30%
Smectite	60-70%
Quartz	5-10%
Other	5-10%
Chemical main structure (RFA)	
SiO_2	63%
Al_2O_3	21%
Fe_2O_3	11%
Other	5%
Glowing loss (DIN 18 128, 550°C)	5%
γ-radiation (Gamma Ray Log)	80-100 API
Bulk weight	1,0 t/m^3
Density of the pellet	1,9 t/m^3
Specific weight of the clay	2,6 t/m^3
Sinking speed in water	21 m/min

Figure 3.4: Mikolit B data sheet (Rotek 2012).

The procedure for creating bentonite plugs with the pellets was very easy since the pellets fell through the water column to depth without bridging both for fullbore plugs and for annulus plugs.

In Figure 3.6 the hydration of a single pellet is shown for 0-70 hours. And it can be seen that almost all of the hydration is completed after 46 hours, by comparing the pellet at 46 hours and 70 hours the additional hydration is small compared to what is reached at 46 hours. The pellet in Figure 3.6 was hydrated in regular tap water.

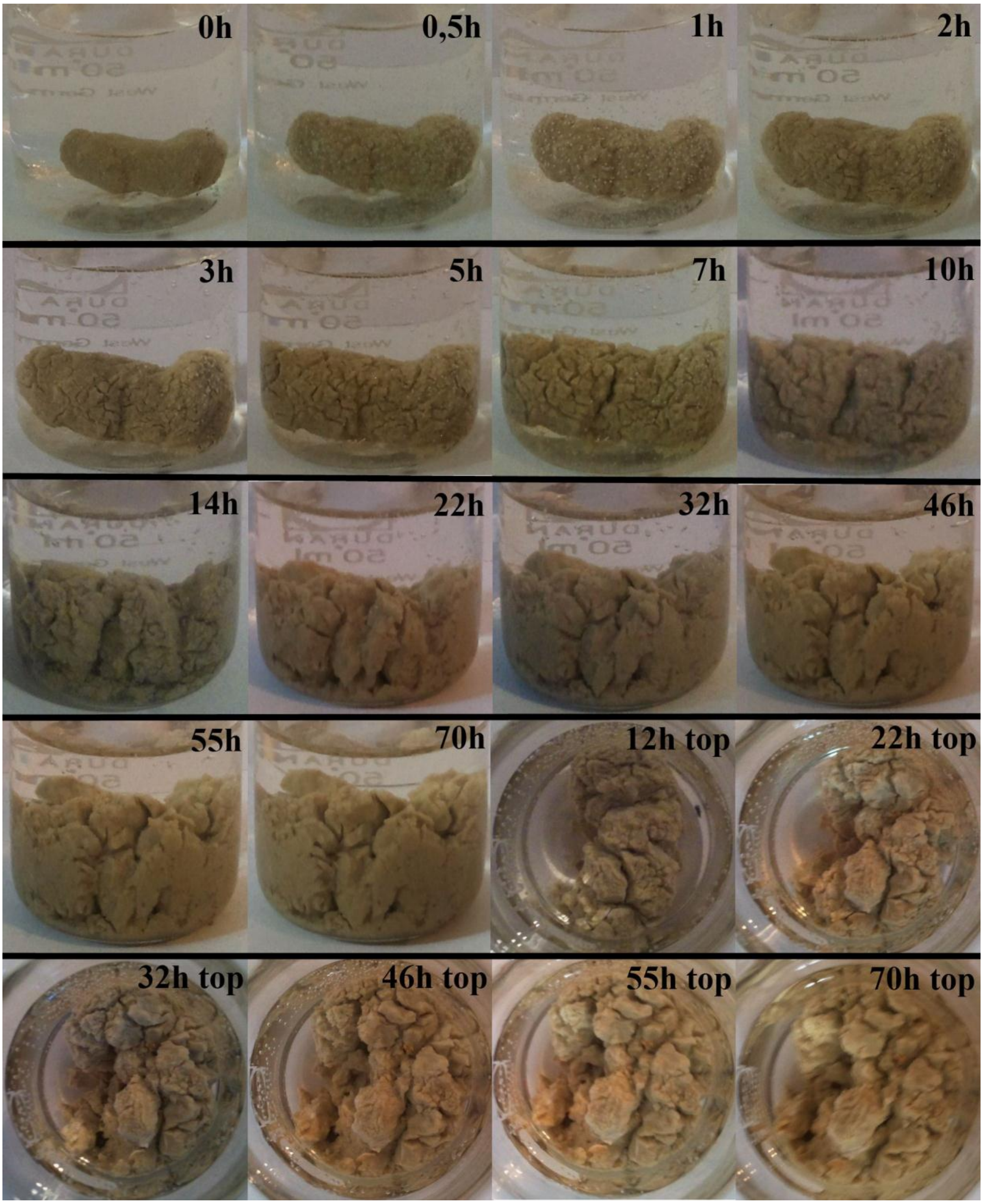


Figure 3.6: Hydration of a single bentonite pellet, 0-70 hours.

The other type of bentonite used in this experiment was dry powdered bentonite from Norbar Minerals AS. As learned in the previous project, if powdered bentonite was added to a plastic pipe with water already in place, the bentonite would just float and clog on the surface of the water, like in Figure 3.8. If the powdered bentonite was placed in the pipe first, and water applied on top, only a small part of the powdered bentonite would hydrate and create a plug, while the rest of the bentonite would be completely dry and unhydrated after two days, see example in Figure 3.7.

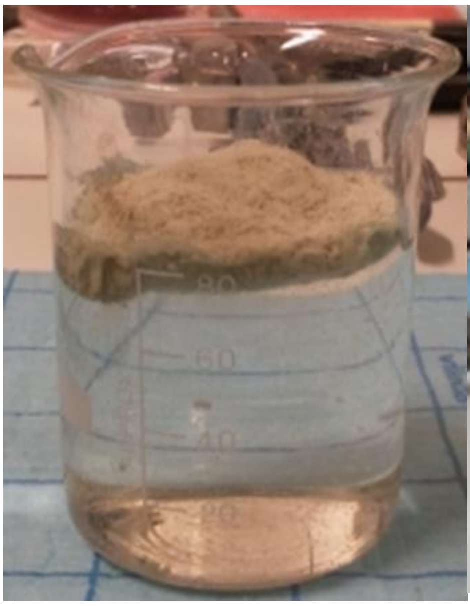


Figure 3.8: Powdered bentonite added on top of water

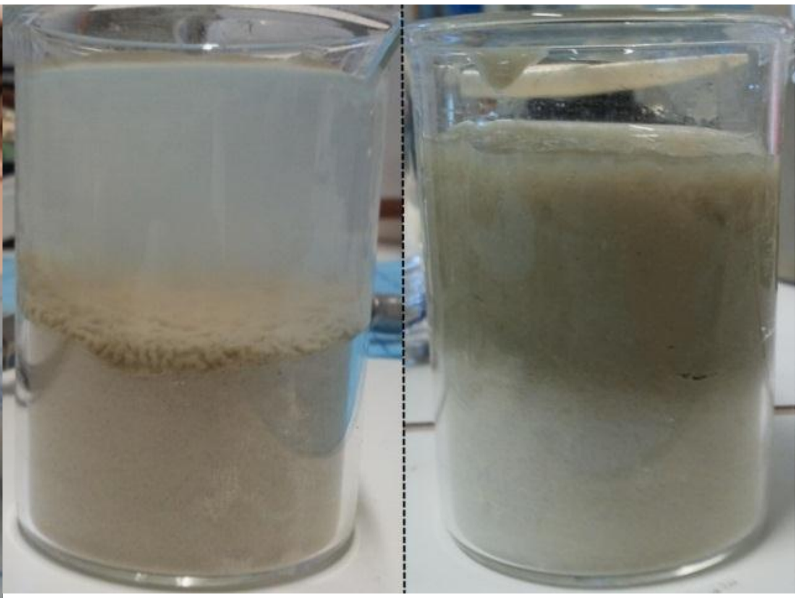


Figure 3.7: Water added on top of powdered bentonite, result after two days of hydration to the right

The solution was to mix powdered bentonite with small amounts of water before adding it to a pipe filled with water, this created larger particles which managed to sink down through the water without floating and clogging up like the powdered bentonite did, see Figure 3.9.

Figure 3.9: Left: Bentonite mixed with small amounts of water before adding to pipe, Right: Immediately after adding the mixed bentonite to a pipe filled with water

The procedure for creating bentonite plugs with powdered bentonite was to weigh wanted amount of bentonite, and then mix each 300g of powdered bentonite with 100ml of water to create larger particles as seen in Figure 3.9. The relevant plastic pipe was filled with sufficient amount of water and the premixed bentonite was carefully dropped down in the plastic pipe to settle at bottom without clogging up in the process.

3.3 Procedure

After the bentonite had been successfully added to the test pipe, the rest of the procedure was the same for both bentonite pellet plugs and bentonite powder plugs.

After let to hydrate for 2-3 days, which was found out to be enough to create a fully hydrated plug, both for bentonite pellets and for powdered bentonite, air pressure was gradually applied through the injection plug at the bottom. The setup can be seen in Figure 3.10, air pressure of 6 bars was taken from the wall, sent through a regulator to be able to carefully increase and decrease the pressure.

After the regulator two pressure sensors was used to measure the pressure, one analog and one digital pressure reader. After the pressure sensors a bleed off valve was added to let out pressure in the line if necessarily. Finally the line was connected to the ¼” connector on the bottom of the plastic pipe. The air pressure was increased in intervals until the whole plug started to move upwards inside the pipe, or the plug failed by creating a channel through the plug and bubbles was seen on top.

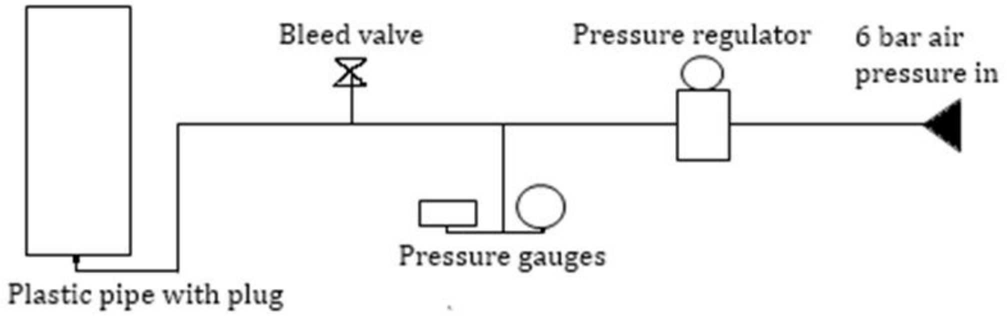


Figure 3.10: Experimental setup

Different lengths of plugs made of powdered bentonite and bentonite pellets were tested, both as fullbore plugs and as annulus plugs. The complete list of plugs made of powdered bentonite can be seen in Table 3.1 for fullbore plugs and Table 3.2 for annulus plugs. Plugs made of bentonite pellets can be seen in Table 3.3 for fullbore plugs and Table 3.4 for annulus plugs.

Test	Bentonite [g]	Water mixed in [ml]	Water in pipe [l]	Plug height after hyd. [cm]
1fpwd	1000	333	3	56
2fpwd	1500	500	4,4	85
3fpwd	1500	500	4,4	85,5
4fpwd	1550	516	4,4	86,5

5fpwd	800	266	2,4	45,5
6fpwd	400	133	1,3	24,5
7fpwd	1200	400	3,6	71

Table 3.1: Fullbore plugs made of powdered bentonite

Test	Bentonite [g]	Water mixed in [ml]	Water in pipe [l]	Plug height after hyd. [cm]
1apwd	1000	333	3,4	91
2apwd	1000	333	3,4	90
3apwd	500	200	1,6	45
4apwd	250	100	0,8	22,5
5apwd	750	300	2,55	67

Table 3.2: Annulus plugs made of powdered bentonite

Test	Bentonite [g]	Water in pipe [l]	Plug height after hydration [cm]
1fpellets	4000	2,6	64,5
2fpellets	5500	3,5	86
3fpellets	5900	2,8	86
4fpellets	3000	1,8	49
5fpellets	3000	1,8	50
6fpellets	5600	3,5	84,5
7fpellets	4000	4	63,5
8fpellets	4200	2,6	65
9fpellets	1400	0,9	24,5

Table 3.3: Fullbore plugs made of bentonite pellets

Test	Bentonite [g]	Water in pipe [l]	Plug height after hydration [cm]
1apellets	3700	2,4	88
2apellets	3700	2,4	89
3apellets	1900	1,2	46
4apellets	1900	1,2	45
5apellets	2800	1,85	66
6apellets	1000	0,65	25

Table 3.4: Annulus plugs made of bentonite pellets

In addition the density of some of the hydrated plugs was measured since this was needed in calculations. This was done by weighing parts of the hydrated plugs with known length and diameter on a scale. The density of the bentonite pellets and the powdered bentonite was also measured to be able to calculate how much the bentonite expanded when forming the plugs.

Water used for hydration of plugs were in all cases regular tap water.

4 Results

All the plugs made in this experiment created a hydraulically solid plug, both for annulus and fullbore plugs. The pressure needed to dislodge the plugs varied from 20kPa to 101kPa. The pressure each plug could resist varied with the length of the plug, if bentonite pellets or powder was used and if it were an annulus plug or a fullbore plug. In the appendix pictures of most of the plugs made can be seen, with picture before hydration, after hydration and at failure.

4.1 Bentonite pellets

4.1.1 Density of hydrated plugs and bentonite pellets

To find the density of the hydrated bentonite pellet plugs two fullbore plugs were carefully extracted out of the test pipe after failure. The top and bottom of the plug was cut off to avoid any inhomogeneous parts of the plug. After cutting, the length was carefully measured and the diameter was set to the inside diameter of the test pipe, the plug was then weighed on a scale and the density was calculated. Figure 4.1 shows one of the plugs after the top and bottom was cut off. Since the procedure for making the pellet plugs were exactly the same for all plugs made, the density found here was used in all calculations where the hydrated density of pellet plugs was needed. The density of the hydrated bentonite pellet plugs was found to be 1,533 g/cm^3, as seen in Table 4.1.

Figure 4.1: Plug 7fpellets after cutting to a length of 28,2cm

Plug nr.	Length [cm]	Weight [g]	Volume [cm^3]	Density [g/cm^3]
7fpellets	28,2	2721	1782,07	1,527
8fpellets	39,6	3851	2502,48	1,539
			Average:	**1,533**

Table 4.1: Density of the hydrated bentonite pellet plugs, averaged over two samples

The density of the bentonite pellets before hydration was found by filling a 1000ml measuring cylinder with 500ml of water, weighing the cylinder with water, adding bentonite pellets until the water rose to 1000ml and weighing the cylinder with water and pellets again. The density of the pellets was found to be 2,025 g/cm^3.

4.1.2 Fullbore plugs

Results from the tests done on fullbore plugs made of bentonite pellets are presented in Table 4.2, with height of hydrated plug, how much pressure it could withstand at failure, pressure at failure minus weight of plug and the average shear strength between the bentonite plug and the plastic pipe.

Test	H [cm] after hydration	P [kPa]	P - weight of plug [kPa]	τ [kPa]
1fpellets	64,5	45,2	35,8	1,24
2fpellets	86	56,2	43,0	1,12
3fpellets	86	74,0	60,5	1,58
4fpellets	49	36,8	29,5	1,35
5fpellets	50	35,0	27,5	1,24
6fpellets	84,5	65,8	52,9	1,40
7fpellets	63,5	53,5	43,6	1,54
8fpellets	65	46,2	36,4	1,26
9fpellets	24,5	20,0	16,4	1,50

Table 4.2: Results from fullbore plugs made of bentonite pellets

The pressure in the third column P [kPa] is the measured pressure in the lab minus pressure from any water above the plug at time of test. The pressure in the fourth column "P - weight of plug [kPa]" is the pressure measured in the lab minus pressure exerted from the weight of all bentonite and water added to the pipe.

The average shear strength between the plug and the outer plastic pipe τ [kPa] is found by multiplying the pressure corrected for weight of material with the cross section area at the bottom of the plug, and dividing by the total surface area of the outer pipe in contact with the plug:

$$\tau = \frac{P \cdot A}{Surface\ area}$$

For a fullbore plug the equation becomes:

$$\tau = \frac{P \cdot A}{Surface\ area} = \frac{P \cdot \frac{\pi}{4} D^2}{\pi \cdot D \cdot H} = \frac{P \cdot D}{4 \cdot H} \qquad \text{(Eq. 4.1)}$$

Where D is the inner diameter of the plastic pipe , H is the height of the hydrated plug and P is the measured pressure minus weight of the plug and water above. If the weight of the plug is not subtracted from P, all the values in the τ [kPa] column in Table 4.2 would have had 0,34 kPa added. All plugs in Table 4.2 were prepared by adding pellets to the test pipe already filled with water, except for plug 3fpellets which had pellets added first and water after. This resulted in a slightly denser plug which may have an impact on the friction between the plug and the pipe, and this data point was therefore not included in calculations.

In Table 4.3 the resulting expansion in percent from dry volume of pellets to hydrated plug is shown, in addition to the calculated average density of the hydrated plug from the weight of the materials added and the height of the hydrated plug.

Test	Bentonite [g]	Dry volume [cm^3]	Hydrated volume [cm^3]	Expansion	ρ calc
1fpellets	4000	1975,7	4050,9	105 %	1,50
2fpellets	5500	2716,6	5409,5	99 %	1,56
3fpellets	5900	2914,2	5409,5	86 %	1,61
4fpellets	3000	1481,8	3071,4	107 %	1,52
5fpellets	3000	1481,8	3134,6	112 %	1,53
6fpellets	5600	2766,0	5314,7	92 %	1,57
7fpellets	4000	1975,7	3987,7	102 %	1,54
8fpellets	4200	2074,5	4082,5	97 %	1,53
9fpellets	1400	691,5	1523,1	120 %	1,51

Table 4.3: Expansion of fullbore bentonite pellet plugs from dry volume of bentonite to hydrated plug

Dry volume is found by dividing the weight of the added bentonite pellets with the density of the pellets before hydration, found in chapter 4.1.1. The hydrated volume is found from the height of the hydrated plug and the expansion is the percentage increase from dry to hydrated volume. From Table 4.3 it can be seen that the smaller plugs have a tendency to expand a bit more than the longer plugs. This can be explained by the expansion of the top of the plug which expanded about the same length upwards the pipe (3-5cm), whether the plug was 26cm or 86cm long (see Appendix A-1 for pictures of pellets plugs before and after hydration). For plug number 3fpellets, pellets were added to the pipe before water, this made the pellets pack closer together and explains the low expansion and higher density for that plug. It can also explain the slightly higher average shear strength in Table 4.2 for this plug.

The calculated density is found by taking the weights of all materials added to the pipe and subtract the weight of excess water after hydration. Some water may have been lost in evaporation during the 2-3 days of hydration, but the data in Table 4.3 is in range with the density of 1,533 g/cm^3 which was measured in chapter 4.1.1 (except for plug 3fpellets which has a slightly higher density due to pellets being added before water).

In Figure 4.2 pressure is plotted against length of plug for fullbore pellet plugs, the pressures are from column 3 in Table 4.2 with weight of plug included. The data point marked with a circle is plug 3fpellets which is the only plug that had pellets added to the pipe before water, which resulted in a bit denser plug. The data in Figure 4.2 seems to indicate that the pressure the plugs can withstand increase linearly with the length of the plug.

This is further indicated in Figure 4.3 where the average shear strength of fullbore pellet plugs is plotted against length of plug, the shear strengths are from the last column in Table

4.2 which have been corrected for weight of plug, so that only the friction between the plug and the plastic pipe is represented. If the pressure the plugs could withstand was increasing more than linearly with the length of the plug, the average shear strength in Figure 4.3 should increase with increasing plug length. This is not seen in Figure 4.3, where the average shear strength seems to be constant or slightly decreasing with the length of the plug.

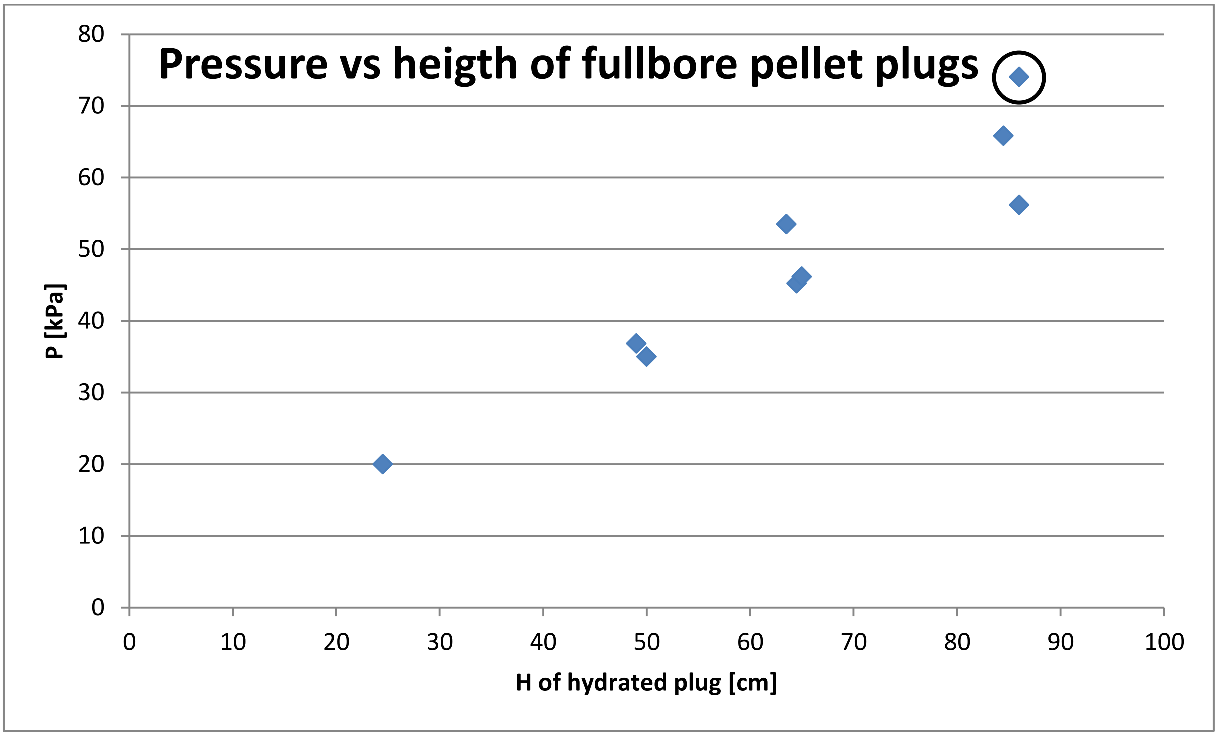


Figure 4.2: Pressure vs height of fullbore pellet plugs

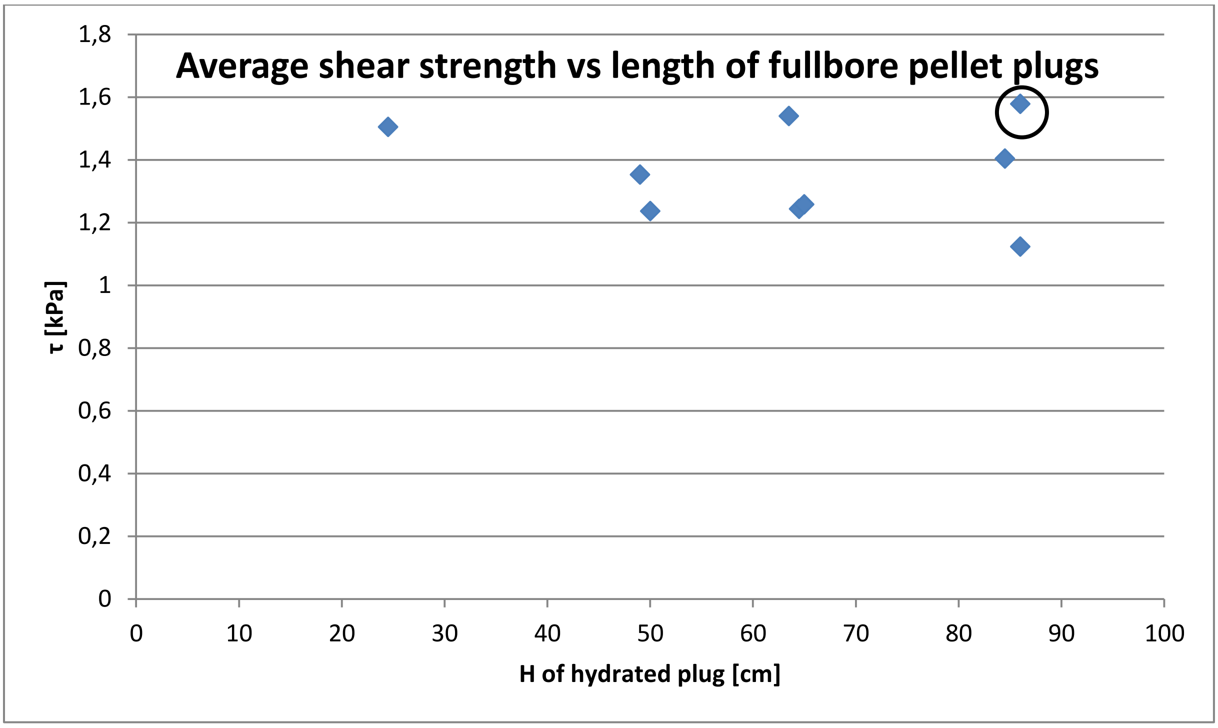


Figure 4.3: Average shear strength plotted against length of fullbore pellet plugs

4.1.3 Annulus plugs

Results from the tests done on annulus plugs made of bentonite pellets are presented in Table 4.4, with height of hydrated plug, how much pressure it could withstand at failure, pressure at failure minus weight of plug and the average shear strength between the bentonite plug and the inner and outer plastic pipe.

Test	H [cm] of hydrated plug	P [kPa]	P - weight of plug [kPa]	τ [kPa]
1apellets	88	100,5	87,3	0,98
2apellets	89	92,6	79,3	0,88
3apellets	46	54,8	48,0	1,04
4apellets	45	54,2	47,5	1,05
5apellets	66	82,4	72,5	1,09
6apellets	25	31,0	27,3	1,08

Table 4.4: Results from annulus plugs made of bentonite pellets

The pressure in the third column P [kPa] is the measured pressure in the lab minus pressure from any water above the plug at time of test. The pressure in the fourth column "P - weight of plug [kPa]" is the pressure measured in the lab minus pressure exerted from the weight of all bentonite and water added to the pipe.

When moving from a fullbore plug to an annulus plug two main effects come into play, the cross section area at the bottom of the plug where the pressure work against decrease from $\frac{\pi}{4}D_o^2$ to $\frac{\pi}{4}(D_o^2 - D_i^2)$. And the surface area of the plug in contact with pipe walls where friction can act increase from $\pi D_o H$ to $\pi(D_o + D_i)H$. The average shear strength between the plug and the outer and inner plastic pipe τ [kPa] in an annular case is:

$$\tau = \frac{P \cdot A}{Surface\ area} = \frac{P \cdot \frac{\pi}{4}(D_o^2 - D_i^2)}{\pi \cdot (D_o + D_i) \cdot H} = \frac{P \cdot \frac{\pi}{4}(D_o + D_i) \cdot (D_o - D_i)}{\pi \cdot (D_o + D_i) \cdot H} = \frac{P \cdot (D_o - D_i)}{4 \cdot H} \quad \text{(Eq. 4.2)}$$

Where D_o is the (inner) diameter of the outer plastic pipe, D_i is the (outer) diameter of the inner plastic pipe, H is the height of the hydrated plug and P is the measured pressure minus the weight of the plug. If the weight of the plug is not subtracted from P, all the values in the τ [kPa] column in Table 4.4 would have had 0,15 kPa added.

For the test equipment used here, the reduction in annular cross section area and increased surface area along the pipe in the annular case result in an reduction factor of 2,26 for the average shear strength if one annular plug and one fullbore plug of the same length withheld the same pressure:

$$\frac{\tau_{fullbore}}{\tau_{annulus}} = \frac{P \cdot D_o}{4 \cdot H} \div \frac{P \cdot (D_o - D_i)}{4 \cdot H} = \frac{D_o}{(D_o - D_i)} = \frac{8{,}97cm}{8{,}97cm - 5{,}0cm} = 2{,}26$$

Expansion in percent from dry volume of bentonite to hydrated plug volume for annuls pellet plugs are presented in Table 4.5. The last column is the calculated average density of the hydrated plug by taking the weight of all materials added, subtracting weight of excess water at hydration and dividing by the volume of the hydrated plug.

Test	Bentonite [g]	Dry volume [cm^3]	Hydrated volume [cm^3]	Expansion	ρ calc
1apellets	3700	1827,5	3833,2	110 %	1,53
2apellets	3700	1827,5	3876,7	112 %	1,52
3apellets	1900	938,5	2003,7	114 %	1,49
4apellets	1900	938,5	1960,2	109 %	1,51
5apellets	2800	1383,0	2874,9	108 %	1,52
6apellets	1000	493,9	1089,0	120 %	1,52

Table 4.5: Expansion of annulus bentonite pellet plugs from dry volume of bentonite to hydrated plug

Annulus pellet plugs seems to expand slightly more than comparable fullbore pellets plugs in Table 4.3, this can be explained by the smaller cross surface area which makes packing of pellets less efficient when freefalling through water in the annular case. The density of expelled annulus pellet plugs was not measured due to the difficulty of getting the hydrated annulus plugs out of the pipe without damage. The measured density of 1,533 g/cm^3 from two expelled fullbore bentonite pellet plugs in chapter 4.1.1 is in the same range as the calculated densities of annulus plugs in Table 4.5.

In Figure 4.4 pressure at failure is plotted against height of annulus pellet plugs, the pressures are from column 3 in Table 4.4 with weight of plug included. The data in Figure 4.4 seems to indicate a linear relationship between length of plug and the pressure it can withstand before failure. This is further indicated in Figure 4.5 where the average shear strength of annulus pellet plugs seems to be constant with respect to the length of the plug.

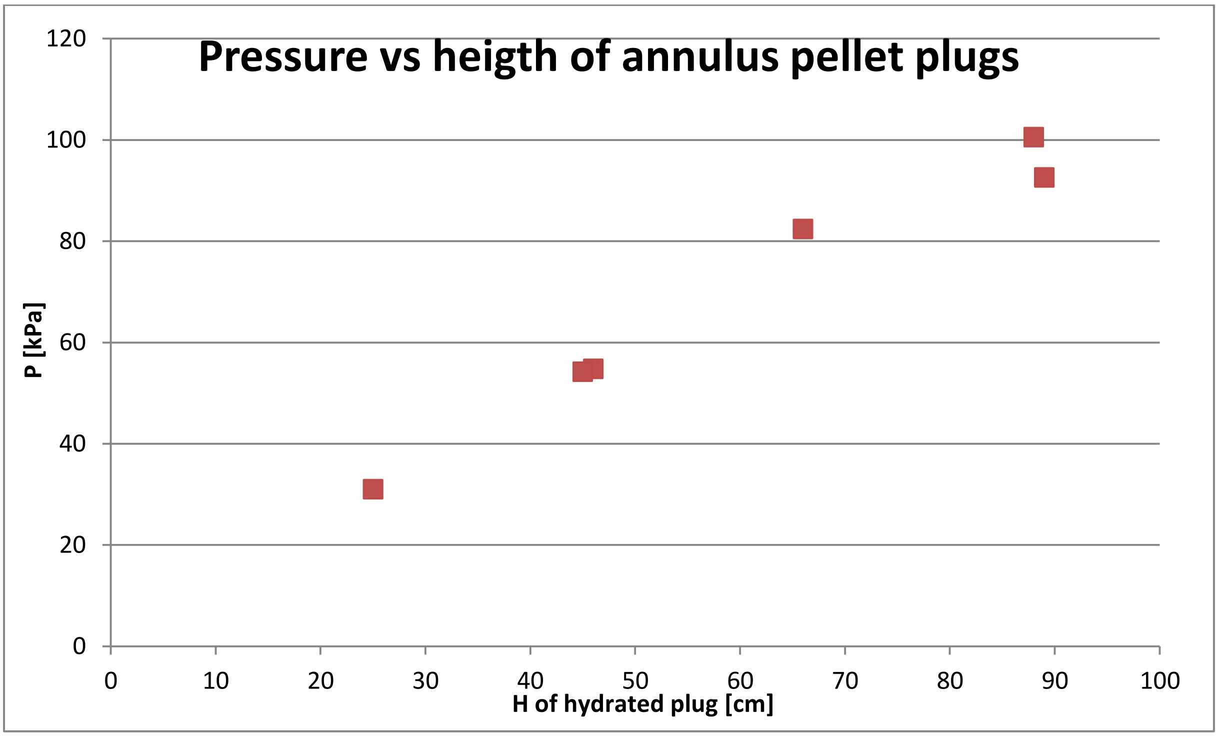


Figure 4.4: Pressure plotted against height of annulus pellet plugs

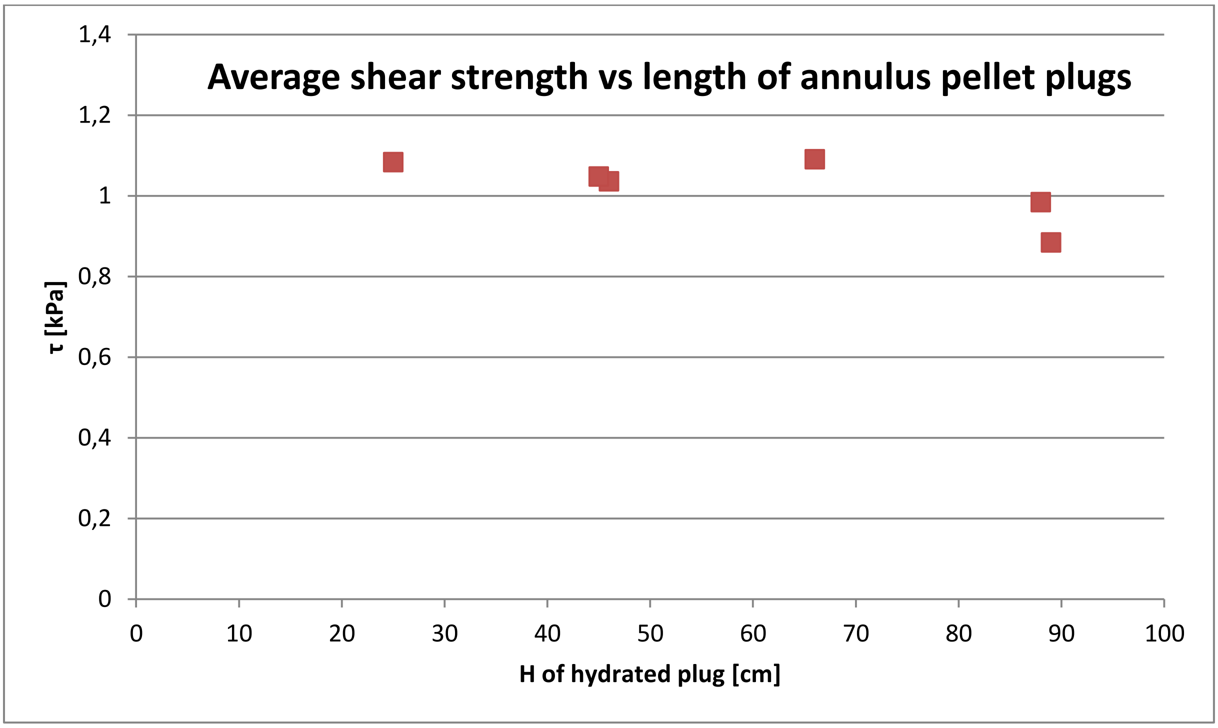


Figure 4.5: Average shear strength plotted against length of annulus pellet plugs

4.1.4 Comparison of fullbore and annulus pellet plugs

In Figure 4.6 failure pressure of both fullbore and annulus bentonite pellet plugs are plotted against length of plug. While in Figure 4.7 average shear strength of both fullbore and annulus pellet plugs are plotted against length of plug.

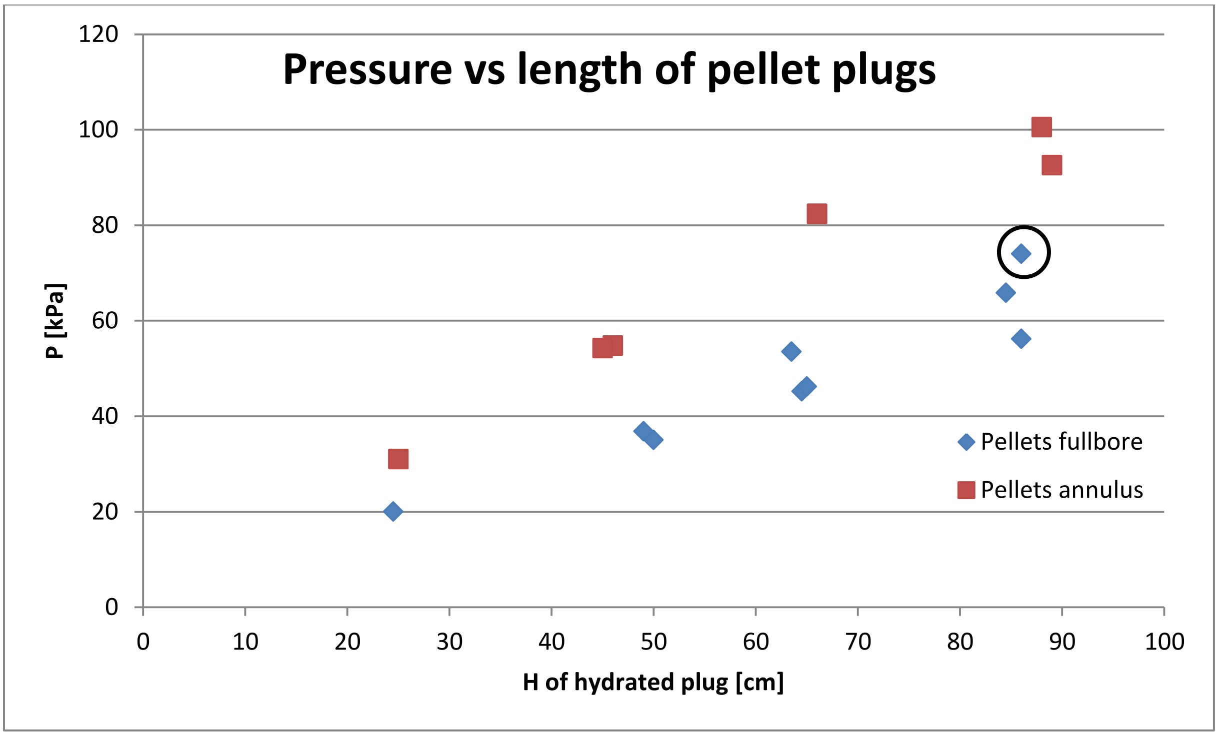


Figure 4.6: Pressure against length of pellet plugs, both fullbore and annulus plugs

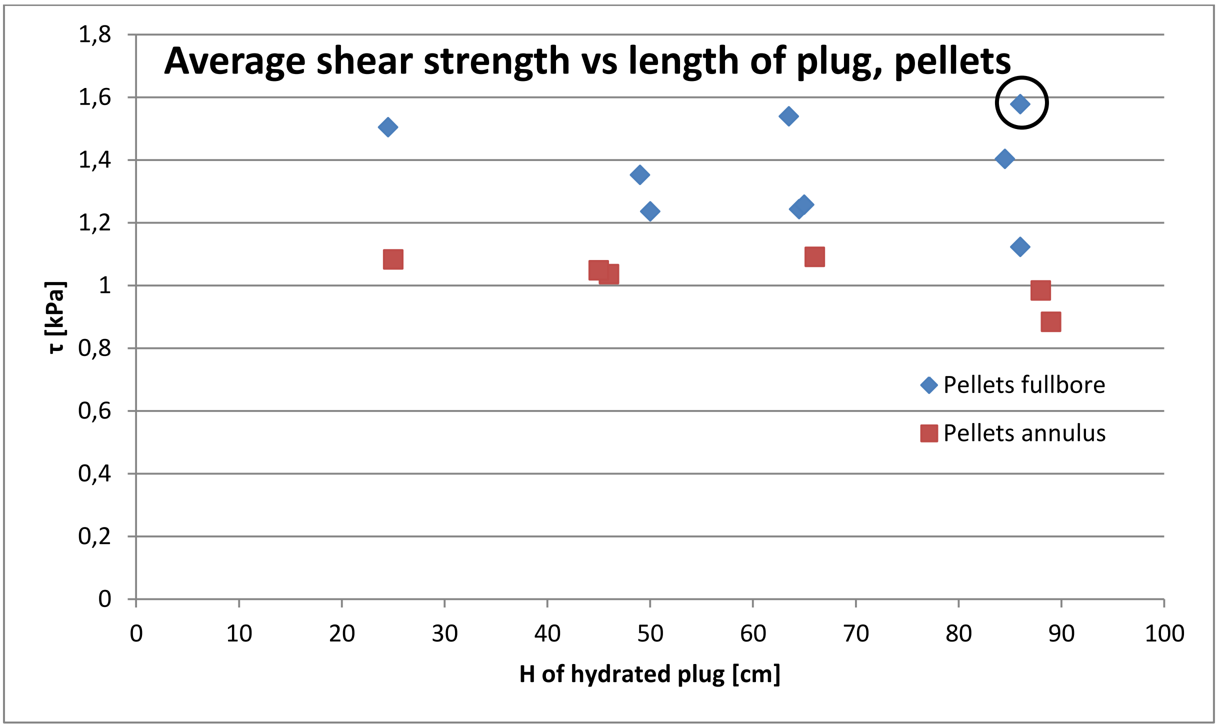


Figure 4.7: Average shear strength plotted against length of pellet plugs, both fullbore and annulus plugs

From Figure 4.6 it is clear that an annulus plug of a given length will withstand a higher pressure than a fullbore plug. But as mentioned before, in an annular case the effect of decreased area where pressure can act to dislodge the plug, and increased surface are of the plug in contact with the pipe wall result in a lower average shear strength. I.e. there is more surface to give friction to the plug and less area for pressure to push the plug out in an annular case. This explains why the shear strengths in Figure 4.7 are lower for annulus plugs even though the pressures in Figure 4.6 are higher.

Both Figure 4.6 and Figure 4.7 seems to indicate that the pressure for fullbore and annulus pellet plugs increase linearly with the length of the plug. By drawing the best horizontal line through the fullbore points in Figure 4.7, or by taking the mean of the average shear strengths of fullbore plugs in column 5 of Table 4.2 (not including plug 3fpellets due to different procedure), the average shear strength between the fullbore pellet plug and the plastic pipe becomes 1,33 kPa.

The average shear strength between annulus pellet plugs and the inner and outer plastic pipe is found to 1,02 kPa by taking the mean of the average shear strengths in column 5 of Table 4.4. An explanation for the lower average shear strength for annulus plugs can be that the volume of bentonite per unit of pipe wall surface area is lower in the annular case. And as a result the bentonite exerts less pressure on the walls after hydration in the annular case compared to the fullbore case.

4.2 Powdered bentonite

4.2.1 Density of hydrated plugs and powdered bentonite

The density of the hydrated plugs made of bentonite powder was found in the same way as the density of the pellets plug. Two fullbore plugs were carefully extracted out of the test pipe, cut into a cylinder and weighed on a scale. Figure 4.8 shows one of the plugs which were extracted from the test pipe. The density found here was used in all calculations where the hydrated density of powdered bentonite was needed. The hydrated density was found to be 1,102 g/cm^3 as seen in Table 4.6. This density is very close to the density found in the previous project of 1,109 g/cm^3, for hydrated powdered bentonite plugs made by following the same procedure as in this thesis, but tested in a smaller test tube with a slightly larger diameter.

Figure 4.8: Plug 7fpwd after cutting to a length of 30,3cm

Plug nr.	Length [cm]	Weight [g]	Volume [cm^3]	Density [g/cm^3]
6fpwd	20,1	1385	1270,20	1,090
7fpwd	30,3	2134	1914,77	1,114
			Average:	**1,102**

Table 4.6: Density of the hydrated bentonite powder plugs, averaged over two samples

For the density of dry powdered bentonite the value found in the previous project was used, since the powdered bentonite used here was taken from the same bag. In the previous project the dry density of powdered bentonite was found to be 1,09 g/cm^3 by weighing two samples of 80cm^3 and 300cm^3 powdered bentonite. This density was used to calculate the volume of bentonite before hydration and to find the resulting expansion after hydration.

4.2.2 Fullbore plugs

Results from the tests done on fullbore plugs made of powdered bentonite are presented in Table 4.7. With height of hydrated plug, how much pressure it could withstand at failure, pressure at failure minus weight of plug, and the average shear strength between the bentonite plug and the plastic pipe.

Test	H [cm] of hydrated plug	P [kPa]	P - weight of plug [kPa]	τ [kPa]
1fpwd	56	52,8	46,3	1,85
2fpwd	85	67,1	57,6	1,52
3fpwd	85,5	44,8	35,1	0,92
4fpwd	86,5	65,6	55,9	1,45
5fpwd	45,5	28,2	23,1	1,14
6fpwd	24,5	26,8	24,2	2,21
7fpwd	71	40,7	32,9	1,04

Table 4.7: Results from fullbore plugs made of powdered bentonite

The average shear strength “τ [kPa]” between the fullbore bentonite powder plug and the plastic pipe was calculated in the same way as for fullbore pellet plugs by using Equation 4.1. If the weight of the plug is included in the average shear strength the values in column 5 of Table 4.7 will increase with 0,25 kPa.

Plug 3fpwd did crack vertically at failure (see picture in Appendix A-2) which explain the lower pressure and shear strength for this plug. For this reason plug 3fpwd was not included in calculations.

Plug 6fpwd’s pressure at failure and shear strength is much higher compared to the short length of the plug than what is seen in the other plugs. This could be a result of the test equipment and the short length of the plug. The pressure can not have acted on the full cross section area of the bottom of the plug when it failed. This problem was not encountered on longer plug lengths where the bottom of the plug could be seen to be compressed upwards a few millimeters from the pressure before the pressure was further increased and the plug failed. This can be seen in Figure 4.9 where plug 2apwd is at a pressure of 60 kPa before the pressure was further increased to failure at 84,5 kPa. A second try on creating a plug identical to 6fpwd gave an even more incorrect reading and resulted in a pressure of 35,85 kPa and a τ of 3,03 kPa. A picture from this plug at failure can be seen in Figure 4.10, where it is clear that the pressure only had acted on a fraction of the bottom of the plug at failure. The single ¼” hole which the air pressure enters is marked with a black circle. Based on this, the data from plug 6fpwd was not used in calculations

Figure 4.9: Bottom of plug 2apwd at a pressure of 60kPa

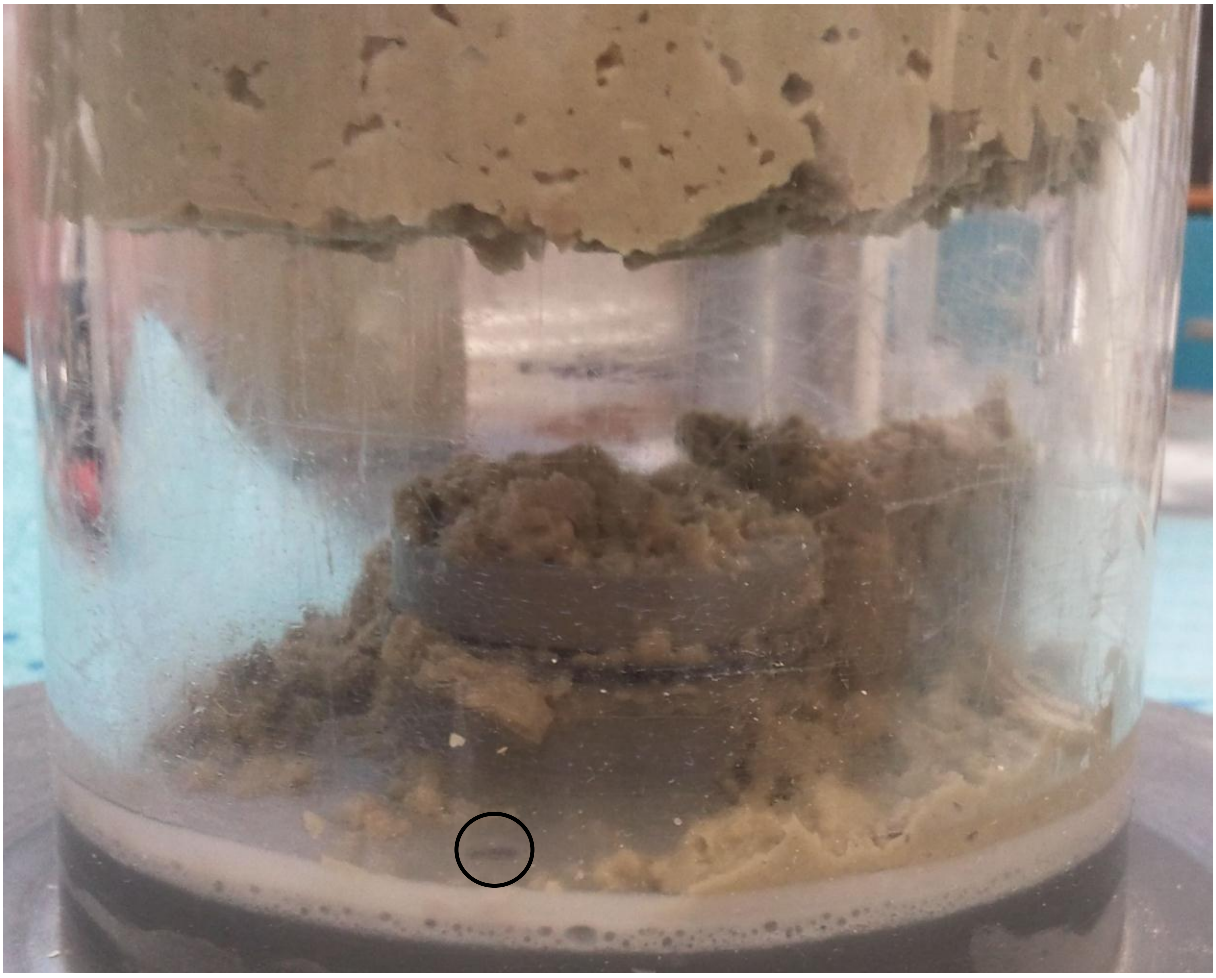


Figure 4.10: A plug with same height as 6fpwd at failure, ¼" air hole marked with a black circle.

Expansion in percent from dry volume of bentonite to hydrated plug volume of fullbore plugs made of powdered bentonite are presented in Table 4.8. The last column is the calculated average density of the hydrated plug by taking the weight of all materials added, subtracting weight of excess water at hydration and dividing by the volume of the hydrated plug.

Test	Bentonite [g]	Dry volume [cm^3]	Hydrated volume [cm^3]	Expansion	ρ calc
1fpwd	1000	917,1	3513,7	283 %	1,18
2fpwd	1500	1375,6	5346,3	289 %	1,15
3fpwd	1500	1375,6	5377,9	291 %	1,16
4fpwd	1550	1421,5	5441,1	283 %	1,15
5fpwd	800	733,7	2850,2	288 %	1,14
6fpwd	400	366,8	1523,1	315 %	1,12
7fpwd	1200	1100,5	4461,6	305 %	1,12

Table 4.8: Expansion of fullbore powdered bentonite plugs from dry volume of bentonite to hydrated plug

Dry volume is found by dividing the weight of the added bentonite powder with the density of the dry powdered bentonite found in the previous project, as mentioned in chapter 4.2.1. The hydrated volume is found from the height of the hydrated plug and the expansion is the percentage increase from dry volume of powder to hydrated plug volume. The calculated densities in Table 4.8 are slightly higher than the measured density of 1,102 g/cm^3

In Figure 4.11 pressure is plotted against length of fullbore plugs made of powdered bentonite. And in Figure 4.12 average shear strength is plotted against length of plugs. In both figures plug 3fpwd which failed by cracking is marked with a black circle, while plug 6fpwd which probably failed at too high pressure due to pressure not acting at the full area as mentioned above is marked in red.

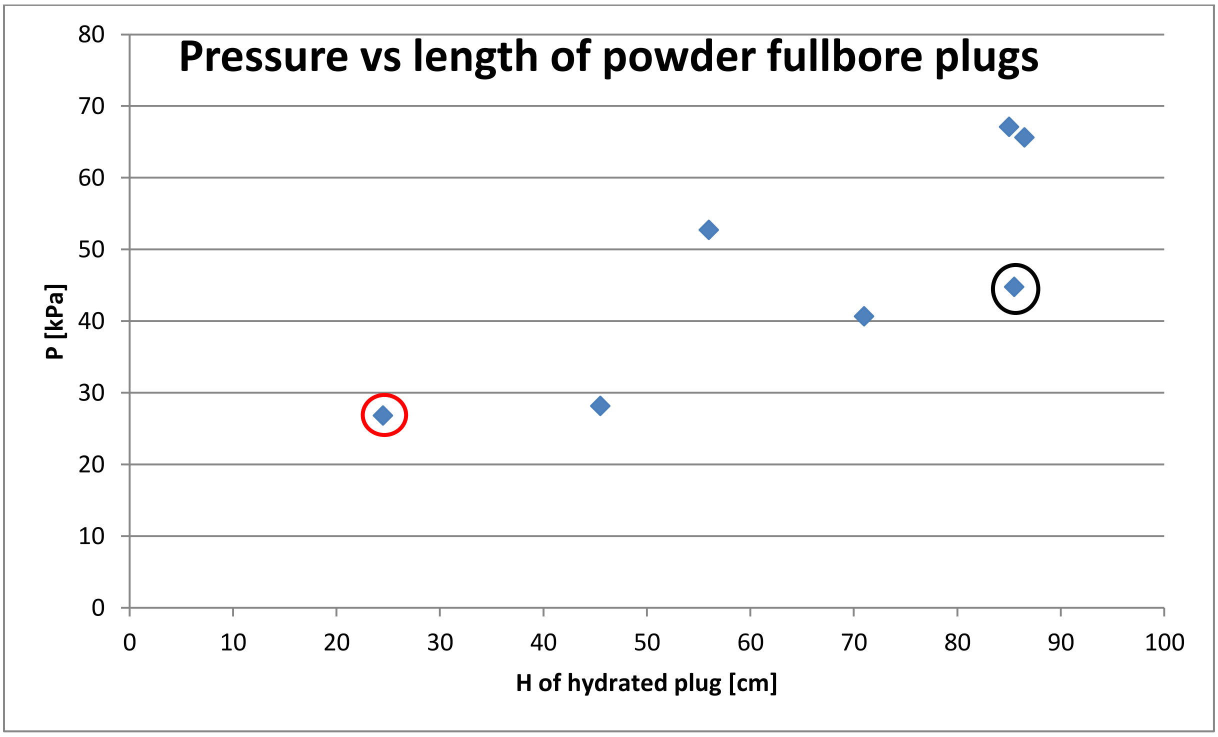


Figure 4.11: Pressure vs height of fullbore plugs made of powdered bentonite

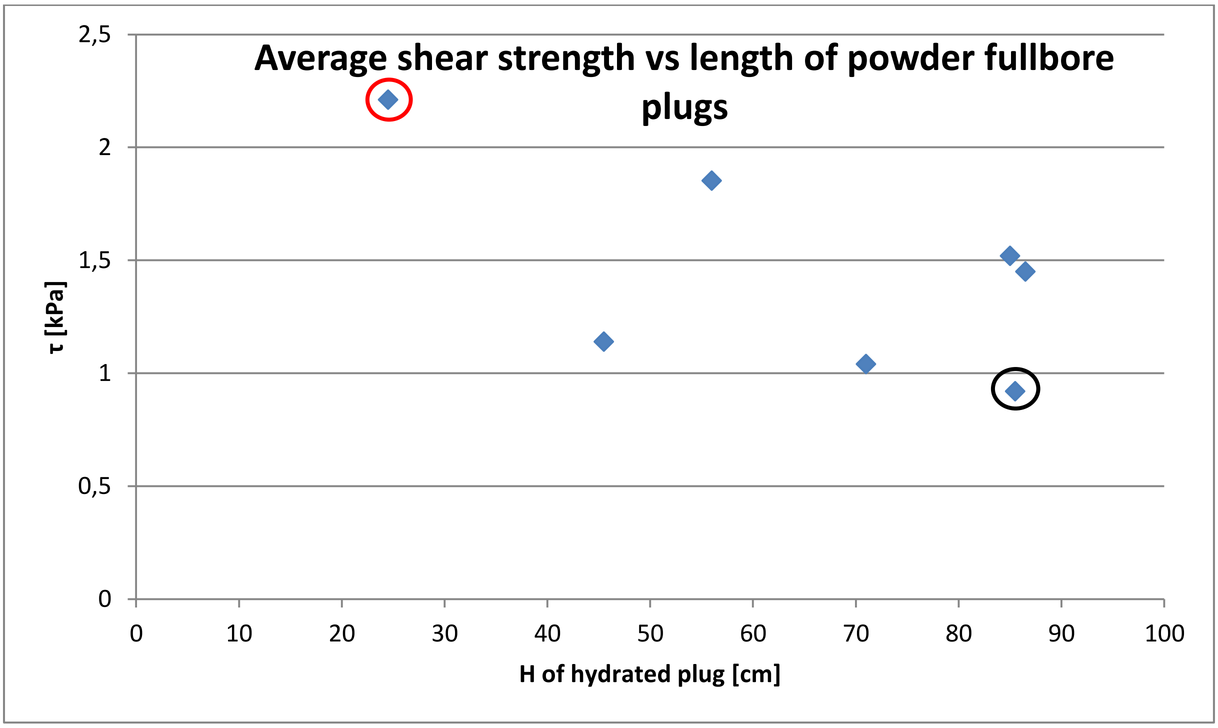


Figure 4.12: Average shear strength plotted against length of fullbore plugs made of powdered bentonite

The data in Figure 4.11 and Figure 4.12 are more scattered than for similar plots made for fullbore pellets plugs (Figure 4.2). A reason for this can be that it is more difficult to create a repeatable homogenous plug using powdered bentonite compared to bentonite pellets. The pressures in Figure 4.11 still seems to be following a linear pattern and in Figure 4.12 the shear strength is not increasing with increasing plug length. A perfect linear relation between pressure and plug length should give a constant shear rate against plug length.

4.2.3 Annulus plugs

Results from the tests done on annulus plugs made of powdered bentonite are presented in Table 4.9

Test	H [cm] of hydrated plug	P [kPa]	P - weight of plug [kPa]	τ [kPa]
1apwd	91	83,3	72,8	0,79
2apwd	90	84,5	74,3	0,82
3apwd	45	55,9	50,8	1,12
4apwd	22,5	24,4	21,9	0,97
5apwd	67	59,3	51,9	0,77

Table 4.9: Results from annulus plugs made of powdered bentonite

The average shear strength "τ [kPa]" between the annulus bentonite powder plug and the inner and outer plastic pipe is calculated in the same way as for annulus pellet plugs by using Equation 4.2. If the weight of the plug is included in the average shear strength, all values in column 5 of Table 4.9 will be increased with 0,11 kPa.

Expansion from dry volume of bentonite powder to volume of hydrated annulus plug is found in Table 4.10.

Test	Bentonite [g]	Dry volume [cm^3]	Hydrated volume [cm^3]	Expansion	ρ calc
1apwd	1000	917,1	3963,9	332 %	1,16
2apwd	1000	917,1	3920,3	327 %	1,15
3apwd	500	458,5	1960,2	327 %	1,15
4apwd	250	229,3	980,1	327 %	1,13
5apwd	750	687,8	2918,4	324 %	1,13

Table 4.10: Expansion of annulus powdered bentonite plugs from dry volume of bentonite to hydrated plug

The expansions of annulus plugs made of powdered bentonite in Table 4.10 are slightly higher than expansions seen for fullbore powder plugs in Table 4.8. This was also seen for pellets plugs and can be explained by the smaller volume available for powdered bentonite to settle in the annular case, which increases the amount of voids between the bentonite particles.

In Figure 4.13 pressure at failure is plotted against length of annulus plugs made of powdered bentonite. The data indicates a linear relationship between the length of the plug and the pressure it can withstand at failure. This is further shown in Figure 4.14 where the shear strength is plotted against plug length and the data seems to follow a horizontal line.

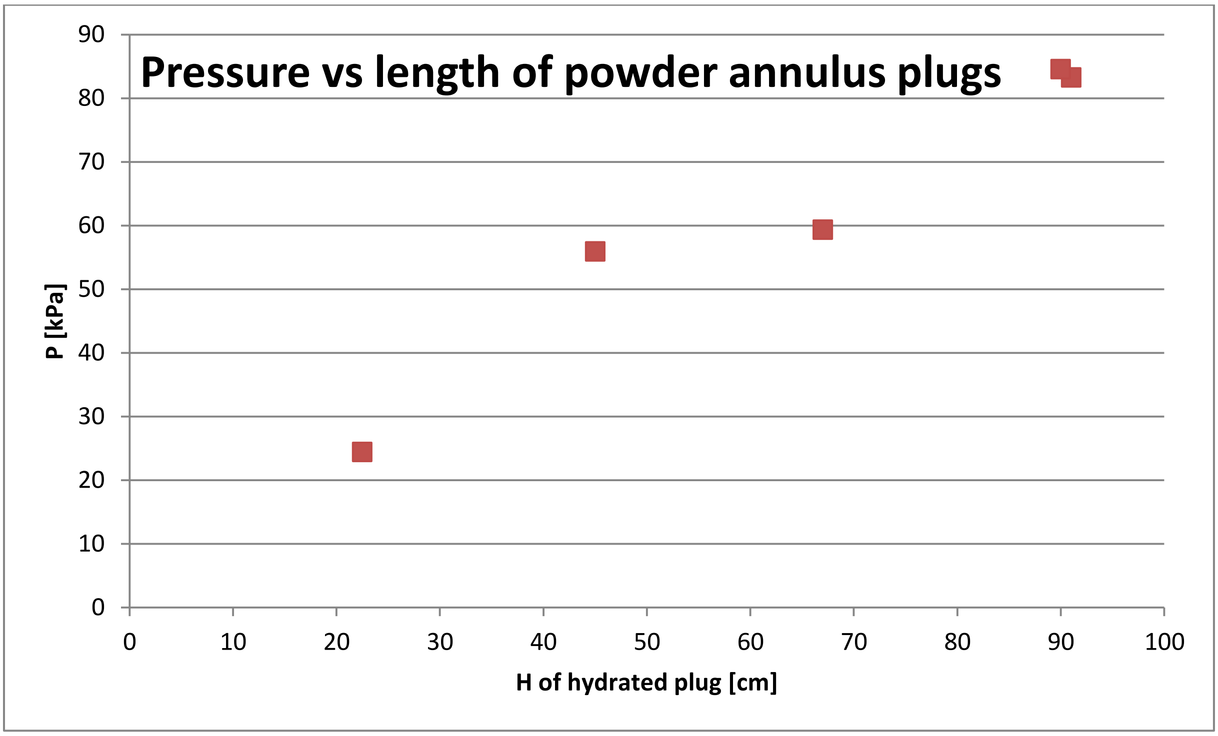


Figure 4.13: Pressure vs height of annulus plugs made of powdered bentonite

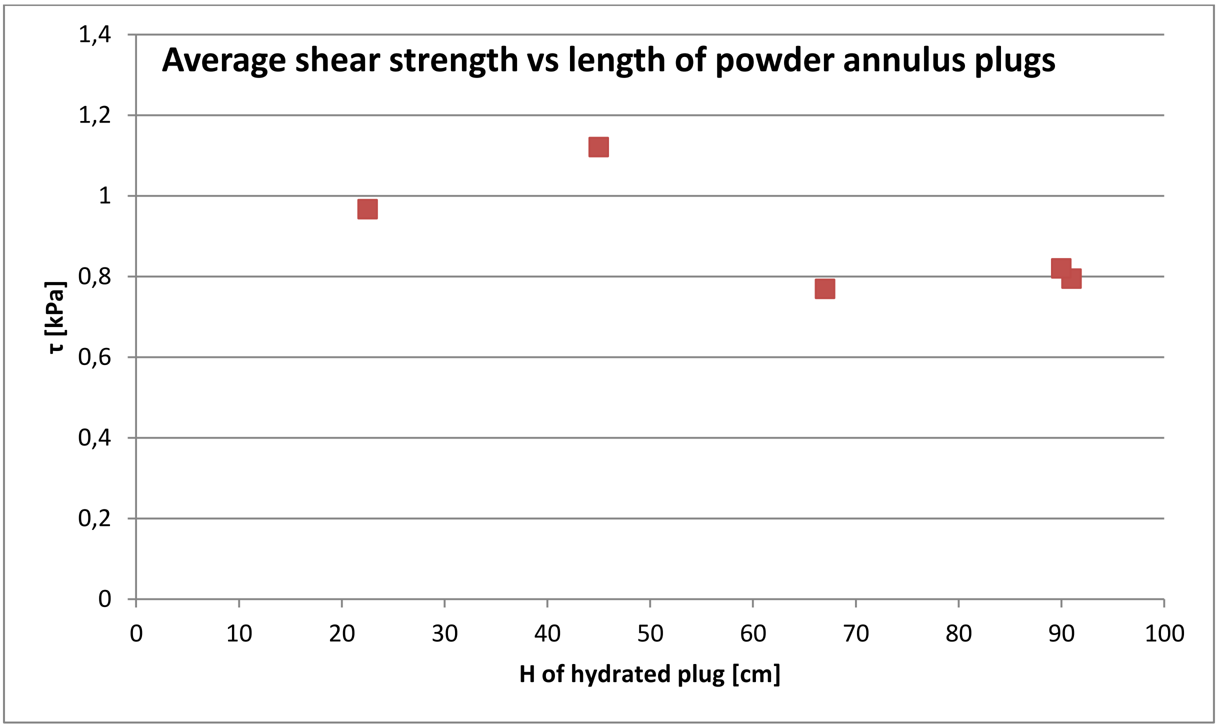


Figure 4.14: Average shear strength plotted against length of fullbore plugs made of powdered bentonite

4.2.4 Comparison of fullbore and annulus plugs made of powdered bentonite

In Figure 4.15 pressure is plotted against length of plugs made of powdered bentonite, the data in this figure is a bit more scattered than for similar plot of bentonite pellet plugs (Figure 4.6). It is more difficult to create repeatable homogenous plugs by using powdered bentonite compared to using bentonite pellets. The trends seen in Figure 4.15 are still similar to those seen for plugs made of pellets. The pressure seems to be increasing linearly with the length of the plugs, especially for the annulus plugs. There is more noise in the fullbore plugs but the average trend is a steady linear increase in pressure with plug length. A linear relationship between plug length and pressure should give constant shear strengths in Figure 4.16, where shear strength is plotted against plug length for powdered bentonite plugs.

By drawing the best horizontal line through the fullbore points in Figure 4.16, or by taking the mean of the shear strengths of fullbore plugs in column 5 of Table 4.7 (not including plug 3fpwd marked with a black circle due to cracking at failure and plug 6fpwd marked with a red circle due to overestimation of pressure) the average shear strength between the fullbore powder plug and the outer plastic pipe becomes 1,40 kPa. This compares to the value of 1,33 kPa found for fullbore pellet plugs.

By drawing the best horizontal line through the annulus points in Figure 4.16, or by taking the mean of the shear strengths of annulus plugs in column 5 of Table 4.9 the average shear strength between the plug and the inner and outer plastic pipe becomes 0,89 kPa. This compares to the value of 1,02 kPa found for annulus pellet plugs.

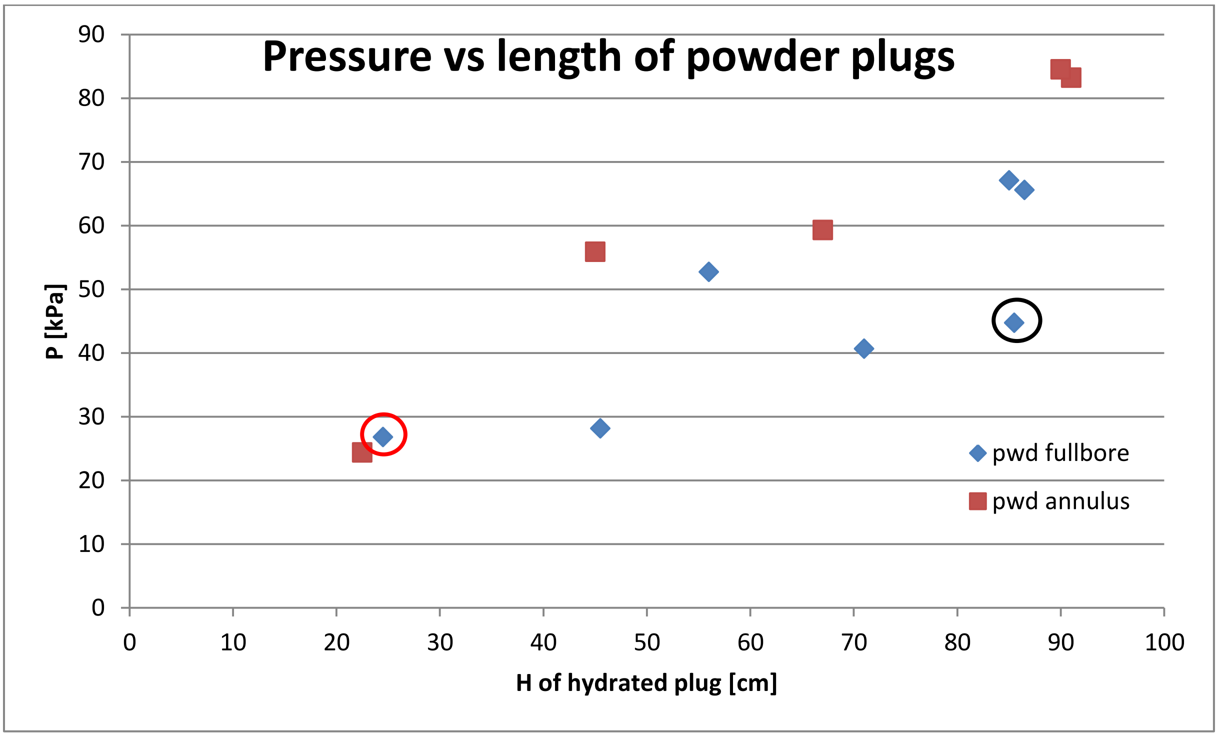


Figure 4.15: Pressure against length of powder plugs, both fullbore and annulus plugs

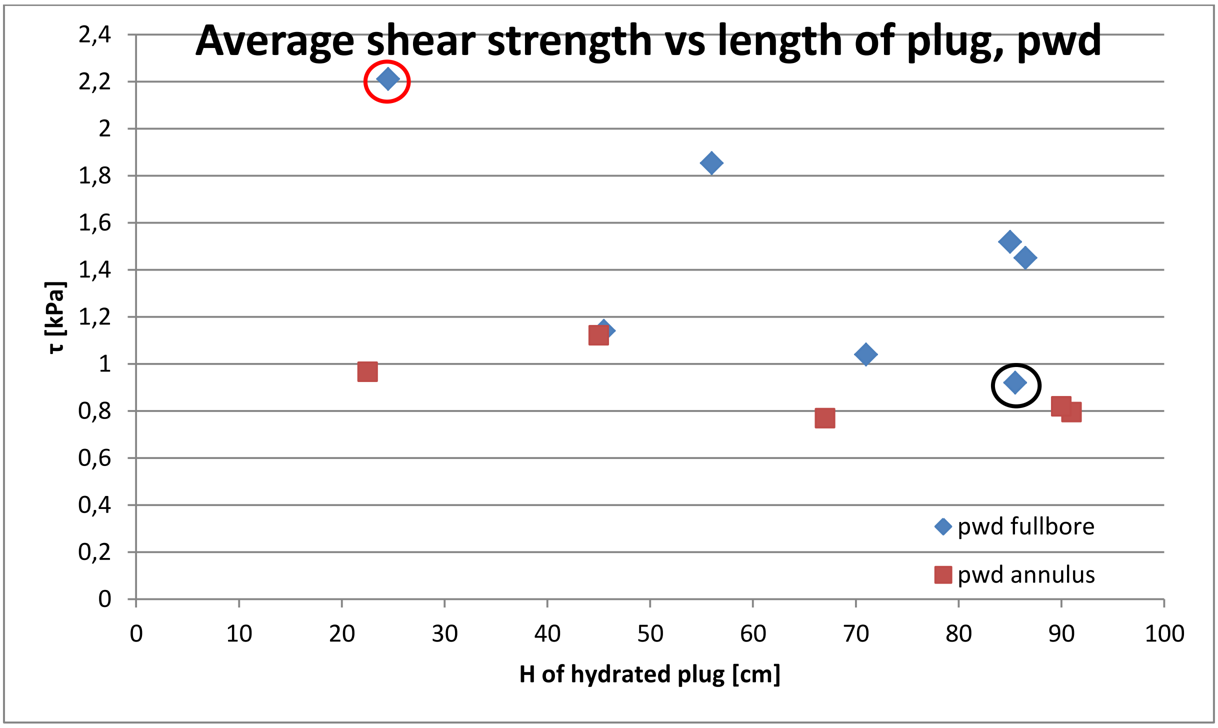


Figure 4.16: Average shear strength plotted against length of pellet plugs, both fullbore and annulus plugs

5 Discussion

5.1 Densities of hydrated plugs and expansion

From Table 4.1 the average density of hydrated pellets plugs was found to be 1,533 g/cm^3, measured from fullbore plugs 7fpellets and 8fpellets. This density was assumed to be approximately correct for all the plugs made of pellets since the procedure for creating the plugs was consistent for all plugs (except for plug 3fpellets where pellets were added to the pipe before water which resulted in a denser plug). As seen in Table 4.3 the expansion of fullbore pellets plugs from dry volume of pellets to hydrated plug was in the range of 92%-120% (excluding plug 3fpellets which expanded 86%). While the expansion of annulus plugs made of pellets in Table 4.5 was in the range of 108%-120%. The dry density of the pellets before hydration was measured to 2,025 g/cm^3.

The density of hydrated pellets plug found here is in range of what is reported in earlier work, Towler et al. (2008) reported the density of their compressed bentonite bars to be 2,31 g/cm^3 and 1,616 g/cm3 after hydration. While Englehardt et al. (2001) reported the density of their compressed bentonite nodules as 2,2-2,05 g/cm^3 and 1,75 g/cm^3 after hydration as seen in Figure 2.16

The density of plugs made of powdered bentonite was found to be 1,102 g/cm^3 in Table 4.6, measured from fullbore plugs 6fpwd and 7fpwd. This is much lower than the density found for pellet plugs but it is explained by the low density of 1,09 g/cm^3 for the dry powdered bentonite used to create the plugs. The expansion of fullbore plugs made of powdered bentonite in Table 4.8 was in the range of 283-315%, while the expansion of annulus plugs made of powdered bentonite in Table 4.10 was in the range of 324-332%. Despite the low hydrated density of plugs made of powdered bentonite they still managed to withstand pressures in the range of what was seen for plugs made of bentonite pellets.

5.2 Evaluation of how the pressure varies with length of plug

The equation (Eq. 2.1) derived by Towler and Ehlers (1997) suggest that the pressure increase with the square of the length of the plug. While experiments conducted by Odgen and Ruff (1992) concludes that the pressure increase linearly with the length of the plug. The data found in the experiments done here seems to indicate that the pressure increase linearly with plug length. But by utilizing the equation derived by Towler and Ehlers (1997) (Equation 2.1 in chapter 2.5.1) the following graphs and plots can be made to evaluate the equation in relation to the results found here.

$$P = K_b \cdot \rho_w \left(\frac{4L_w H}{D} + \frac{2\gamma_b H^2}{D} \right) + \rho_w \cdot (L_w + \gamma_b H) \qquad \text{(Eq. 2.1)}$$

Where P is the pressure measured at failure, K_b is a friction factor between the bentonite plug and the test pipe, L_w is length of water above plug at hydration, H is the length of the hydrated plug, ρ_w is density of water, γ_b is the specific gravity of the hydrated plug, and D is the outer diameter of the plug.

To test the equation, data from annulus plugs made of bentonite pellets are used to find the friction factor K_b from a plot of $[P - \rho_w \cdot (L_w + \gamma_b H)]$ versus $[\rho_w (4L_w H + 2\gamma_b H^2)/(D - d)]$ as seen in Figure 5.1. Note that D in the equation has been replaced by D-d to account for annulus plugs, where D is the outer diameter of the plug and d is the inner diameter of the plug.

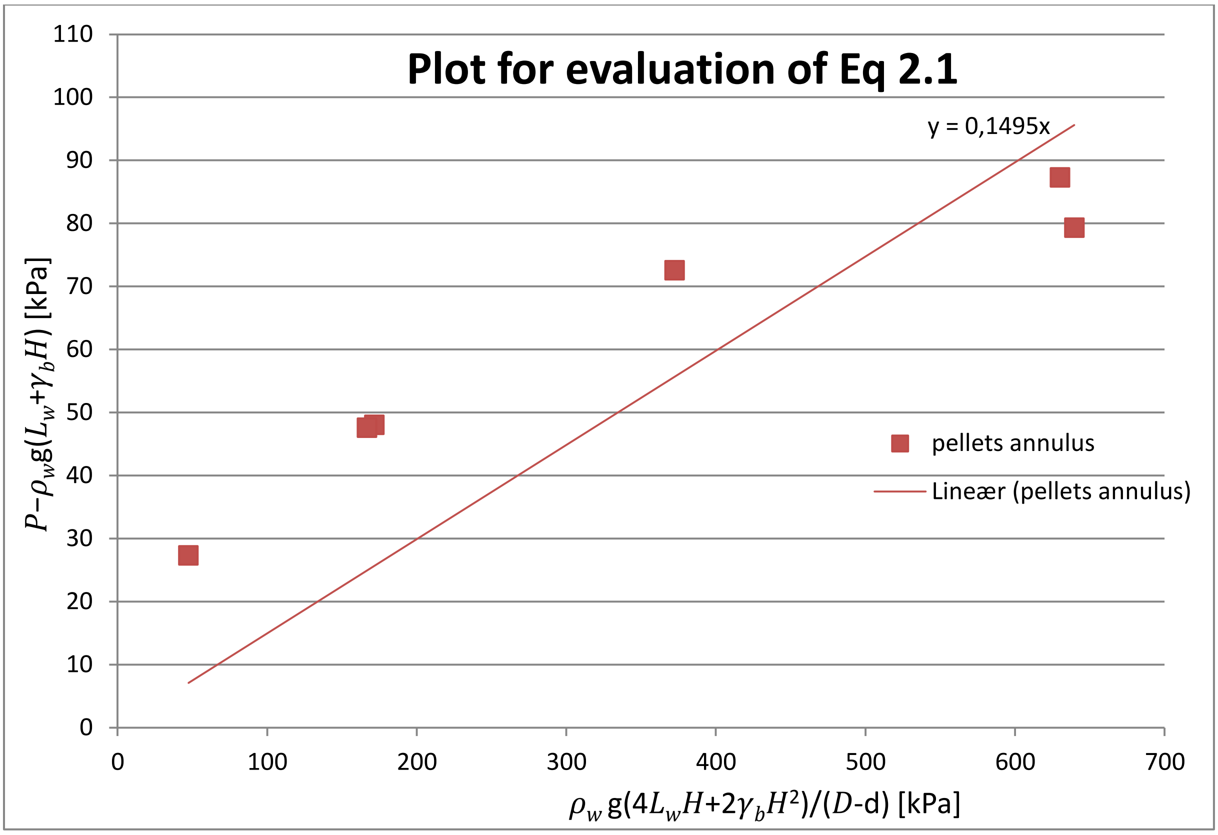


Figure 5.1: Plot for evaluation of Eq. 2.1 by using data from annulus pellet plugs

If Equation 2.1 is correct for estimating pressures versus plug length, the data points in Figure 5.1 should fit to a straight line through origin, where the slope of the line is the friction factor K_b. This is not seen in Figure 5.1 where the data points seems to be too high at lower plug lengths and too low at higher plug lengths to fit such a line. The friction factor K_b of annulus pellet plugs is 0,1495 from the slope of the line in Figure 5.1. The plot seen in Figure 5.1 is similar to the plot made by Towler and Ehlers (1997) in Figure 2.9 and by Towler et al. (2008) in Figure 2.13.

In Figure 5.2 the actual measurements on annulus pellet plugs have been re-plotted together with estimated pressures from Equation 2.1, using the friction factor K_b of 0,1495, which assume that the pressures increase with the square of the plug length. In addition to the estimated pressures using Equation 4.2 and the average shear strength τ of 1,02 kPa found for annulus pellet plugs, which assume a linear relationship between pressure and length of plug. The pressures were estimated for plug lengths up to 200cm while the longest plug measured in the experiments here had a length of 89cm.

$$\tau = \frac{P \cdot (D_o - D_i)}{4 \cdot H} \rightarrow P = \frac{\tau \cdot 4 \cdot H}{(D_o - D_i)} \qquad \text{(Eq. 4.2)}$$

From Figure 5.2 it is clearly seen that the estimated green line from Equation 4.2 represents the measured values of annulus pellet plugs best. And by continuing the trend up to 200cm the green line also seems to be most plausible. At a plug length of 200cm the linear model (Eq. 4.2) estimates a pressure of 206 kPa while the quadratic model (Eq. 2.1) estimates a pressure of 453 kPa. At a plug length of 10m Eq. 4.2 estimates 10,3 bar while Eq. 2.1 estimates 113,3 bar.

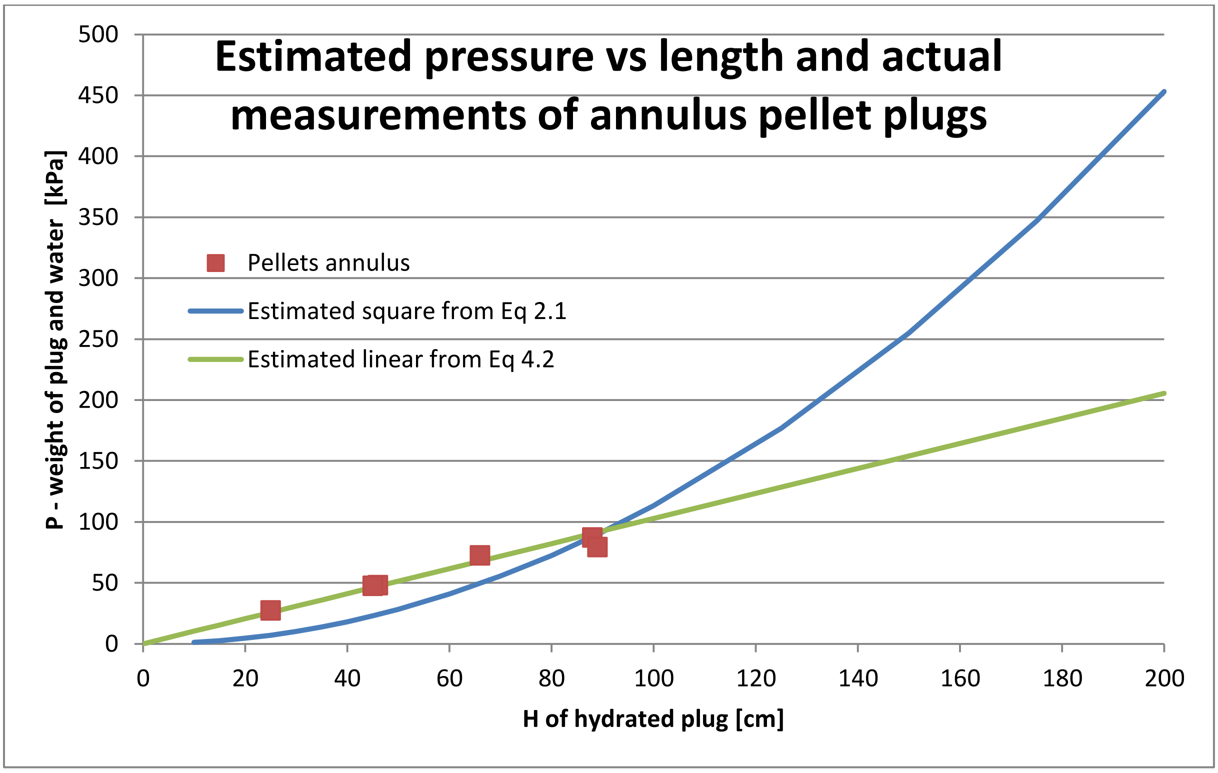


Figure 5.2: Estimated pressures against length of plugs for annulus pellet plugs, actual measurements included.

By plotting the same as in Figure 5.2 for pellets fullbore plugs, powder annulus plugs and powder fullbore plugs the same effect is seen. The results from the experiments conducted here indicate a linear relationship between plug length and pressure according to Eq. 4.2. This is also seen in Figure 4.2, Figure 4.4, Figure 4.11 and Figure 4.13. If the pressure was to increase more than linearly with the length of the plug the average shear strengths in Figure 4.3, Figure 4.5, Figure 4.12 and Figure 4.14 should increase with the length of the plug. But instead they are all almost horizontal or slightly decreasing with increasing plug length.

5.3 Shear strength of plugs, discussion and comparison of results

For pellets plugs the average strength τ was found to be 1,33 kPa for fullbore plugs and 1,02 kPa for annulus plugs. For plugs prepared by powdered bentonite the average strength τ was found to be 1,40 kPa for fullbore plugs and 0,89 kPa for annulus plugs. With these shear strengths and the assumption of linear increase of pressure with plug length the following equation can be used to calculate the total pressure a plug of a given length can withheld:

$$P = \frac{\tau \cdot 4 \cdot H}{(D_o - D_i)} + \rho_b \cdot g \cdot TVD \qquad \text{(Eq. 5.1)}$$

Where P is the pressure, τ is the average shear strength, H is the length of the plug, D_o is the (inner) diameter of the outer plastic pipe, D_i is the (outer) diameter of the inner plastic pipe, ρ_b is the density of the hydrated plug, g is the constant of gravity and TVD is the true vertical length of the plug. If equation 5.1 is used for fullbore plugs, D_i becomes zero and the equation is still valid.

In Figure 5.3 Equation 5.1 has been used to plot failure pressure versus plug length for pellets plugs up to 100m long. This is valid for pellets plug in a plastic pipe with an inner diameter of 8,97cm, and for the annular case the outside diameter of the inner plastic pipe is 5,00cm. The pressures seen in Figure 5.3 will probably be a few factors higher in a real well with similar dimension, due to the surface of steel casings being much rougher and having a higher friction than the plastic pipes used here. But the main findings of pressure varying linear with the length of the plug will still be true.

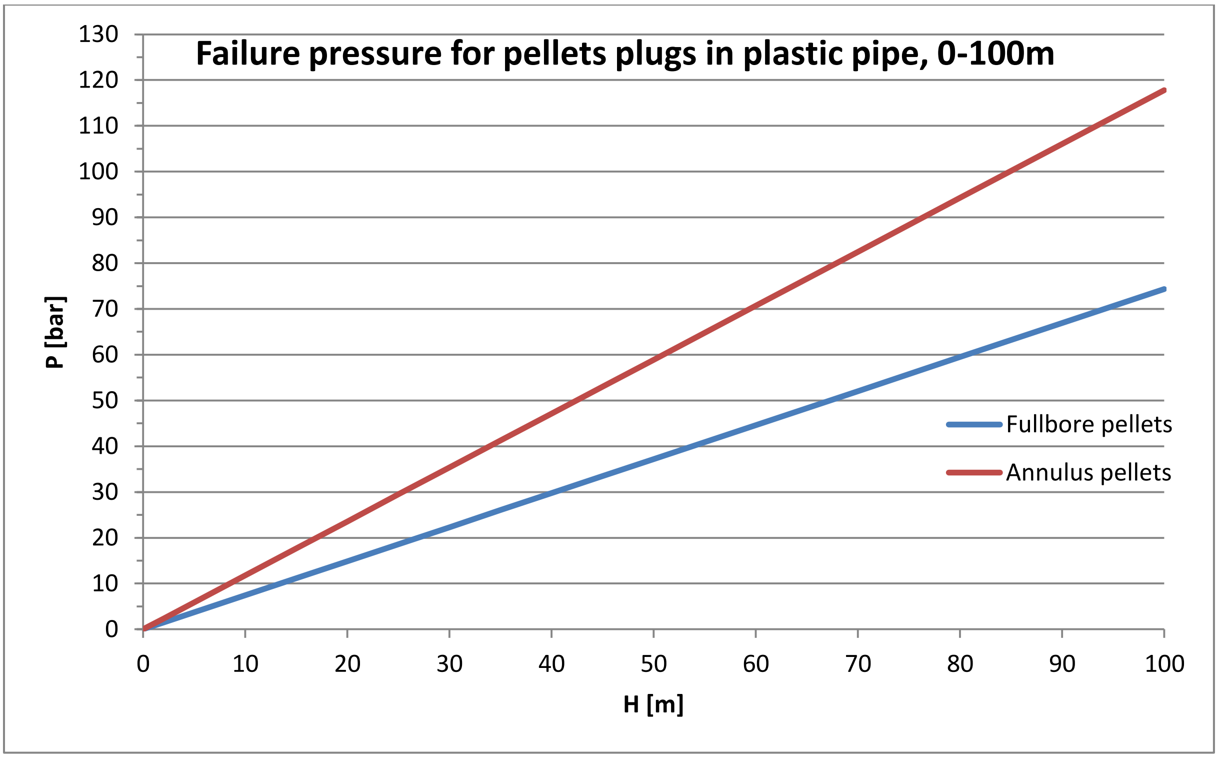


Figure 5.3: Failure pressure for pellets plugs in plastic pipe, 0-100m, using equation 5.1

Even though the shear strength found for annulus pellets plugs (1,02 kPa) is lower than for fullbore plugs (1,33 kPa), an annulus plug of identical height as a fullbore plug can withstand a pressure 58,5% higher than the fullbore plug (this can be seen in Figure 5.3). This is due to the increased wall surface area for friction and the decreased area for pressure to displace the plug in the annular case. For plugs made of powdered bentonite (shear strength of 0,89 kPa for annulus plugs and 1,40 kPa for fullbore plugs) an annulus plug can take a pressure 37,2% higher than a fullbore plug with identical height.

In an e-mail from Sandaband they reported the strength of sandaband plugs to be determined by the weight of the plug, in addition to a yield point multiplied with the length of the plug. The yield point was reported as 2,8/(D_o-D_i) [psi/ft] where D_o-D_i is given in inches, for a plug in a 4" tubing the yield point becomes 2,8/4 = 0,7 psi/ft. Which means that a sandaband fullbore plug with a length of 1 foot in a 4" tubing can take a pressure of 0,7 psi before failure, in addition to the weight of the plug.

By converting to SI units the yield point reported for sandaband equals a shear strength τ of 0,402 kPa. This can now be compared with the shear strength found here between bentonite pellets plugs and plastic pipe of 1,33 kPa for fullbore plugs and 1,02 kPa for annulus plugs. According to the experiments done here, a plug made of bentonite pellets can withstand a pressure about 3 times as high in a plastic pipe as a sandaband plug in a steel tubing, not including the effect of the density of the material. But the sandaband plug get extra help from the higher density of 2,15 g/cm^3 compared to the density of 1,533 g/cm^3 found for hydrated pellet plugs. For a 100m TVD plug the effect of density equals 21,1 bar for the sandaband plug and 15,0 bar for the pellet plug. A 100m long fullbore sandaband plug would seal a pressure of 39 bar including weight of material, compared to 74,3 bar for a fullbore bentonite plug as seen in Figure 5.3.

In tests by Ogden and Ruff (1992) the shear strength of 4 different bentonite chip/pellets products was found to be varying from 3,4-27,3 kPa. Where the 10,19 cm ID outer steel pipe used was roughened to simulate borehole roughness by machining 3,1mm deep grooves spaced at 9,3mm along the length of the test pipe. Two different casings of 2,67cm and 4,83cm outer diameter were installed in the 10,19cm ID steel pipe to create annulus plugs. The much higher shear strengths found by Ogden and Ruff compared to the values of 0,89-1,40 kPa found in the experiments done here can be explained by the increased roughness in the steel pipe they used compared to the plastic pipe used here.

They also concluded that the shear strength was independent of plug length, i.e. the pressure increase linearly with the plug length. It was also seen that when moving from annulus plugs made with the smaller inner casing of 2,67cm OD to the larger inner casing of 4,83cm OD the shear strength decreased. Which is in agreement with the reduction in shear strength from 1,33 kPa to 1,02 kPa when moving from fullbore pellet plugs to annulus plugs found here.

By calculating the shear strength of the plugs in Figure 2.12 tested by Towler et al. (2008) where fullbore bentonite plugs were tested in a 6 ¼" ID steel pipe the shear strengths varies from 9,5-17,2 kPa. This is in the same range of shear strengths found by Ogden and Ruff, but much higher than the shear strengths found in the experiments conducted here. Again the explanation can be the roughness of the surface of the 6 ¼" ID steel pipe compared to the smooth surface of the plastic pipe used here.

5.4 Failure mechanism of the plugs

All plugs made of bentonite pellets failed in shear failure by moving upwards in the test pipe as a solid cylinder, with no channeling or vertical cracks at failure. This can be seen from the pictures in Appendix A-1 where pellet plugs are pictured before hydration, after hydration and at failure. This indicates that the plugs made of bentonite pellets are sufficiently hydrated after 48 hours to not have any weak spots or channels for pressure to escape. And by looking at the hydration of a single pellet from 0-70 hours in Figure 3.6, most of the expansion is completed after 48 hours. In the tests done by Ogden and Ruff (1992) all four bentonite products experienced channeling up to 24 hours of hydration time, but at 72 hours of hydration only one of the four products failed by channeling (see Figure 2.15).

For plugs made of powdered bentonite, all plugs except plug 3fpwd failed by shear failure. This can be seen in Appendix A-2 where plugs made of powdered bentonite are pictured before hydration, after hydration and at failure. This cannot be explained by the hydration time of 48 hours or more, which should be enough to fully hydrate powdered bentonite. However, the procedure for creating powdered bentonite plugs resulted in less control of the homogeneity of the plugs compared to plugs created by bentonite pellets. For plug 3fpwd, a weak point must have been located near the base of the plug which led to vertical channeling and cracks at failure.

5.5 Placing of bentonite

In the experiments conducted here bentonite pellets performed better than powdered bentonite in regards to placement and creating a homogenous plug. Bentonite pellets could be poured at a very quick rate both for fullbore and annulus plugs without bridging or sticking, and in all tests the pellets fell nicely through the water column to the bottom of the test pipe creating a homogeneous plug. The powdered bentonite needed to be poured more careful and at a much slower rate, if poured too fast the powdered bentonite started clogging up and sticking together, which created larger particles and led to voids and a more inhomogeneous plug. The usage of powdered bentonite would be unsuitable for field cases due to early hydration, bridging, sticking and the low density.

As seen in the literature study, bentonite have been used to create plugs in many oil and gas wells, but for all cases this have been in onshore wells. Englehardt et al. (2001) reports from a field case where 19 wells were permanently plugged and abandoned using bentonite nodules, the nodules were surface poured with great success and the deepest well had a length of 1040m TVD. Clark and Salsbury (2003) reports from a field test in Australia after more than 500 wells have been abandoned across USA using bentonite nodules (marketed as Zonite). The Australian well had a TVD of 850m and bentonite nodules were surface poured to create a 220foot long plug.

5.6 Combining bentonite with sand plug

Studies done on soil plugs in pipe piles by Randolph et al. (1991), Murff et al. (1990) and Randolph et al. (1992) have shown that relatively short plugs of soil can take very high loads due to arching of forces and “lock-up” of the plug inside the pile. The strength of a soil plug under drained conditions (no increase of pore pressure in the plug during loading) can be estimated from equation 2.4 proposed by Randolph et al. (1991).

$$q_b = \left(e^{\frac{4\beta h}{D}} - 1\right)\frac{D\gamma'}{4\beta} - \gamma' h \qquad \text{(Eq. 2.4)}$$

The exponential term in Equation 2.4 leads to a rapid increase in the end bearing capacity q_b of the plug with increasing height to diameter ratio.

A soil/sand plug which Equation 2.4 applies for is permeable and cannot be used to seal off a wellbore by itself, pressured fluids would simply flow through the soil/sand plug. By combining the high strength of a sand plug with the sealing properties of a plug made of hydrated bentonite, the resulting plug would be impermeable to flow due to the bentonite and able to withstand large forces due to the sand plug. This could be achieved by placing a sand plug on top of a plug made of bentonite. The length of the bentonite part would only need to be long enough to ensure that the plug is impermeable to flow, while the sand plug on top would contribute most of the total pressure capacity and resist movement of the bentonite plug, see Figure 5.4 for an example plug.

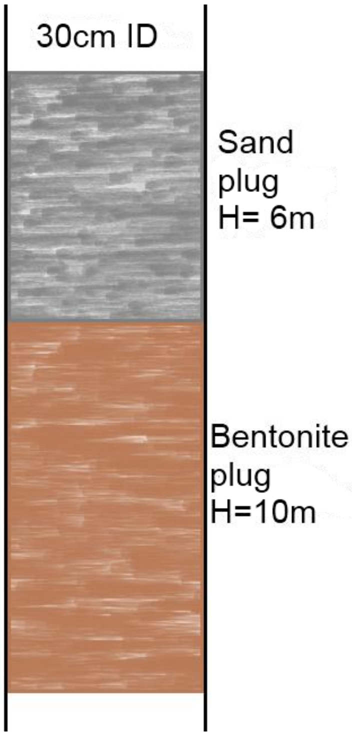


Figure 5.4: Example of a sand plug on top of a bentonite plug

By using typical parameters for a sand, with an effective self-weight γ' of 11 kN/m^3 and a conservative lower estimate for β of 0,15, Eq. 2.4 gives the graph in Figure 5.5 of pressure it can withstand versus height of sand plug in a 30cm ID casing. At a height of only 6m (H/D ratio of 20) the theoretical strength of the sand plug is 8950 bar.

For the example in Figure 5.4, the strength of the 10m bentonite part of the plug would be 3,27 bar from Equation 5.1, using the shear strength of 1,33 kPa found in the experiments here. While the theoretical strength of the sand plug would be 8950 bar from Equation 2.4.

To avoid the bentonite plug getting squeezed through the permeable sand plug, the bottom of the sand plug could have a transition zone from small grain size to larger grain size.

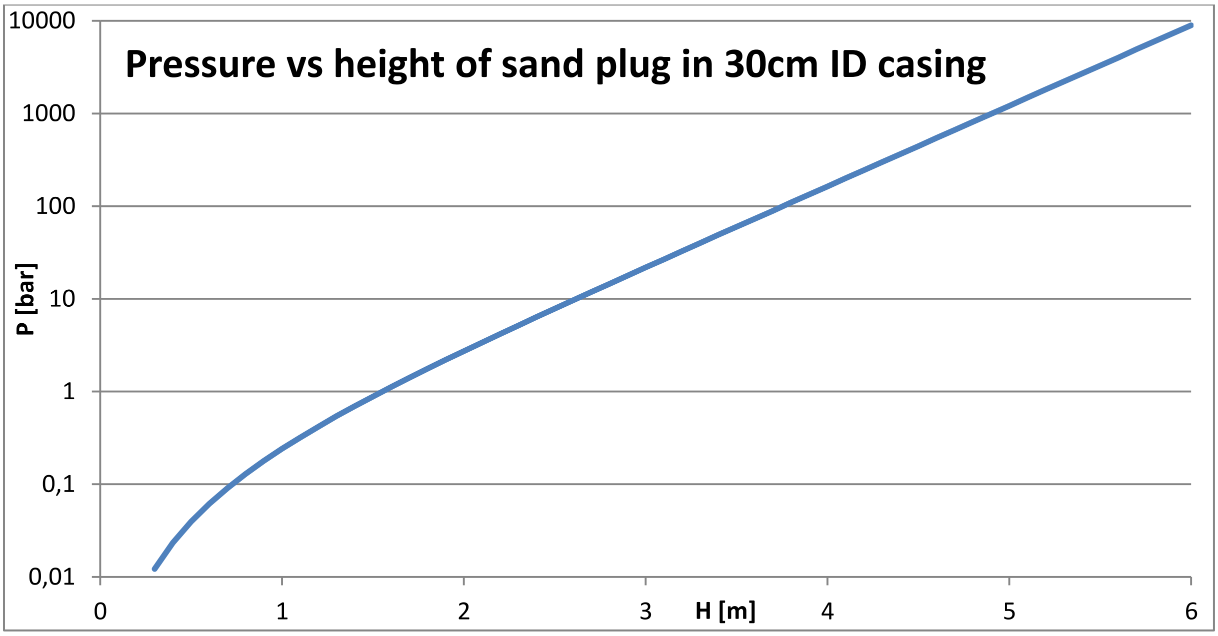


Figure 5.5: Pressure versus height of sand plug in a 30cm ID casing, from equation 2.4

5.7 Evaluation of bentonite

All the plugs made in this experiment created a hydraulically solid plug, both for annulus and fullbore plugs. The pressure needed to dislodge the plugs varied from 20kPa to 101kPa with plug lengths from 23cm to 91cm.

The required properties of a well barrier according to NORSOK D-010 are the following:

- Impermeable
- Long term integrity
- Non shrinking
- Non brittle
- Ductile, able to withstand mechanical loads
- Resistance to substances like H_2S, CO_2 and hydrocarbons
- Wetting, to ensure bonding to steel

From the experiments conducted here and the reviewed literature, a plug made of hydrated bentonite fulfills all the required properties. Englehardt et al. (2001) and Clark and Salsbury (2003) reports the permeability of hydrated bentonite to 0,001-0,0001 mD, while cement has a permeability of 0,1-0,001 mD. Englehardt et al. (2001) mentions that bentonite has been identified as an excellent sealing material for high-level nuclear waste deposits due to its ability to confine groundwater movement and resist alteration with time. Englehardt et al. (2001) reports that a 100 foot bentonite plug was tested to 1500 psi, and long term stability was verified over a 9 month period. In the same study, bentonite submerged in saturated H_2S water hydrated to 70% of what was seen in freshwater.

Hydrated bentonite is also non-shrinking, non-brittle and ductile because bentonite swell and expand during hydration and creates a plastic mass. This leads to a flexible plug which can heal and reshape itself if the surrounding environment changes. This is a major advantage compared to cement which has the tendency to shrink while setting, and during subsurface movements can crack and loose the integrity.

Wetting and bonding to steel have been confirmed for hydrated bentonite by experiments done by Ogden and Ruff (1992), Towler and Ehlers (1997) and Towler et al. (2008).

For plug and abandonment of onshore wells where bentonite was poured/gravity fed into the well, Englehardt et al. (2001) report cost savings compared to cement of 20-40%, due to no need for pump trucks, coiled tubing and bulk units. While Clark and Salsbury (2003) estimate cost savings of 50% (see Figure 2.21). But bentonite in nodules/pellets form is not pumpable in the same form as sandaband and cement are, this is a disadvantage for offshore application since a smaller coiled tubing vessel cannot be used to deliver bentonite nodules/pellets into a well.

In Figure 5.6 the plug heights needed to achieve a plug capacity of 200 bar (2900 psi) in a 5 ½” casing (12,73cm ID) are shown for the studied materials. For sandaband the shear strength of 0,402 kPa and density of 2,15 g/cm^3 were used. For bentonite in plastic pipe the shear strength found here for fullbore bentonite pellets plug of 1,33 kPa and density of 1,533 g/cm^3 were used. For bentonite in steel casing the shear strength was estimated by multiplying the shear strength found in plastic pipe with a factor of 5 to give a shear strength of 6,65 kPa, this was done to adjust for the increased roughness in steel casing compared to plastic pipes (Ogden and Ruff (1992) have reported shear strength of 3,4-27,3 kPa for bentonite in steel while measurements by Towler et al. (2008) indicates 9,5-17,2 kPa). For a combination of a sand plug and a 10m bentonite plug a 2m long (H/D ratio of 15,7) sand plug in a 12,73 cm ID casing was found to have a theoretical capacity of 200 bar using the same procedure as in Figure 5.5.

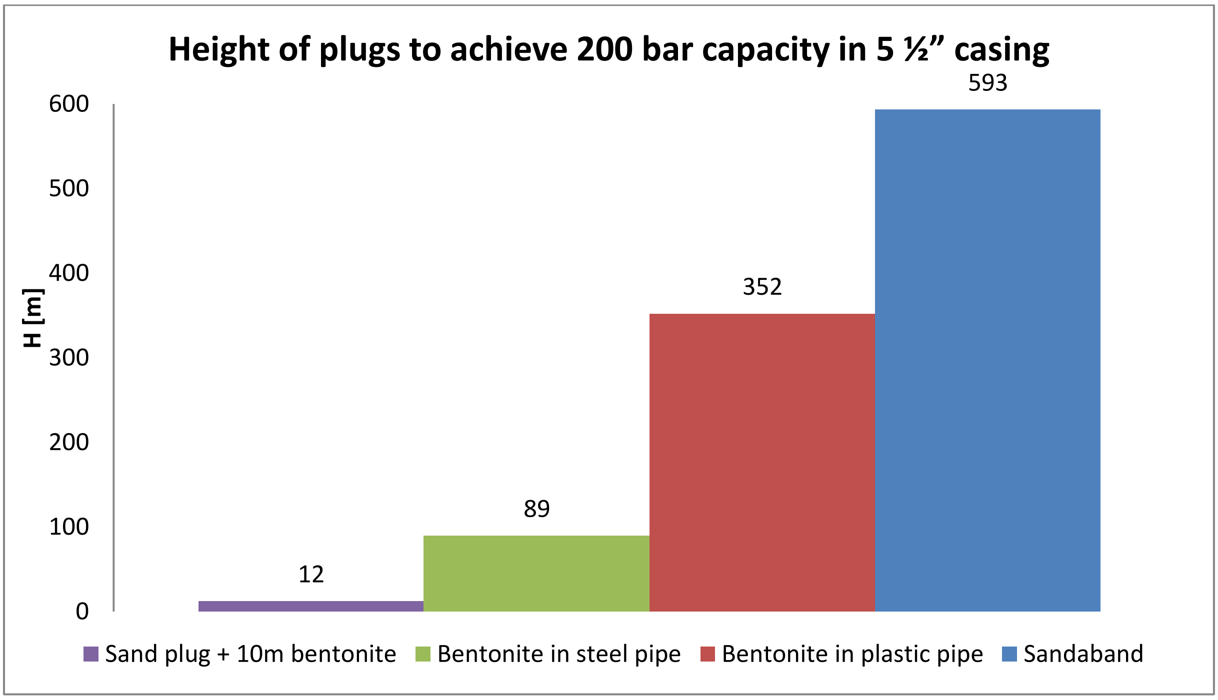


Figure 5.6: Height of plugs to achieve 200 bar capacity in a 5 ½" casing.

5.8 Methods and limitations

The shear strengths measured here are for plastic pipes, and not for steel tubulars as found in oil and gas wells. The absolute value of the shear strengths between a bentonite plug and a steel pipe will be higher than the values found here due to increased roughness. But the main findings of pressure varying linearly with plug length will still be true.

In some of the experiments dry powdered bentonite was used to create plugs, this was possible since the bentonite only had to sink through a maximum of 1m of water before reaching the settling depth. The plugs created by powdered bentonite ended up being less homogenous and repeatable than the plugs created by bentonite pellets. This can be seen from the test data on plugs made of powdered bentonite, which shows more scatter than the results from plugs made of bentonite pellets. But the overall trend of pressure increasing linearly with plug length are seen for both powder and pellet plugs.

The pressure readings at failure have some uncertainties connected, in a few cases the plug failed while the pressure was still increasing after a small turn on the regulator. In these cases it was important to pay close attention to the pressure sensors.

On some of the shorter plugs tested the pressure did not act on the full cross section area of the bottom of the plug when it failed (see example in Figure 4.10), which resulted in an overestimation of the plug capacity. For this reason data from plug 6fpwd was not used in calculations. This problem was not encountered on longer plug lengths, where often the bottom of the plug could be seen to be compressed upwards a few millimeters before the pressure was further increased and the plug failed. This problem on shorter plug lengths could have been avoided by distributing the injected air pressure at the bottom of the plug over a larger area, instead of using a single ¼” injection hole as done here.

There were some uncertainties when measuring the height of the hydrated plugs, since the top of the hydrated plug consisted of a transition zone from the plastic mass of the plug to a more slurry state at the top. This can be seen in the pictures of plug 1apellets in Appendix A-1, where the height of the water above the pellets is 8cm before hydration. While after hydration the height of the free water is about 2cm, followed by 4cm of bentonite in a slurry state which do not contribute to the friction of the plug. The final height of the hydrated plug was then measured up to the point where the slurry started, for the pellet plugs this was in the range of 2-4 cm above the height of the pellets before hydration. For plugs made of bentonite powder the uncertainty in the height of the hydrated plug was less since the top of the plugs did not expand upwards from the height before hydration, this can be seen in Appendix A-2.

5.9 Further work

Bentonite plugs should be made in a steel pipe with more roughness than the plastic pipe used here to find the shear strength between hydrated bentonite and steel.

How to accurately place the bentonite without bridging/clogging and avoiding early hydration should be investigated. If necessarily, compressed bentonite (pellets/nodules/granulates) could be coated with a suitable retarder to delay the hydration process for application in deeper wells. Investigate methods for placement of bentonite and sand downhole in offshore wells.

Studies and experiments should be carried out on combining a bentonite plug with a sand plug located on top. Tests should be carried out to make sure that the bentonite will not be pushed through the sand plug and cause leakage.

6 Conclusion

- All the plugs made in this experiment created a hydraulically solid plug, both for annulus and fullbore plugs. The pressure needed to dislodge the plugs varied from 20kPa to 101kPa with plug lengths from 23cm to 91cm.
- The pressure was found to increase linearly with the length of the plug for both fullbore plugs and annulus plugs, whether bentonite pellets or dry powdered bentonite were used to create the plugs. This leads to the shear strength τ being independent of plug length.
- The shear strength between the hydrated plugs made of bentonite pellets and the plastic pipe was found to be 1,33 kPa for fullbore plugs, while the shear strength between the hydrated bentonite pellets plug and the inner and outer plastic pipe was 1,02 kPa for annulus plugs. For plugs prepared by powdered bentonite the shear strength was found to be 1,40 kPa for fullbore plugs and 0,89 kPa for annulus plugs.
- The shear strength τ was found to decrease when moving from fullbore plugs to annulus plugs. But the increased surface area available for friction in the annular case leads to a higher total plug capacity for annulus plugs. Annulus plugs made of bentonite pellets were found to take 58,5% more pressure than fullbore plugs with identical height. For plugs made of powdered bentonite, annulus plugs were found to take 37,2% more pressure than fullbore plugs.
- The density of the hydrated bentonite pellets plugs was found to be 1,533 g/cm^3. The expansion of fullbore pellets plugs from dry volume of pellets to hydrated plug was 92%-120%, while the expansion of annulus plugs was 108%-120%. The dry density of the pellets before hydration was measured to 2,025 g/cm^3.
- The density of plugs made of powdered bentonite was found to be 1,102 g/cm^3. The expansion of fullbore plugs from dry volume of powdered bentonite to hydrated plug was 283-315%, while the expansion of annulus plugs was 324-332%. The dry density of the powdered bentonite before hydration was measured to 1,09 g/cm^3.
- Theory and experiments from soil plugs in driven piles predict that a relatively short sand plug can resist very large forces. By placing a suitable sand plug on top of a bentonite plug, the result could be a short total plug length which is impermeable due to bentonite and can resist large forces due to the sand plug.

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Appendix A

Appendix A-1 Pellets plugs

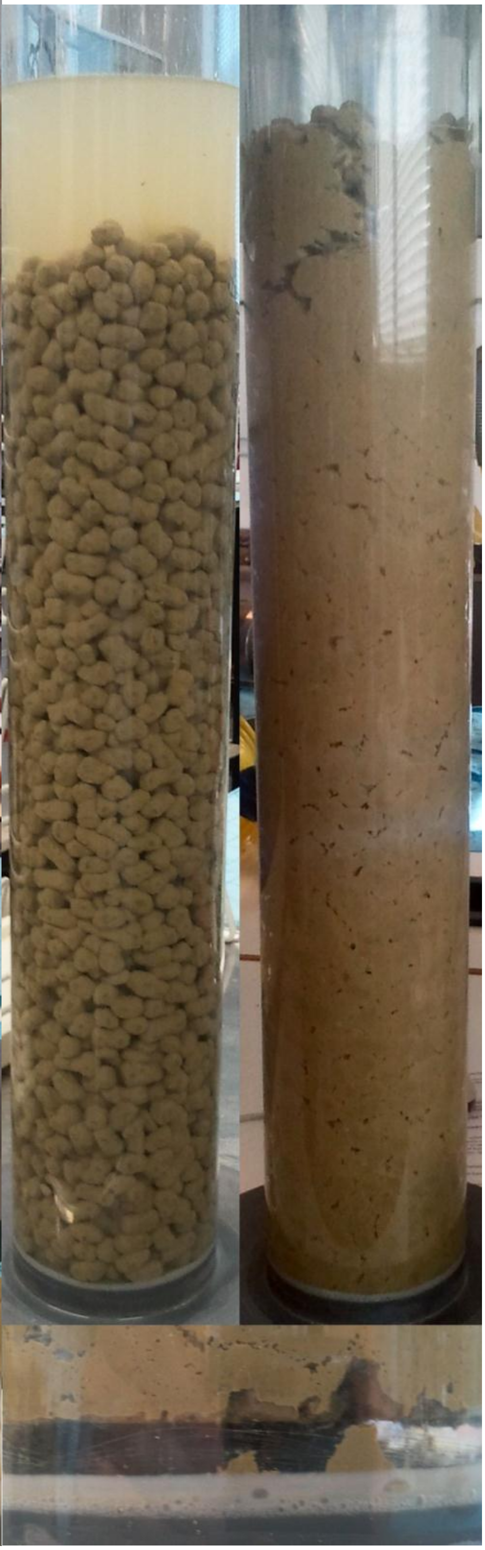
Picture of pellet plugs before, after hydration and at failure is included here.

Left: Plug 1fpellets

Right: Plug 2fpellets

Plug 3fpellets

Plug 4fpellets



Plug 5fpellets

Plug 6fpellets

Plug 7fpellets

Plug 8fpellets

Plug 9fpellets

Plug 1apellets

Plug 3apellets

Plug 4apellets

Plug 5apellets

Plug 6apellets

Appendix A-2 Powder plugs

Picture of plugs made of powdered bentonite before, after hydration, and at failure is included here.

Plug 2fpwd

Plug 3fpwd

Plug 4fpwd

Plug 5fpwd

Plug 7fpwd

Plug 6fpwd

Plug 2apwd

Plug 3apwd

Plug 5apwd

Plug 1apwd

Plug 4apwd