FACULTY OF SCIENCE AND TECHNOLOGY

MASTER'S THESIS

Study program/specialization: **Petroleum Engineering / Drilling Technology**	Spring semester, 2023 Open
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Title of Master's thesis:

Plug and Abandonment Technologies evaluation and Experimental material testing.

Credits (ECTS): 30

Keywords:

NORSOK
Portland Cement
SiO2
Rheology
Leakage test
M-modulus
UCS
Cut and pull
Section milling
PWC
Water absorption

Number of pages: 139

Supplemental material/other: 10 (Appendix)

Stavanger, 15.06.2023

Acknowledgements

I would like to extend my deepest appreciation to my supervisor, Mesfin Belayneh Agonafir, for his invaluable time, support, guidance, and feedback throughout this thesis. His expertise and knowledge have been instrumental in shaping the direction and quality of my work.

I am deeply grateful to my wife for her unwavering love, understanding, and support throughout this journey. Her encouragement, patience, and sacrifices have been the foundation of my success. I am truly grateful for being my source of strength.

I would also like to extend my heartfelt appreciation to my family for their unconditional love and support. I am fortunate to have such a loving and supportive family who have always been there for me.

Additionally, I am grateful to my friends for their friendship, encouragement, and understanding. Their presence in my life has provided a sense of camaraderie and support that has been instrumental in overcoming challenges and staying motivated.

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Abstract

The conventional method to plug and abandonment (P&A) is characterized by its time-consuming nature, high costs, and associated challenges and risks related to Health, Safety, and Environment (HSE) considerations. In recent years, there has been a growing focus on P&A operations to enhance efficiency and reduce costs. Furthermore, cement plays a critical role in the P&A process, and any failures in its performance can result in various issues such as loss of zonal isolation, loss of wellbore integrity, and potential leakage.

This thesis examines the performance and challenges associated with conventional plug and abandonment (P&A) technologies, including cut and pull, section milling, and perforate, wash, and cement (PWC). Case studies are presented to assess the P & A technologies. Moreover, new alternative technologies, solutions, and tools that aim to improve P&A operations are reviewed. This thesis also experimentally investigated the impact of using nano-SiO_2 in G-class cement with a 0.44 water-to-cement ratio (WCR).

The findings from field trials and laboratory research indicate that alternative technologies, solutions, and tools have demonstrated promising improvements in performance and effectiveness. However, it is necessary to conduct further research and establish performance guidelines before implementing these alternatives. Based on the considered case study, PWC demonstrated significant time savings, with a 65% reduction in operational time compared to section milling and a 70% reduction compared to cut and pull operations. Moreover, the addition of an optimal dosage of 0.242 wt. % SiO2 (by weight of cement) resulted in a significant increase in the uniaxial compressive strength (UCS) of neat cement. After 3 days and 28 days of curing at atmospheric pressure and temperature, the UCS improved by 39.53% and 24.88%, respectively. Additionally, the optimal SiO_2 reduced the water absorption of the neat cement, by 15.00% after 3 days and 20.14% after 28 days cured at 105^{o}C and atmospheric pressure.

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A= Cross-sectional area, mm^2

F_{max} = Max load applied before failure, N

G = Shear modulus, GPa

K = Bulk modulus, GPa

M = P-wave-modulus, GPa

M_w = Mass wet (after submersion in water), g

M_d = Mass dry (before submersion in water), g

ΔM = Change in mass, %

V_p = Compressional wave velocity, m/s

ρ = Density of the given cement plug, kg/m3

σ = Uniaxial compressive strength, MPa

τ = Shear stress, lbf/100ft2

τc= Casson yield stress, lbf/100ft2

μc= Casson plastic viscosity, lbfs/100ft2

List of abbreviations

API = The American Petroleum Institute
ASV = Annular Safety Valve
BOP= Blowout preventer
BHA= Bottom hole assembly
CBL = Cement Bond Log
DAQ = Data Acquisition Software
DOS=Downhole Optimization Sub
DEA= Danish Energy Agency
EOR = Enhanced Oil Recovery
FIT= Formation Integrity Test
HSE =The health and safety executive
ID = Inner Diameter
LOT = Leak Off Test
MPE= The Ministry of Petroleum and Energy
NCS = Norwegian Continental Shelf
NPD = Norwegian Petroleum directorate
NP = Nanoparticle(s)
OPC = Ordinary Portland Cement
OD = Outer Diameter
PSA = Petroleum Safety Authority
PV = Plastic Viscosity
P&A = Plug and Abandonment
PWC=perforate, wash and cement
PIT =Pressure Integrity Test
RPM = Rotations Per Minute
SCP = Sustained Casing Pressure
TOC=Top of Cement
UCS = Uniaxial Compressive Strength
USIT =Ultrasonic Image tool
WCR = Water to Cement Ratio
WOC = Wait on Cement
wt% = Weight percent
XLOT =Extended Leak-off Test
%bwoc = Percent by weight of cement

1. Introduction

This MSc thesis provides a comprehensive overview of plugging and abandonment (P&A) operations in the oil and gas industry. The study begins by examining the regulations and standards according to NORSOK D-010 that apply to P&A operations on the Norwegian Continental Shelf (NCS), as well as the properties of cement and alternative materials used in P&A activities. It also evaluates the conventional P&A technologies based on real-world case studies.

The thesis then focuses on experimental studies that investigate the impact of nanoparticle silica on 0.44 conventional G-class cement. The mechanical, and rheological properties of cement are characterized by destructive and non-destructive tests. The research aims to provide insights into the potential of Silica-nanoparticles to improve the performance and reliability of cement plugs used in P&A operations.

1.1 Background and Motivation

The Norwegian Oil and Gas Association has provided a "conservative estimate" for the total cost of plugging and abandonment in Norway. They estimate that the cost of permanently plugging 3,000 wells using a drilling rig, at an average of 35 rig days per well, would be around 420 billion NOK, assuming rig-day rates of 4 million NOK. If this plugging process takes place over 20 years, the total cost for P&A for the next 40 years could be close to 900 billion NOK. However, this estimate is based on 2013 rig rates, which are higher than current rates.[1]

Reducing the total cost of permanent good plugging is critical in Norway because 78% of the expenses for P&A operations represent tax deductions for operators and partners. The high cost of P&A operations reduces the income for the Norwegian state from petroleum activities. The P&A challenge is a cross-disciplinary problem that requires addressing both technical and economic aspects.[1]

The utilization of conventional plug and abandonment (P&A) approaches today comes with various challenges that require attention and resolution. These challenges include high costs and time-consuming processes. One way to address the cost issue is by reducing the time-consumption associated with P&A operations. To achieve economic sustainability, operating companies must invest in targeted research and development, introducing alternative new technologies, procedures, tools, and solutions. Through these advancements, the improvement of P&A operations can effectively reduce costs.

In addition, cement is also a critical component in the plug and abandonment (P&A) of oil and gas wells. P&A activities involve permanently sealing the wellbore to prevent any potential leaks of oil, gas, or other fluids that could impact the environment or pose a risk to human health and safety. Cement is used to create a series of cement plugs that are placed at various depths within the wellbore. These plugs are designed to permanently seal off the wellbore and prevent any fluids or gases from migrating up the wellbore and escaping into the environment. The number and location of the cement plugs are determined by the specific regulatory requirements and the characteristics of the well.

According to NORSOK D-010 well integrity is defined as the "*Application of technical, operational and organizational solutions to reduce risk of uncontrolled formation fluids throughout the lifecycle of a well.*" [2] in addition in NORSOK D-010, the Regulatory guidelines require that cement used in oil and gas wells meet specific criteria. These criteria include [2]:

- Low permeability
- Long-term integrity
- Resistance to corrosions (CO_2, H_2S), etc.
- Mechanical properties to resist down-hole pressure and temperature
- Non-shrinking and able to bond to the formation and casings of metal steel
- Positioning

Moreover, multiple studies have indicated that failures in the cement used in oil and gas wells are among the most common reasons for reduced well integrity. In other words, cement failures are a significant factor that can lead to the degradation of the well's structural integrity, potentially causing issues such as fluid migration.

In the "pilot well integrity survey" conducted by the Petroleum Safety Authority Norway (PSA) based on supervisory audits from 406 wells on the Norwegian Continental Shelf. The survey included a representative selection of production and injection wells variation in age and development categories. The results of the survey indicate that 18% (75 of 406 wells) of the wells in the survey have integrity failures, issues, or uncertainties.[3]

Figure 1.1 illustrates that most of the integrity problems are within barrier elements such as tubing (38%), annulus safety valves (ASVs) (12%), casing (11%), and cement (11%) Specifically, problems with ASVs included leakage or failure, while casing problems included leakage or non-gastight connections and collapsed casing. According to the survey, various problems related to cement were identified in the context being discussed. These issues included the absence of cement behind the casing and above the production packer, as well as the likelihood of leaks occurring along cement bonds or through the cement micro-annulus. These problems accounted for approximately 11% of all the integrity issues identified in the survey. In summary, the survey highlighted specific concerns regarding the integrity of cement in the mentioned areas and indicated the occurrence of leaks in these locations.[3]

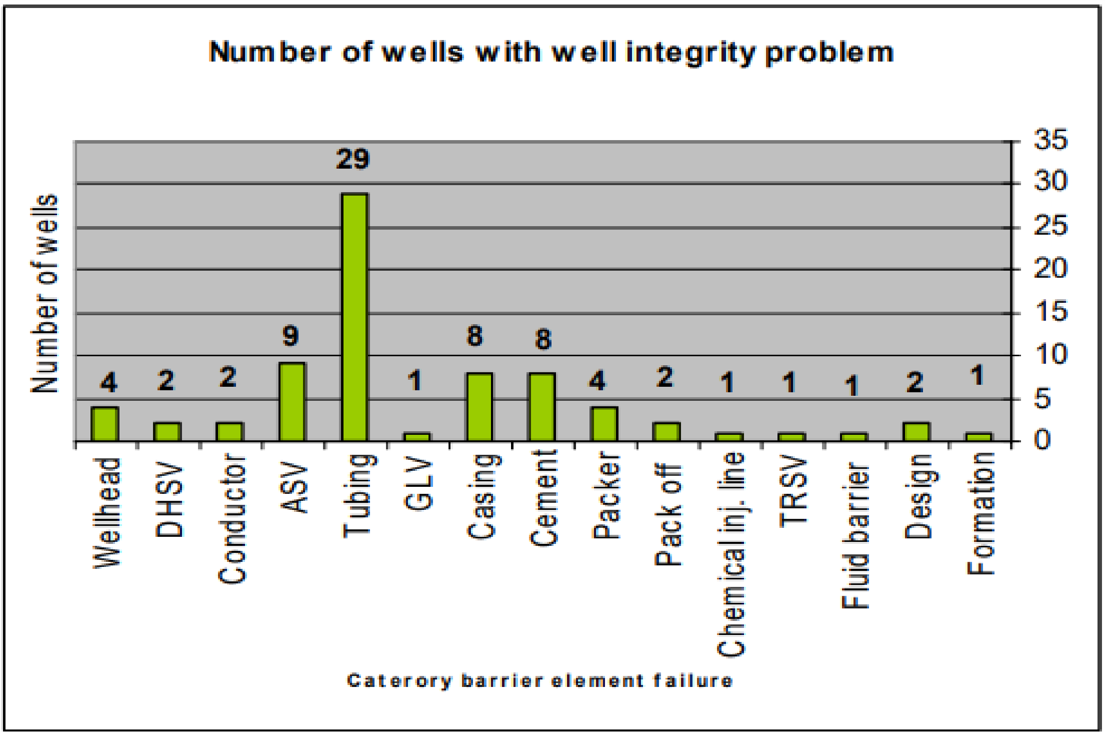


Figure 1.1: Number of wells with integrity failure, issues or uncertainty, and category of barrier element failure.[3]

When cement fails to perform as intended, it can lead to a wide range of problems, including poor zonal isolation, loss of wellbore integrity, and ultimately, leakage. These problems not only cause financial losses but also pose significant safety and environmental risks. As a result, there is an urgent need to address cement-related issues and find effective alternative solutions to prevent future failures. Exploring alternative materials such as geopolymers, creep shale, bismuth alloy, and thermite resin offers potential solutions to mitigate cement-related issues, improve wellbore integrity, and prevent failures.

1.2 Problem Formulation

Plug and Abandonment (P&A) operations in oil and gas wells are critical to ensure environmental and safety compliance. The conventional approach for plug and abandonment (P&A) is known for being a time-consuming and expensive process and is accompanied by various risks and challenges that involve Health, Safety, and Environment (HSE) considerations.

Currently, cement is the conventional material used for P&A operations, but the current cement materials do not meet all the criteria defined by the NORSOK D-010 standard, (the issues raised in section 1.1). Therefore, it is essential to improve the material properties of cement to address this issue and improve the reliability and effectiveness of plugging and abandonment (P&A) operations. Additionally, alternative P&A materials are being researched, including the use of Sio_2 nanoparticles in cement. The research issues to be addressed are:

- The conventional plugging material and the current P&A technologies in the North Sea
- The performance and effectivity of the current P&A technologies
- The alternative P&A materials and technologies under research and development
- The impact of nanoparticles on the properties of neat G-class cement

1.3 Scope and Objective

The main objective of this thesis is to evaluate the research issues addressed in section 1.2. The work comprises of literature study on the conventional and alternative plug and abandonment technologies and materials. Field case studies of the P & A and their comparison in terms of their effectivity along with operational time. The second part deals with an experimental study. The effect of silica nanoparticles on the 0.44 G-class Portland cement. The characterization of the cement plug and slurry was through the destructive method (Uniaxial compressive strength, UCS) and the non-destructive method (Sonic, Water absorption, leakage, and viscosity). Figure 1.2 shows the summary of the research methods applied in this thesis work.

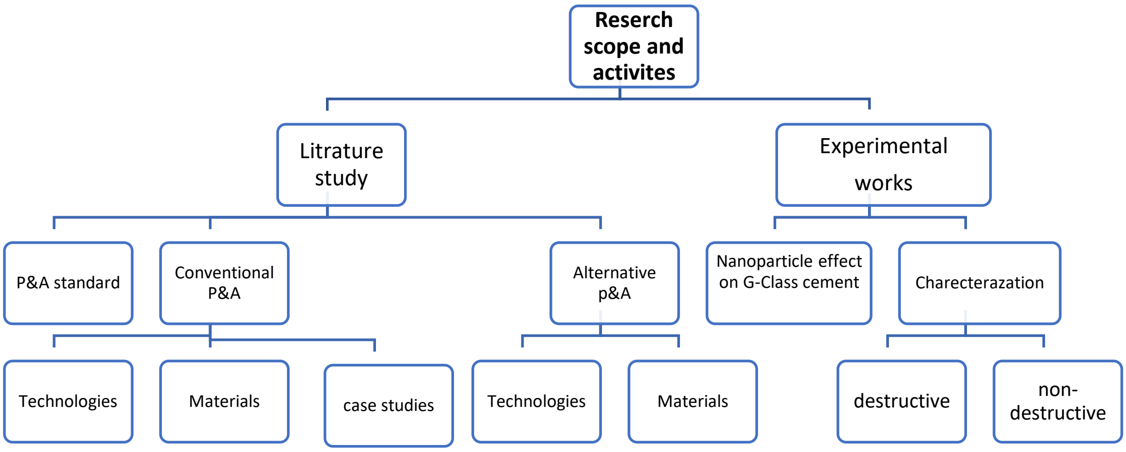


Figure 1.2 Summary of research works implemented in this thesis work.

2. P&A definitions, regulations, and requirements

This chapter introduces P&A (Plug and Abandonment) activities, focusing on definitions, regulations, and requirements. It covers the essential terminology and concepts related to P&A, explores the regulatory framework governing these activities, and outlines the specific requirements and guidelines that must be adhered to during the P&A process.

2.1 Terminology associated with P&A Of oil & gas wells

2.1.1 Plug and abandonment

The abandonment phase typically occurs when the economically recoverable reserves have been depleted. At this point, the well's production has declined to a level where the operating income generated from the remaining reserves is lower than the operating expenses required to maintain production. As a result, continuing to operate the well becomes financially unviable. The primary objective of the abandonment phase is to properly secure the well to prevent any leakage of hydrocarbons, fluids, or gases into the surrounding formations or the environment. This is achieved by a process known as "plugging." Plugging involves placing cement or other specialized materials in the wellbore to create a barrier that seals off the reservoir or any permeable zones and isolates it from other formations. Figure 2.1 provides a simplified illustration demonstrating the concept of a plug in this context.

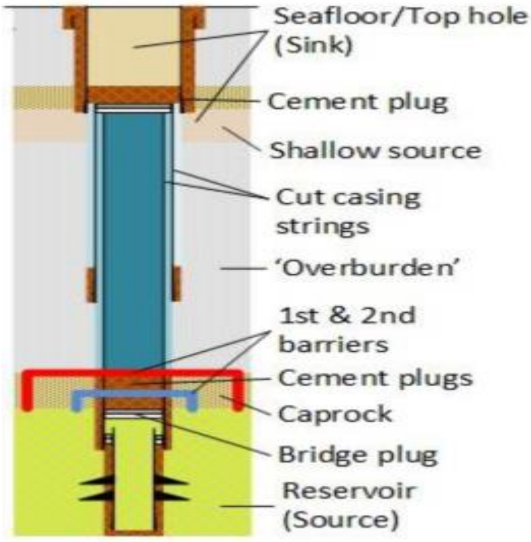


Figure 2.1 Illustration of Plug [4]

2.1.2 Barriers

According to NORSOK, In P&A operations, various types of barriers are employed to ensure effective isolation and containment. Three types of barriers commonly utilized include:

- Primary well barrier: This barrier is positioned to separate the entry source, whether it is a normal pressure formation or an over-pressured formation, from the surface or seabed. Its purpose is to prevent the migration of fluids and gases to the upper sections.
- Secondary well barrier: Serving as a backup to the main well barrier, this secondary barrier provides an additional layer of protection against the same entry source. It acts as a contingency measure in case the primary barrier fails or experiences any issues.
- Open hole to surface plug: Positioned at the top of the barrier sequence, this plug is the final barrier to be placed in the well. Its purpose is to seal off any flow from the exposed well formations after the removal of casings. It effectively isolates and contains any remaining fluids or gases within the well.

2.1.3 Materials

Portland cement is the most commonly used barrier material. (Details are given in Chapter 4).

2.1.4 Cap-rock

Caprock serves as a vital component for maintaining reservoir pressure stability. When drilling for fuel extraction, the cap-rock is pierced, creating a pathway to the reservoir. Consequently, the pressure differential between the reservoir and the tubing enables the upward flow of oil or gas through the well. In P&A operations, the primary objective is to effectively seal the reservoir using a barrier material that closely resembles the properties of the cap-rock. By successfully implementing this barrier, we aim to restore the conditions to a state comparable to the pre-drilling stage, ensuring proper containment and pressure regulation.[2] Figure 2.4 shows restoring the cap rock by implementing a permanent barrier.

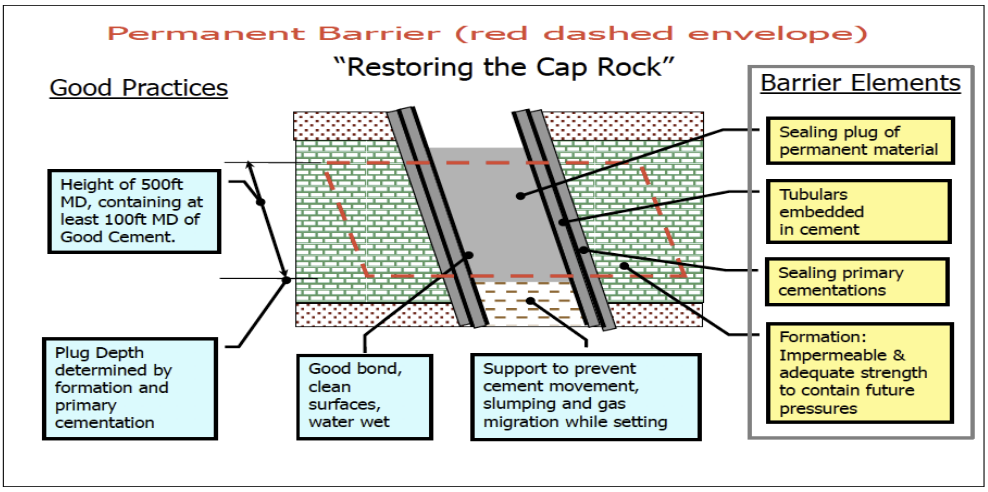
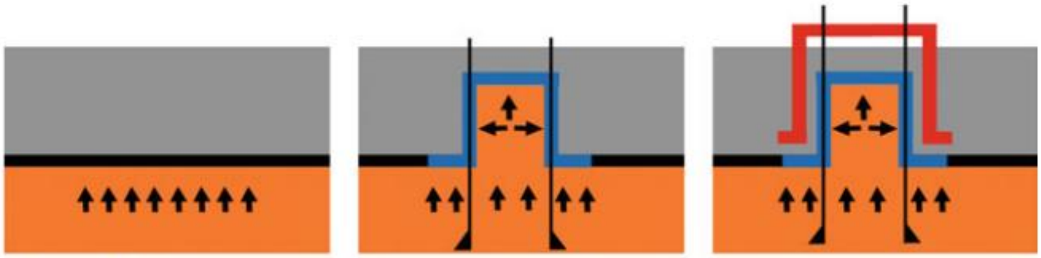


Figure 2.2 Illustration of Permanent Barrier and Cap-rock [5]

2.1.5 Two barriers Philosophy

The philosophy of well barriers emphasizes the importance of equipping wells with an adequate number of barriers to prevent uncontrolled flow from potential sources. It is widely accepted that a single failure of a well barrier component should not result in unacceptable consequences. Therefore, it is recommended to have two independent well barriers in place: a primary barrier and a secondary barrier. This principle, often referred to as the "hat-over-hat" principle, ensures that the secondary barrier serves as a backup to the primary barrier. By employing this approach, the risk of uncontrolled flow can be minimized, enhancing the overall safety and integrity of the well.[6]


Cap rock holds the pressure

Primary barrier hold the pressure

Secondary barrier is independent of primary and acts as back-up

Figure. 2.3 Two-barrier philosophy shown using the "hat-over-hat" representation [6]

2.1.6 Environmental plug

While primary and secondary barriers, known as Plan A and Plan B respectively, effectively manage the pressure from beneath, it is important to distinguish the environmental plug from a barrier in terms of its pressure control capabilities. The environmental plug is primarily designed to fulfill environmental requirements rather than act as a pressure-holding barrier.

The environmental plug serves several key functions:[6]

1. It prevents the exposure of the surrounding environment to potentially hazardous fluids present in the annulus.
2. By acting as a plug, it minimizes the risk of leaks originating from unidentified sources in close proximity to the surface.
3. It helps minimize the likelihood of fluid swabbing from the sea or nearby freshwater into the formation through the annular space.

While the environmental plug lacks the ability to control pressure like a barrier, it plays a crucial role in ensuring environmental protection during P&A operations. Figure 2.4 is a simple illustration of a typical oil/gas well before and after P&A.

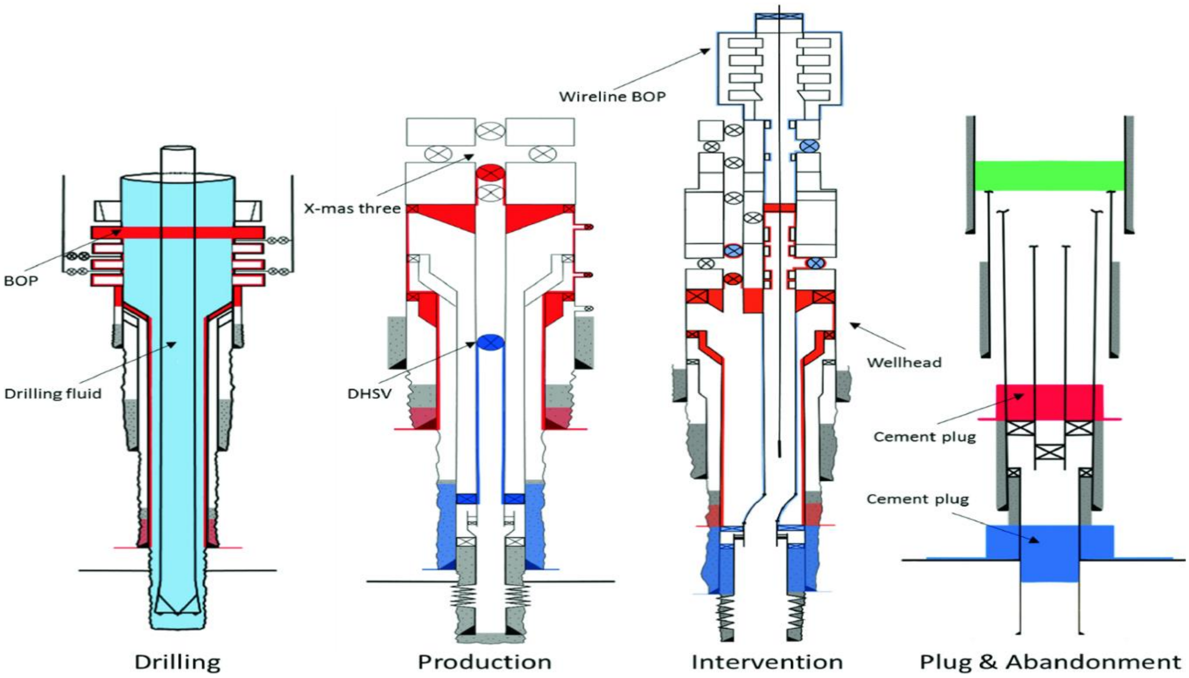


Figure 2.4 Simplified illustration of a typical drilling to P&A [6]

2.1.7 Mechanical Plugs

There are two commonly used types of mechanical plugs for well plugging and abandonment: bridge plugs and cement retainers. The choice of plug type depends on whether cement needs to be pumped below the plug for perforation sealing, known as squeeze cementing. If cementing below the plug is unnecessary or when a balanced cement plug has already been positioned below the mechanical plug, a bridge plug can be utilized.[7].

Setting mechanical plugs in a well can be accomplished using different methods such as workstring tubing, coiled tubing, or wireline techniques. Tubing or coiled tubing is commonly used in well conditions where pressure is present. Mechanical plugs typically consist of four main components: 1) the plug body, which can be made of materials like steel, cast iron, or composites; 2) slips, metal components that grip the casing to secure the plug in place; 3) packing material, which is a rubber or nylon ring that expands outward when the plug is set in the well; and 4) an on/off tool that allows the plug to be set and later released for retrieving the tubing or wireline after setting.

The downhole setting of the tool varies depending on the specific manufacturer's design. Generally, the tool is lowered to the desired location and rotated to release the slips, which secure the plug to the casing. The plug is then raised or lowered (depending on the application) to expand the sealing element against the casing. Once the desired tension is applied to the tool, it can be set and released. In cases where necessary, the tool may be rotated again to release a secondary set of slips, which keeps the tool expanded and set before release. For wireline set tools, certain versions employ explosives or hydraulic systems to set the slips and packing element before release. [7].

2.1.7.1 Bridge Plugs

Bridge plugs are mechanical plugs used to create a secure seal within a wellbore for the purpose of plugging. These plugs are designed to provide a solid barrier that can withstand pressure differentials and prevent fluid flow. In certain scenarios, bridge plugs are constructed to be easily drillable, allowing for re-entry into the wellbore at a later time if needed.

Typically made of cast iron, bridge plugs feature dual slips and a sealing element positioned between the slips. The plug is set in the wellbore and then cement is applied on top to create a complete seal of the reservoir below. In situations where there is a risk of moderate to high-pressure gas flow from the area beneath the setting depth, a bridge plug can be employed to seal the wellbore before cementing. This helps minimize the possibility of pressurized water or gas contaminating the cement. Figure 2.5 illustrates a typical cast iron bridge plug commonly used for well plugging and abandonment purposes.[7]

Figure 2.5 Cast Iron Bridge Plug [7]

2.1.7.2 Cement Retainer

A cement retainer is a mechanical plug that is installed above a specific zone in the wellbore for the purpose of cementing (Figure 2.6). It is particularly useful when dealing with higher pressured zones that require squeeze-cementing prior to plugging. Cement retainers are typically constructed from drillable materials, allowing for subsequent re-entry into the reservoir if necessary.[7]

The installation process of a cement retainer is similar to that of a bridge plug. Once the retainer is set in the well, cement can be pumped through the plug to squeeze it into the perforations or open-hole area below the retainer. Pressure can be applied to the zone below the retainer without the risk of cement traveling up the wellbore beyond the retainer. By exerting pressure to force the cement through the perforations, an effective sealing of the well is achieved during plugging.

Once the desired amount of cement has been squeezed below the retainer, the tubing is pulled upward out of the retainer, and a mechanical flap closes the hole, ensuring a secure seal of the cement below the cement retainer. Additional cement is typically placed on top of the retainer to further enhance the seal of the reservoir. The figure illustrates a typical cement retainer used in these applications.

Figure 2.6 typical cement retainer [7]

2.2 The Regulatory Authorities

Operators, agencies, and companies are obligated to comply with local laws, regulations, methodologies, manuals, and standards set forth by regulatory authorities when it comes to securing and plugging abandoned wells. These regulatory requirements serve as the minimum criteria that operators must meet to ensure the safe decommissioning and proper plugging of abandoned wells, safeguarding the present and future interests.

While operators are bound by these minimum requirements, it is prudent for them to go beyond these standards by considering factors of safety. By exceeding the minimum requirements, operators can mitigate the risk of potential failures or future leakage through the plugged well. Failure to meet the minimum requirements or experiencing leaks in the near future could result in additional costs for operators, either through the need to redo the task or in the form of penalties imposed by the regulatory authorities. Hence, operators must adhere to higher standards and exercise due diligence to avoid such undesirable outcomes.

Countries have varying rules, regulations, and recommended practices when it comes to the plugging of wells. However, the fundamental reasons, ideas, and concepts remain the same to safeguard the environment from harmful emissions and pollutants by appropriately sealing the abandoned wells, ensuring the long-term integrity of the system. For instance, there are differences in regulations between the UK continental shelf and the Norwegian side. In the UK, a plug length of only 100 feet (30 meters) is required for well plugging, whereas in Norway, a plug length of 100 meters is mandated according to NORSOK D-010 guidelines. [6]

2.3 The Regulatory Authority in the Norwegian Sector

Norwegian Petroleum directorate (NPD) is one of, the four sectors of the North Sea. The sector division along with the regulatory authority of sectors are presented below.

	Sectors	**Regulatory body**
1	United Kingdom	The health and safety executive (HSE), the department that oversees the petroleum activities in Britain
2	Danish	Danish Energy Agency (DEA)
3	Dutch	Dutch Supervision of mine
4	Norwegian	Norwegian Petroleum directorate (NPD)

Table 2.1 the four sectors of regulatory bodies of the North Sea [6]

The NPD serves as the specialized governmental directorate and administrative body for the Norwegian Continental Shelf (NCS). It acts as an advisory entity to the Ministry of Petroleum and Energy (MPE) in Norway. In the maritime territory of Norway, there exists an independent government regulator called the Petroleum Safety Authority (PSA) Norway. The PSA is responsible for ensuring safety and emergency preparedness within the Norwegian petroleum industry. Regarding plug and abandonment (P&A) activities on the NCS, the PSA serves as the regulatory authority. It reviews proposed P&A plans and oversees the P&A operations.[6]

2.4 NORSOK Standards

In Norway, the plugging activities for abandonment wells are carried out according to the NORSOK D-010 standard. This standard is implemented by an independent organization called Standards Norway. The NORSOK D-010 standard provides detailed guidelines and descriptions on how the plugging activities should be conducted to ensure well integrity in drilling and well operations.

To ensure compliance with regulations and meet functional requirements, it is recommended to use NORSOK D-010 as a baseline standard. This standard outlines the minimum performance and functionality requirements for the safe design, planning, and execution of well operations. Although operators may have their specific requirements and processes, they must at least adhere to the guidelines set by NORSOK D-010.

NORSOK D-010 employs a distinct terminology to distinguish between requirements and guidelines. The usage of the term "shall" in this standard denotes that certain actions or criteria must be met without deviation unless there is agreement from all parties involved. Meanwhile, the term "should" in the standard indicates recommended solutions among several possibilities, without necessarily excluding others. In essence, "should" suggests a preferred action, but it is not mandatory.[2]

All operations including P&A operations on the NCS are mainly regulated by the Norwegian petroleum act (OSPAR) and NORSOK standards. NORSK D-010 focuses on well integrity by defining the minimum functional and performance-oriented requirements and guidelines for well design, planning and execution of well operations in Norway.

NORSOK D-010 standards provides a comprehensive overview of abandonment activities in oil and gas industry. It covers various topics related to abandonment, including well barriers, abandonment activities, general guidelines, well barrier schematics, abandonment design, suspension, temporary abandonment, permanent abandonment, and other relevant topics. The guidelines focus on ensuring safety, environmental protection, and cost-effectiveness throughout the abandonment process. NORSOK D-010 provides recommendations for establishing effective well barriers to prevent fluid and gas migration and maintaining well integrity. It also offers detailed guidelines for designing abandonment procedures, considering factors such as well type, reservoir characteristics, and environmental considerations. The guidelines address temporary suspension requirements, as well as the procedures for permanent abandonment, including the placement of permanent barriers, equipment removal, and wellbore plugging. Other topics covered may include regulatory compliance, risk assessment, documentation, and reporting requirements. NORSOK's comprehensive guidelines assist industry stakeholders in safely and responsibly decommissioning oil and gas wells. [2]

2.5 Requirements for the Permanent Well Barrier

According to the NORSOK D-010 standard, a permanent source barrier is required to have a few qualifications.

a) Long-term integrity
b) Low permeability
c) Materials should not have reduced properties.
d) Able to withstand the impact of equipment and loads
e) The materials must be resistant to chemicals such as H_2S, CO_2 and hydrocarbons
f) Non-shrinking
g) Wetting to ensure bonding to steel

In addition, there are four conditions of approved resource restriction mentioned in NORSOK D-010[2].

1. Length
2. Position
3. Verification
4. The Number of Well Barriers

2.5.1 Length requirement

NORSOK specifies requirements for the length of cement plugs used. The length of the cement plug also affects the verification requirements for external barriers. The length requirements vary depending on the type of plug and whether a foundation is used. For open hole cement plugs, the length should be 100 m MD with a minimum of 50 m MD above any inflow/leakage point. For cased hole cement plugs, the length should be 50 m MD if set on a mechanical or cement plug as a foundation, otherwise, it should be 100 m MD. For open hole to surface plugs installed in surface casing, the length should be 50 m MD if set on a mechanical plug, otherwise, it should be 100 m MD.

According to NORSOK, a one continuous cement plug can serve as both the primary and secondary barrier if certain external barrier requirements are met. To do so, verification of both the casing cement and formation is necessary. If the plug is placed in a cased hole, it must be situated on top of a foundation. When placing the plug in an open hole, it should also be situated on a foundation and extend at least 50 meters into a casing.[2]

2.5.2 Position requirement

According to the NORSOK standard D-010, the position of a plug in a well must ensure that the strength of the formation at that depth is greater than the potential pressure from below. The strength of the formation is referred to as the formation integrity pressure and is determined during drilling by performing tests such as Pressure Integrity Test (PIT), Formation Integrity Test (FIT), Leak Off Test (LOT), or Extended Leak-off Test (XLOT). These tests are used to determine the strength of the formation and ensure that the placement of the plug is safe and can withstand potential pressures from the reservoir.[2]

2.5.3 Verification of WBE's

Verifying the integrity of newly installed well barrier elements (WBEs) is crucial to ensure well integrity. Although the process of placing the barriers may not be complex, it is important to confirm that they are installed at the correct depth and possess the necessary properties to permanently seal the well. According to NORSOK D-010, the integrity of a WBE should be verified either through pressure testing using a differential pressure or other specified methods if pressure testing is not possible. WBEs that require activation should also be function tested. A re-verification is needed if any WBE's condition changes or if there is a change in loads during the remaining life cycle of the well, including the drilling, completion, and production phases.[2].

2.5.3.1Internal WBE

To ensure the integrity of a well, it is necessary to verify all barriers installed within it to ensure they are located at the correct depth and have the necessary sealing capabilities. The well barrier element (WBE) must be capable of withstanding a differential pressure test, where ΔP = P1 - P2, with P1 and P2 being the potential pressures above and below the WBE, respectively. Although the pressure test direction should be towards the external environment, it can be performed in the opposite direction if the WBE is designed to seal in both flow directions. NORSOK D-010 requires a zero acceptable leak rate for a WBE, but acceptance criteria should be established to account for volume, temperature effects, air entrapment, and media compressibility. When leak rate cannot be measured, the maximum allowable pressure leak criteria must be established [2]. Pressure testing of a cement barrier is unnecessary if it is placed on a foundation that has already undergone pressure testing. However, it must be verified through tagging.

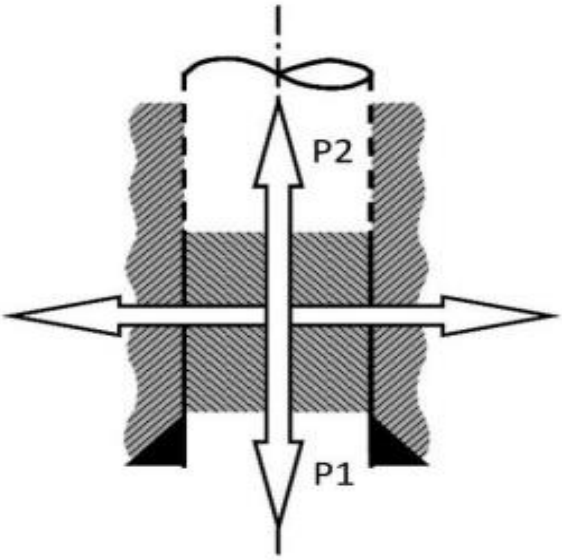


Figure 2.7 Verification of well barrier element [2]

2.5.3.2 Negative pressure Test

To ensure that the well barrier element (WBE) has mechanical integrity and is properly isolating in the direction of flow, the inflow or negative pressure test is conducted by reducing the hydrostatic pressure above the WBE. According to NORSOK D-010, the test should last at least 30 minutes with stable readings for approval. Monitoring the pressure during the test is necessary to detect any increase indicating a leak, while stable readings indicate proper sealing. This test is performed during different drilling and well activities.[2]

2.5.3.3 Positive Pressure Test

The positive pressure test is performed to verify the integrity of a well barrier element (WBE) in the opposite direction of flow. The pressure is created by pressuring the well after setting the WBE. There are two types of tests: a low-pressure test and a high-pressure test. The low-pressure test must be stable for a minimum of 5 minutes at 15-20 bar, and the high-pressure test's pressure values must be equal to or exceed the maximum pressure that the WBE may be exposed to. During the test, pressure is monitored, and stable pressure readings must be observed for a minimum of 10 minutes for the test to be approved.[2]

2.5.3.4 Tag Top of Cement (TOC) & Load Test

The process of tagging TOC confirms that the WBE is at the required depth. A load test is performed during the same operation to check the WBE's integrity. If the workstring stays constant while weight is applied, the plug is approved. Otherwise, if the workstring changes position, the cement plug is of bad quality. "Dress off" may be necessary if the uppermost part of the cement plug is of bad quality. The load test will give insufficient results if the cement has not set for enough time.

2.5.3.5 External WBE

The integrity of the external well barrier element (WBE), both vertically and horizontally, must be confirmed. NORSOK D-010 requires a minimum of a 30m interval with acceptable bonding and formation integrity, as verified by logging of casing cement, to be approved as a permanent external WBE. Chapter 5 explains the evaluation of annular WBE, including two main types of logs, Cement Bond Log (CBL) and ultrasonic Image tool (USIT), as well as the use of shale as annular WBE.[2]

2.5.4 The Number of Well Barriers

The number of barriers required for fluid containment depends on the type of fluid and its potential to flow upwards. There are different types of barriers, including primary, secondary, and surface barriers. In the case of hydrocarbon formations, both primary and secondary barriers are required, regardless of their flow capacity. However, if the formation contains water without the potential to migrate, only one barrier is necessary. If the water has the potential to migrate, both barriers are needed.

According to NORSOK D-010 guidelines, if multiple reservoirs or perforations are situated within the same pressure regime, they can be considered as a single reservoir. In such cases, it is required to install primary and secondary well barriers.[2]

2.6 Minimum functional and operating requirements for materials

The selection of well barrier materials, their quantity, placement, length, and installation method should be based on a thorough assessment of various factors. These factors include the condition of the well, the composition of fluids, pressures involved, structural strength, potential flow levels, and stability, as well as the environmental impact. Currently, cement is commonly employed as a well-barrier material due to its properties that resemble those of rock replacement.

Cement is not only the material that could be placed as a well barrier for P&A. Even NORSK- standards does not tell that only using the cement for plugging the well. NORSK standard does not bind the operators to use the cement for plugging the abandoned well [2]

Guidelines also provide other materials that may be qualified if possessing the following properties:

a) Low permeability

b) Long-term integrity

c) Resistance to corrosions (CO_2, H_2S) etc.

d) Mechanical properties to resist down-hole pressure and temperature

e) Non- shrinking and able to bond to the formation and casings metal steel

f) Placement

g) Durability for barrier materials

h) Removal and reparability

2.6.1 Low permeability

It is not feasible for any materials to possess absolute zero permeability when used as a barrier. Even cap-rock, which is known for its low permeability, has permeability values typically ranging from 0.001 to 1 micro-Darcy. Therefore, it is essential for barrier materials to exhibit a similarly low permeability, comparable to that of cap-rock. Although the permeability of cap-rock is already quite low, the barrier materials, such as cement with a permeability of 10 micro-Darcy, are performing satisfactorily in maintaining an acceptable level of impermeability [8].

The most effective materials for preventing fluid leakage are those that provide a high level of sealing, although achieving 100% sealing is not possible. Fluid leaks occur when there are micro cracks or cracks in the barrier, creating pathways for the fluid to escape. These cracks are gaps that can develop due to the material's permeability, poor workmanship during placement, or over time. When a crack forms, it represents an integrity breach that extends entirely through the barrier. As a result, the barrier fails due to de-bonding, dissolution, or further cracking. While complete elimination of fluid leakage is not attainable, selecting materials with strong sealing properties can significantly minimize the risk.[8] Figure 2. shows barrier failure modes.

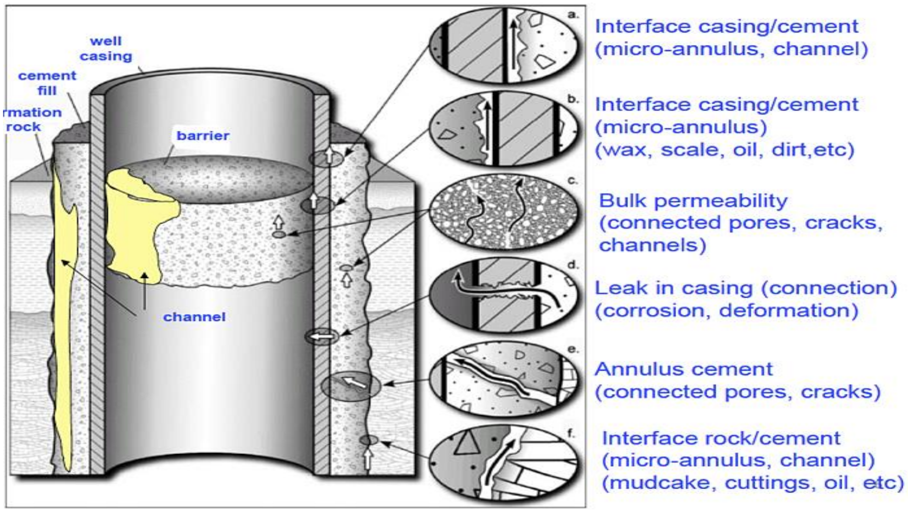


Figure 2.8 Barrier Failure modes that may require risk assessment when abandoning a well [8].

2.6.2 Long-term integrity

The ability of the materials to maintain their structural and functional integrity over an extended period. It implies that the materials should not deteriorate or degrade significantly over time due to chemical attacks or other factors.

When the long-term integrity of materials exists, it means that they can withstand potential challenges or corrosive substances that may be present in the environment or surrounding conditions. This integrity helps prevent issues such as de-bonding (loss of bonding between materials) and the development of cracks as time passes. [9]

2.6.3 Corrosions resistance (CO_2, CH_4, H_2S etc.)

The materials used in plug and abandonment (P&A) operations should possess a high level of resistance to substances such as CO2, CH4, H2S, and brine. These substances are known to be highly corrosive and have the potential to deteriorate metals and isolation barriers. Additionally, the presence of water and microorganisms, including bacteria that can digest barrier materials, should also be taken into consideration and addressed appropriately.[10]

It is crucial that the selected materials do not react with down-hole fluids, including gases, as this property ensures their resistance to chemical interactions. By having this inherent resistance, the materials automatically exhibit the required property of not reacting with gases.

2.6.4 Mechanical property to resist down-hole pressure and temperature.

The mechanical properties of barrier materials are of utmost importance in plug and abandonment (P&A) operations, specifically in relation to their resistance against down-hole pressure and temperature. The Earth's crust is dynamic, experiencing plate tectonic movements, earthquakes, volcanic activities, and varying loads over time. This variability can result in changes in fluid levels within reservoirs, leading to fluctuations in pressure. To ensure the integrity of barriers, it is crucial to select materials with excellent mechanical properties capable of withstanding both static and dynamic load conditions. These materials should be able to accommodate the expected variations in pressure and temperature in the future.[8]

During the abandonment process, rapid decompression can pose a risk to specific barrier materials. The pressure may decrease due to the normal drainage of formation fluids, while it can also increase as a result of reservoir recharging through connections with other formations or re-pressurization via fluid or gas injections for storage purposes. It is important to consider the potential effects of such changes in pressure on the selected barrier materials.

Moreover, temperature changes within a field can occur throughout its production life. Factors such as fluid injection and gas storage can influence these variations. Understanding the geological patterns and potential temperature fluctuations is essential when choosing suitable barrier materials. [8]

2.6.5 Not shrinkage

The material should not shrink with the passage of time and able to bond to form with rock formation and casings metal steel. Materials should pass the bond stress test.

2.6.6 Placement

To ensure the effective placement of a permanent barrier material in a wellbore at the desired depth, it is crucial for the material to possess specific requirements. The material should have properties that facilitate the displacement of existing fluids and enable the formation of a continuous sealing medium. Moreover, the barrier material should be capable of performing as intended, maintaining its sealing integrity despite any potential contamination. [9]

It is essential that barrier materials meet specific requirements for positioning and stability. Once the barrier is placed, it is crucial for it to remain securely fixed and immovable, both horizontally and vertically, even when subjected to the pressures exerted in those directions. This stability is vital to maintain the integrity of the barrier and prevent any unwanted fluid migration or leakage. By securely adhering to the designated locations, the barrier materials can effectively withstand the pressures and maintain their intended position throughout the P&A process.[8]

The ability to verify the placement of the barrier is also essential, particularly in deviated wells where the path may not be straight. The barrier material should allow for verification procedures to confirm its proper positioning and adherence to the desired depth. This verification process ensures that the barrier is correctly placed and effectively fulfilling its intended function.

2.6.7 Durability for barrier materials

With the passage of time, the barrier material should not degrade due to chemical and micro-organism attack. If the material and hence barrier degrades then its sealing capabilities or positioning are going to lost which we do not want. It should be able to endure wellbore fluctuating conditions for ages. The material should pass the durability test.[8]

2.6.8 Removal and reparability

The barrier utilized in temporary abandonment scenarios should have the capability of being easily removed and repaired. This is particularly important when the intention is to re-enter the wellbore after a certain period of time. The barrier material should possess properties that allow for its straightforward removal using conventional industrial methods such as drill bits, mills, acid, and other appropriate techniques. In situations where leakage occurs through the barrier, it becomes necessary to restore the well's integrity through repair. Hence, the barrier should be designed to facilitate easy removal and reparation. This ensures that any potential damage or breaches in the barrier can be addressed promptly and effectively, allowing for the restoration of well integrity. [8]

3. Plug and abandonment (P&A) Technologies

When a well has reached the end of its productive life or is no longer economically viable, it becomes necessary to seal and abandon it in order to ensure environmental protection and the safety of individuals. Over time, a diverse array of traditional and innovative technologies has been developed specifically for plug and abandonment (P&A) operations. This chapter will explore various P&A technologies, with a particular focus on three prominent methods: cut and pull, section milling, and perforate, wash, and cement (PWC). Additionally, case studies will be presented to illustrate real-world applications of these technologies, highlighting their effectiveness and significance in the abandonment process. By examining these P&A technologies and their practical implementation, we can gain a comprehensive understanding of the methods used to securely seal and abandon wells, safeguarding the environment and ensuring the well's long-term integrity.

3.1 The main steps for plug and abandonment.

The main steps for plug and abandonment [11] as shows in figure 3.1

- Removing or opening steel structures: This entails removing or opening the steel components in the wellbore to gain access for subsequent operations.
- Cleaning the plug setting area: Thoroughly cleaning the area where the plug will be positioned to ensure proper placement and effectiveness. This involves clearing away debris or obstructions.
- Setting the plug: Placing the plug in the designated location to isolate the specific section of the wellbore that requires abandonment. This step is essential for preventing unwanted fluid movement.
- Verifying the results: After the plug is installed, conducting tests and inspections to confirm its successful installation and functionality. The aim is to ensure that the plug effectively isolates the targeted section

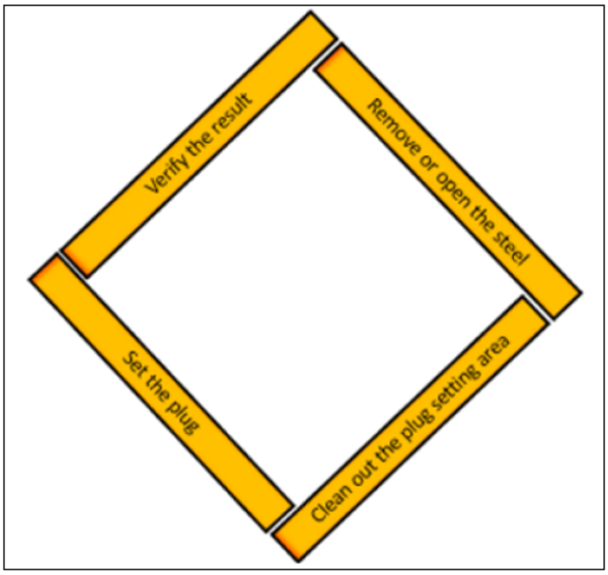


Figure 3.1 Illustration of the P&A square [11]

3.2 cut and pull technology

During plug and abandonment (P&A) and slot recovery operations in the oil and gas industry, a preferred alternative method for removing casing strings is cut-and-pull. This technique is particularly useful in permanent P&A operations with inadequate or absent annular barriers, especially when dealing with long sections of uncemented casing. It involves making a circumferential cut above a casing coupling and utilizing a hydraulically engaged spear to pull the casing out of the wellbore. Unlike the traditional method that relies on the working unit's pulling capacity through the workstring and bottom hole assembly, advancements in cut-and-pull techniques have introduced downhole hydraulic pulling tool anchors capable of generating significant pulling force without fully utilizing the working unit's capacity.[6][12]

3.2.1 Methods for Casing Removal in Well Operation

Various techniques are available for the extraction of casing from a well during plug and abandonment operations, with the selection of downhole tools depending on the specific requirements of the task: [13]

1. Cut-and-pull: This method involves cutting the casing and then pulling it out of the well. However, cut-and-pull operations can be challenging if the cut casing becomes stuck and difficult to remove. To enhance the chances of successful casing removal while

minimizing the number of runs, one-trip cut-out-pull systems are employed. These systems incorporate a cutter and spear in a single bottom hole assembly (BHA) along with downhole hydraulic pulling tools.

2. Pilot or Casing Milling: In cases where cut-and-pull operations are unsuccessful, milling the casing from the top down is an alternative approach. Pilot or casing milling involves using specialized tools to mill through the casing, allowing it to be removed. While it is possible to accomplish hundreds of feet of pilot milling in a single trip, this method can be time-consuming and requires a mud system and surface unit to handle the cuttings generated during the milling process (known as swarf).

3. Section Milling: Section milling is the preferred option when the casing cannot be efficiently removed along its entire length due to it being stuck over a significant portion above the desired interval for casing removal. In this method, a casing cut out is made, and a window of 50 to 165 ft. (15 to 50 m) is milled to facilitate the removal of the desired section.

3.2.2 Challenges in Casing Cut and Pull Operations

A major challenge encountered during casing cut and pull operations in plug and abandonment procedures is the casing getting "stuck" due to settled barite in the annulus outside the casing. As illustrated in figure 3.2, If the annulus sediment (settled barite) does not flow around the casing collars during pulling, the casing is stuck. The presence of sediment phases, including settled barite, formed during gravity separation of drilling fluid over time contributes to this problem. Friction and bonding between the sediments and casing, as well as the presence of casing collars, can significantly impede casing removal. The flowability and rheological properties of the sediments play a crucial role in determining the ease of casing removal.[12]

Additional Challenges

1.Casing Collars: The presence of casing collars can contribute to casing getting stuck during cut and pull operations. The interaction between sediments and collars affects the flow of sediments, potentially hindering the casing removal process.

2.Cementation: Cementation in the annulus can create additional challenges during casing cut and pull operations. The bond strength between the cement and casing, as well as any potential cement channeling or irregularities, can impact the ease of casing removal.

3.Wellbore Deformation: Over time, wellbore deformation, such as formation compaction or swelling, can occur, further complicating casing cut and pull operations. Wellbore deformations can increase the friction between the casing and surrounding formations, making casing removal more difficult.

4.Wellbore Integrity: The integrity of the wellbore, including factors like corrosion, casing damage, or formation collapse, can present challenges during casing cut and pull operations. Damaged or compromised casing may impede smooth casing removal.

5.The time-consuming nature of these operations. The process of cutting a casing section and pulling it out of the well requires careful execution and can take a considerable amount of time to complete.

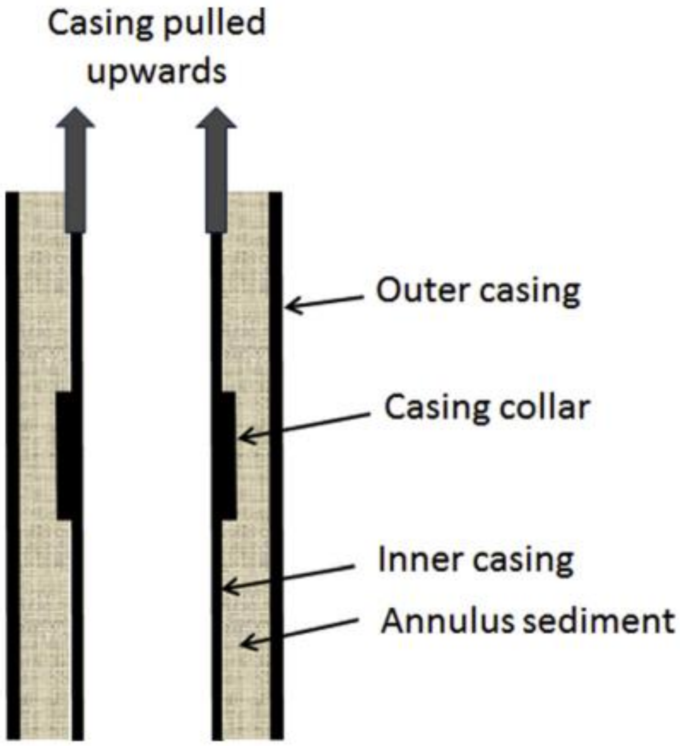


Figure 3.2 Illustration of possible cause of stuck casing during casing pulling operations [12]

3.2.3 Cut and pull case studies

One of the common methods of plugging and abandoning a well is by using the "cut and pull" technique, which involves cutting the well casing and removing it from the wellbore.

3.2.3.1 Case Study 1: Multiple Cuts

In this case study, the challenge was to remove a partially stuck 13⅜-inch, 72 lb./ft. N-80 casing from a well located close to the surface. The casing needed to be extracted to a depth of 1,283 ft. (391 m). Initially, a single cut-and-pull operation was attempted but proved unsuccessful. Casing milling was not a viable option due to the shallow and weak formation, which presented anticipated issues with equivalent circulating density (ECD) exceeding the fracture gradient.[13]

To address the situation, an operation was planned to cut and pull the 13⅜-inch casing in approximately 40-ft. (12-m) sections starting from the casing hanger at 153 ft. (46.6 m) down to the required depth. Previous experience in the same well abandonment campaign, using advanced milling technology, had successfully achieved 17 cuts in a single run, instilling confidence that the cutting process could be performed with a limited number of trips.

The first hydraulic cutting run involved performing 30 individual cuts commencing from 1,283 ft. (391 m) down to 190 ft. (57.9 m), within an 18-hour operation. The total cutting time amounted to 4 hours and 12 minutes, with an average cut time of just 8.4 minutes per cut. However, due to the casing hanger being unable to be freed within the capabilities of the jack-up rig, and limited space close to the surface for anchoring a hydraulic pulling tool, two additional cuts, labeled #31 and #32, were necessary, taking an average of 3.5 minutes per cut. Figure 3.3 shows the knives used in this process.

Figure 3.3 New knives (left) versus used knives after 30 cuts (middle) [13]

Eventually, an overpull of 400 Klb was required to successfully release the casing hanger and the initial 18 ft. (5.41 m) of casing. Subsequent spear runs were conducted, successfully retrieving all casing down to cut #22. However, at cut #22, unacceptably high over-pulls were encountered, leading to two additional cuts, #33 and #34, with an average cutting time of 3.5 minutes per cut. Similar occurrences prompted the need for the final two cuts, labeled #35 and #36.

In total, 40 pulls were executed over a span of 144 operational hours. Unfortunately, there were four pull runs where no casing could be recovered due to pipe blockages that could not be resolved with the maximum available overpull. The overpull required to free the casing pieces ranged from 30 to 450 Klb, with an external casing packer (ECP) successfully being freed with 450 Klb of overpull. Surface handling was minimized as each casing piece could be immediately laid out without additional surface cuts.

The utilization of advanced milling technology enabled the accomplishment of 30 casing cuts in a single trip, with each section being pulled free using the rig's pulling capacity while minimizing surface handling. This cut-and-pull methodology ensured the safe and efficient removal of the stuck casing from the well, especially in a scenario where pilot milling was not a feasible option.

3.2.3.2 Case study 2: LOCK & LOAD System from Archer

According to Archer, the Lock & Load System is a versatile tool that enables various operations to be performed in a single trip during P&A operations. These operations include installing the Lock or Spartan Plug, placing cement on top of the plug, hanging off the Bottom Hole Assembly (BHA) in the wellhead during nippling, dressing off the cement plug, cutting casing, and pulling casing.[14]

The Lock & Load running tool in figure 3.4 is designed to maintain full pressure integrity and features a large slick internal diameter (ID) suitable for cementing. It also incorporates an integral cutting structure to remove excess cement before verifying its integrity through tagging.

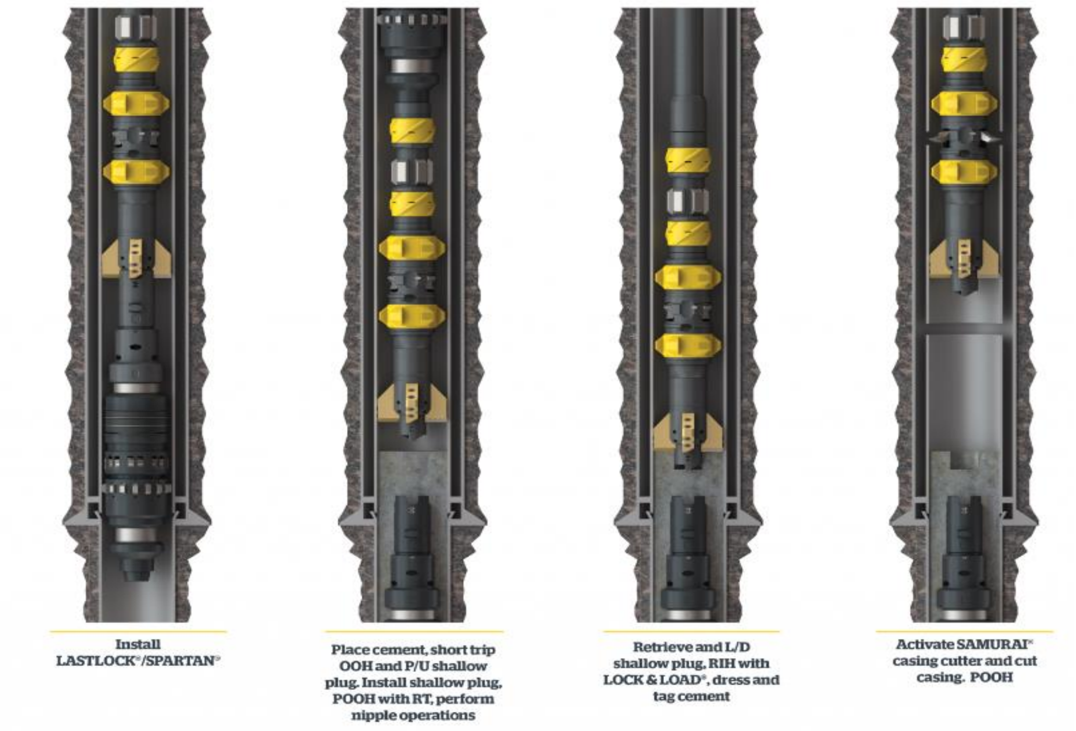


Figure 3.4 The Lock & Load system from Archer [14]

The tool offers several benefits in typical applications. By combining multiple operations into one trip, it helps save rig time, reducing operational costs. It also minimizes the need for additional equipment inventory, owning to its ease of on-site redress. Moreover, it decreases the handling of the BHA on the rig floor, streamlining operations and enhancing safety.

The Lock & Load System is compatible with LASTLOCK and SPARTAN plugs, providing flexibility in plug selection. It has a casing size range of 7", 9 5/8" / 10 3/4", and 13 3/8" / 14", with a tool internal diameter of 2.875". Additionally, it allows for convenient redressing on the rig site, further improving operational efficiency.

The Archer LOCK & LOAD System is a multi-functional tool that enables various operations to be carried out in a single trip during well interventions. It offers benefits such as time savings, reduced equipment inventory, and improved rig floor handling. The tool is designed for compatibility with specific plug types and allows for on-site redressing, enhancing its versatility and efficiency.

3.2.3.3 Case Study 3: Hydraulic Pulling Tool

The limitations posed by platform load capacities, rig pulling capacity, and workstring capabilities often present challenges during casing removal operations for permanent well abandonment. Additionally, performing high overpulls using surface equipment carries significant safety risks, as it exposes personnel and infrastructure to potentially dangerous trapped energy that can rapidly and violently release if any component in the system fails.[13]

To address these challenges and mitigate safety risks, a hydraulic pulling tool in figure 3.5 was employed, utilizing a downhole device that anchors within a parent casing string and applies pump pressure instead of relying solely on overpull. This approach enables the application of maximum force to stuck pipe while limiting surface capabilities and isolating the pulling force downhole, thereby minimizing exposure to trapped energy.

Figure 3.5 Hydraulic pulling tool, the anchor section [13]

In the North Sea, an operator faced the task of cutting and pulling 9⅝-inch and 13⅜-inch casings from five platform wells for slot recovery. The presence of cement and barite behind the casing strings at the desired cut depths increased the likelihood of casing sticking, necessitating the pulling of shorter sections

A hydraulically activated downhole pulling and jacking assembly was utilized, along with a casing spear for each casing recovery run, providing the operator with up to 1.8 million pounds of downhole pulling force for each attempt. Interchangeable anchors were supplied to engage the 13⅜-inch and 20-inch casings, allowing the pulling tool to be used for either the 9⅝-inch or 13⅜-inch casings by swapping the anchors and spears at the surface. The operating depths for the campaign ranged from 663 ft. (202 m) to 3,593 ft. (1,095 m), with pull loads reaching as high as 1.23 million pounds using the downhole pulling tool.[13]

In instances where the stuck casing sections could not be moved using the pulling assembly, the tool and spear were released, and the casing was cut at a higher point in the wellbore. The pulling assembly could then be utilized again to remove the casing in shorter sections.

Through the implementation of the hydraulic pulling assembly, the desired lengths of the 9⅝-inch and 13⅜-inch casings were safely and successfully pulled from all five wells. The increased load capacity and localized applied force provided by the hydraulic pulling tool allowed the operator to complete a challenging casing pulling campaign efficiently and effectively that would have been otherwise unachievable. By leveraging this technology, the operator overcame limitations and achieved successful casing removal while ensuring safety and operational efficiency.

3.2.3.4 Case Study 4: The Harpoon cut-and-pull spear

According to *Baker Hughes* and *Joppe et al* a new and improved method of cutting and pulling casings has been developed. This technique was utilized by an operator in the Norwegian Sea to remove the upper section of 9 5⁄8-in., 53.5-lb/ft casing in order to carry out a slot recovery operation required for a planned open hole side tracking operation in a deviated well. The intervention team ran a new cut-and-pull spear, along with a multi-string cutter, into the well to a depth of 4,017 ft (1,224 m) using a bottom hole assembly (BHA). The slips were activated by applying rotation and upward movement once the desired depth was reached, and then rotation was ceased once overpull was recorded. The packing element stack was energized by the force of the overpull, and after the packing elements were activated, the mandrel was unlocked from the rest of the tool, and the spear was prepared for cutting. Tension was applied to the casing string, rotation was initiated, and the cutting tool severed the casing cleanly at 4,021 ft (1,225 m) within three minutes. This newly developed technology offers an efficient and effective means of cutting and pulling casings for slot recovery operations, which may improve the overall efficiency and cost-effectiveness of well interventions. [15],[16]

The well-intervention team encountered difficulties while trying to retrieve the casing from its original cut point. However, they managed to release the spear without any problems by applying a force of 2,000 lbf (907 kgf) and rotating slowly to the right until the spear disengaged and moved down the casing. The team then rotated an additional 15 turns, applied set-down weight, and the spear fully disengaged. After this, the string was lifted to a neutral weight of 168,000 lb (76,204 kg), and the element was allowed to relax for 10 minutes. The team then successfully relocated the spear at a higher point in the casing, specifically at 2,933 ft (894 m). The spear was reset in overpull mode, and with an overpull force of 343,000 lbf (155,582 kgf), the 95⁄8-in. casing was successfully released and recovered. A figure is provided to show the Harpoon cut-and-pull spear recovering the casing string.

Figure 3.6 Sketch of the Harpoon cut-and-pull spear recovering the casing string [16]

According to Baker Hughes the implementation of a new cut-and-pull spear proved to be highly advantageous for a Norwegian Sea operator. This spear allowed the intervention team to perform a slot recovery operation, removing the upper section of 95⁄8-in., 53.5-lb/ft casing, and enabling the planned open hole side tracking operation in a deviated well. With the spear, the team was able to set the tool at depth, perform a clean casing cut, unset, and reposition the spear farther uphole, reset the tool to lock it to the casing ID, and retrieve the top casing section all in one trip. This saved 19.5 hours of rig time and an estimated $650,000, compared to the traditional method, which would have required two separate runs and taken an estimated 36 hours. The new cut-and-pull spear proved to be highly efficient, cost-effective, and time saving for the operator. [15].

3.2.3.5 Case Study 5: The tubing partly retrieved

To plug a well, it is usually necessary to remove the tubing and packers beforehand. However, if they are stuck, they need to be cut first. Statoil has developed a new method of performing a plugging operation without removing the tubing. This method involves a standard cut and pull, but instead of lifting the entire tubing out of the well, it is only raised to the height of the cement plug. If there is a casing behind the tubing, the cement must be verified before the cement can be placed directly. The cement is then pumped through the tubing and allowed to harden. Afterward, the tubing is lowered and left on top of the cement plug. This method saves time by not having to remove and handle the entire tubing on the surface. Statoil has estimated that this method has saved an average of 12.8% of the time. Figure 3.7 illustrates the process, and figure 3.8 shows the percentage of time savings. [17].

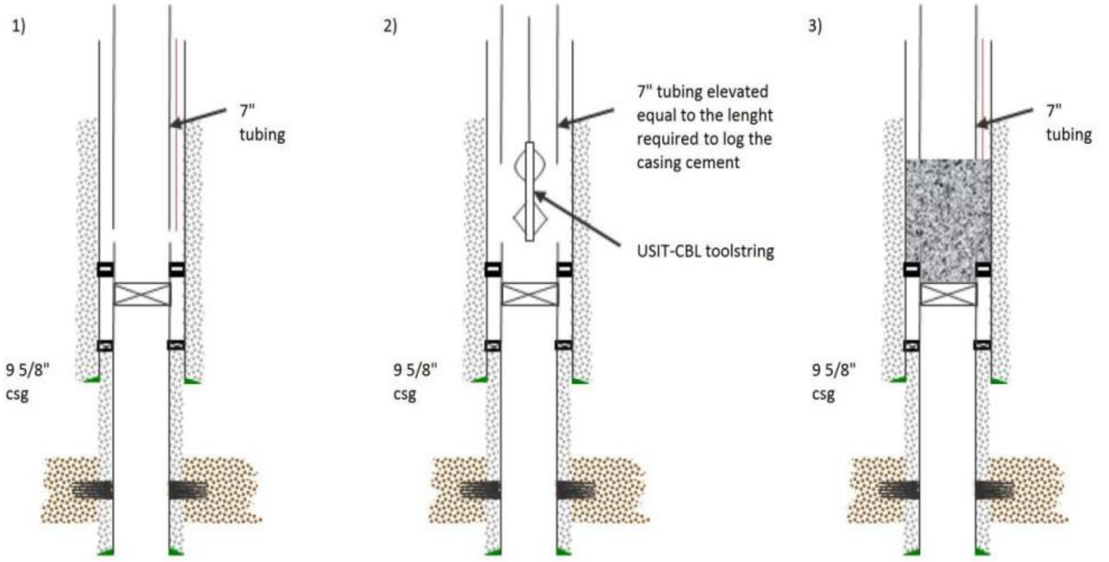


Figure 3.7 Tubing partly retrieved to place cement [17]

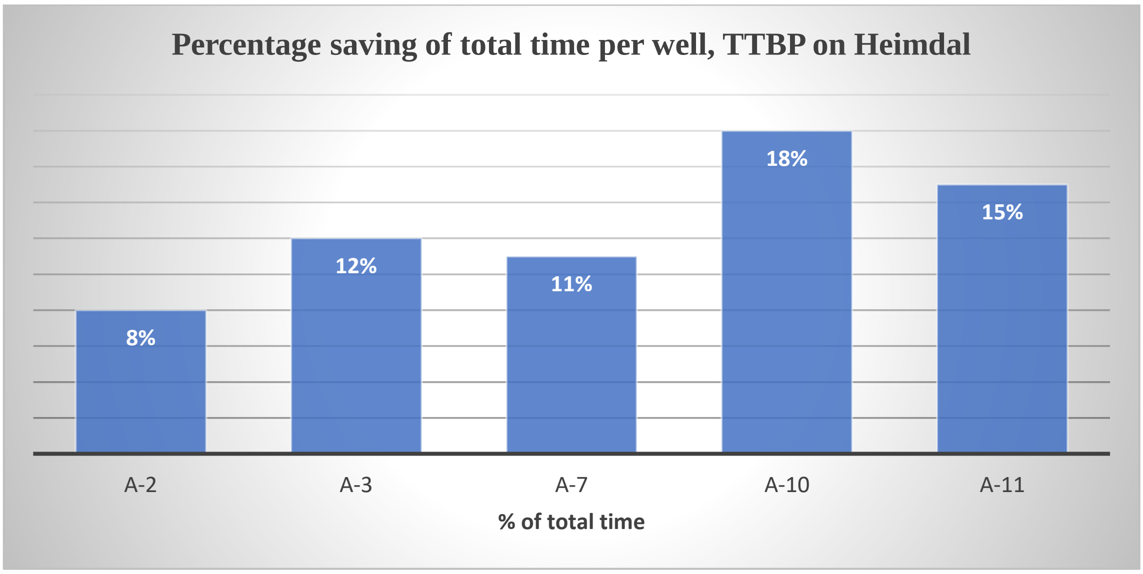


Figure 3.8 Percentage saving of total time per well, TTBP on Heimdal [17]

3.3 Section milling

Section milling is a technique employed to establish a cross-sectional barrier towards the formation when the annulus material cannot serve as an adequate annular barrier (figure 3.9). This method involves the utilization of specialized milling blades and cutters to remove specific sections of the well where the casing string is either fully or partially cemented.[12]

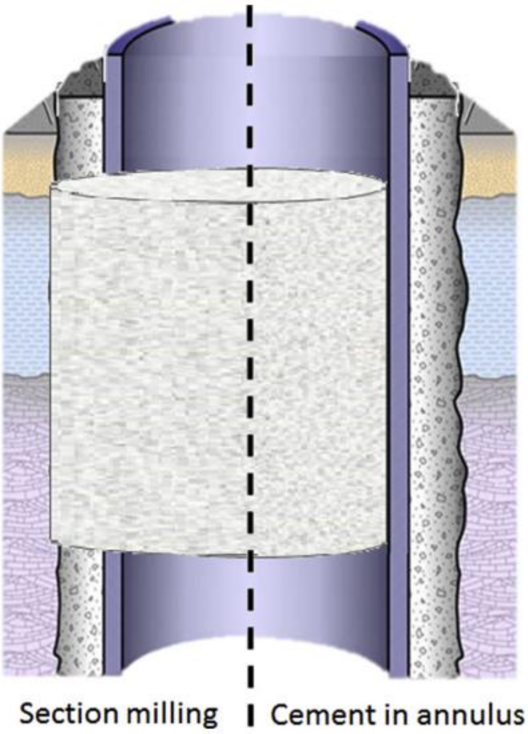


Figure 3.9. Illustration of good annulus cement (right) and establishing annulus barrier by section milling (left).[12]

Section milling is employed to address the presence of poor casing cement or uncemented casing, which is a significant issue in various operations, including rigless plug and abandonment (P&A) operations. In conventional practice, section milling involves the removal of a portion of the casing and cement by grinding it away. The main aim of section milling is to create a more reliable barrier in situations where the casing cement is inadequate or absent. During the section milling process, it is crucial to maintain a clean hole by effectively removing swarf, which refers to the metal fillings or shavings generated during the casing removal. After section milling, the newly opened window is under-reamed to expose fresh formation, ensuring better access and subsequent operations. Then, a cement plug is placed Ultimately, section milling plays a crucial role in mitigating the challenges posed by poor casing cement or uncemented casing, enabling the successful execution of P&A and other relevant operations.[6]

In cases where cut & pull cannot be used to remove the casing, section milling is a commonly used alternative method. The milling tool used for section milling contains expanding cutting knives that mill away a portion of the casing. After milling through the casing, the tool continues to mill through the cement and formation, a process known as undreaming. Undreaming ensures that the cement is in contact with fresh formation, leading to optimal bonding. This process is illustrated in Figure 3.10. In traditional section milling, the selected section is milled from top to bottom

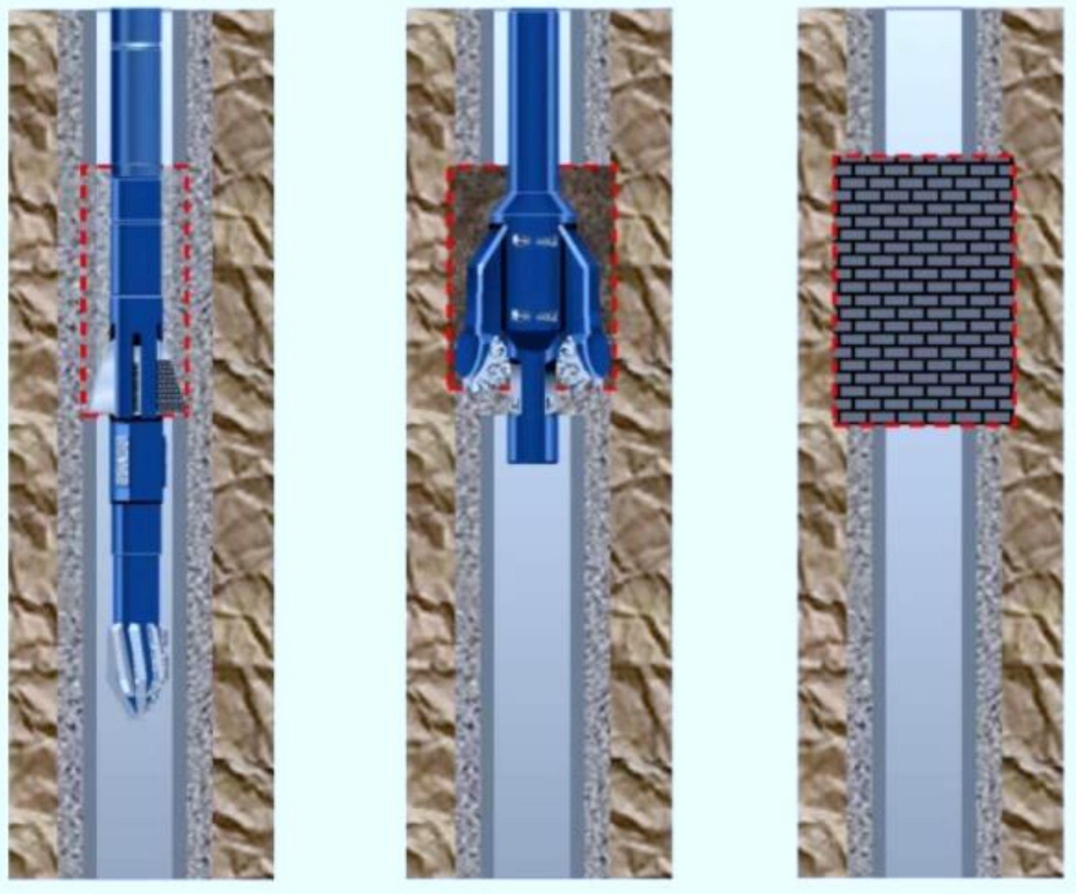


Figure 3.10 Section milling operations. In the leftmost milling casing, then underreaming formation perform and lastly placing cement plug [18]

3.3.1 Historical and conventional section milling

Historically, section milling was a two-step process that required separate equipment for milling the casing and undreaming the formation. This meant that at least two runs were required to complete the process. However, modern equipment allows for the entire section milling process to be completed in a single run, making the process more efficient. Figures 3.11 and 3.12 depict the equipment historically and conventionally used in section milling.

Figure 3.11 Historical section milling performed with two separate tools [18]

Figure 3.12 A combined tool that both mills the casing and under-reams the formation [18]

3.3.2 Challenges of Section Milling in P&A

Section milling technology, while beneficial in plug and abandonment operations, presents certain challenges that need to be addressed. One significant challenge is the time-consuming nature of the section milling process. It takes a considerable amount of time to mill through the casing, which can delay the overall progress of the P&A operation.

Another challenge is the generation of swarf shown in figure 3.13, which refers to the metal debris produced during the milling process. Exposing the Blowout Preventer (BOP) to swarf can have adverse effects on its performance and integrity. When a section milling operation covers a distance of 50 meters, it can produce up to four tons of swarf. The removal of such a large volume of swarf from the borehole before cementing becomes necessary to prevent any potential complications.

Figure 3.13 Accumulates of Swarf on the tools, forming "bird-nests" [17]

During section milling operations, several challenges can arise. The required viscosity profile of the fluid used for milling can lead to Equivalent Circulating Densities (ECD) that exceed the fracture gradient of the open hole. This can result in problems such as losses while circulating, swabbing, well control issues, poor hole cleaning, and packing off of the Bottom Hole Assembly (BHA). Insufficient clearance of swarf and debris from the wellbore can cause the milling, clean out, or underreaming BHAs to become stuck. Additionally, the accumulation of swarf and casing debris in the annular and ram BOP equipment can seriously affect their function. These issues pose risks to the operation's success and can lead to downtime and delays in the milling process.[19]

Addressing these challenges in section milling technology is crucial for efficient and safe plug and abandonment operations. Finding ways to minimize the time required for section milling and optimizing the removal of swarf can significantly enhance the overall effectiveness of the process. Improvements in milling techniques, equipment, and fluid design can contribute to reducing the time and resources required for section milling, improving operational efficiency and safety.

3.3.3 Section Milling case studies

3.3.3.1 Case study 1: Swarf-Less Milling Technology

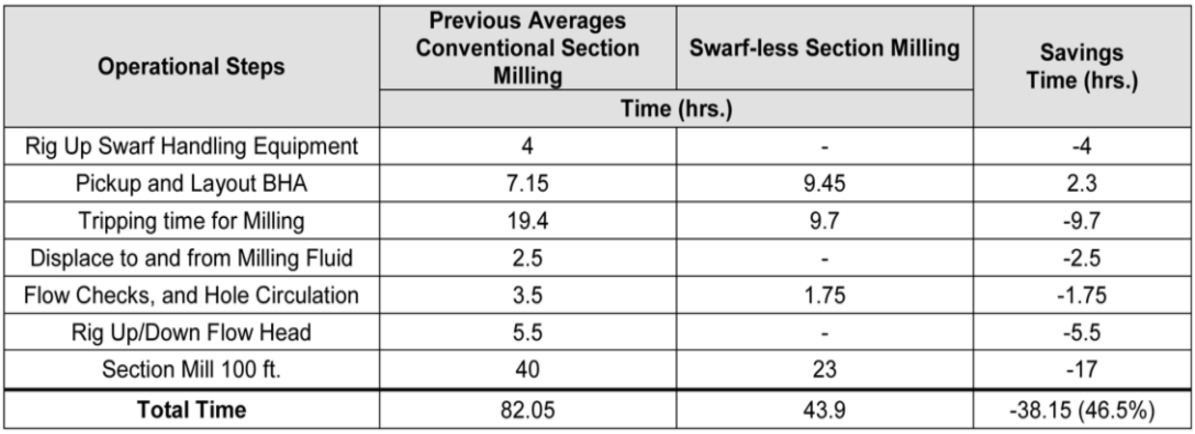
In 2020, a technology known as Swarf-less Section Milling was used successfully in a P&A (plug and abandonment) campaign in the North Sea. The operator of this campaign had a requirement to place a cost-effective 30m (about 100 ft.) barrier in wells with partially cemented 9.625" casing. As the campaign had been ongoing for some time, an opportunity arose to compare Swarf-less Milling with the previously used Conventional Section Milling.[20]

Conventional Section Milling involves the use of a milling tool to remove sections of casing from the wellbore, with the resulting metal debris or "swarf" being extracted from the well using specialized equipment and a milling fluid. This process can be time-consuming, requiring two trips to complete the operation and posing additional risks due to the handling and disposal of the swarf.[20]

Swarf-less Section Milling is a milling technique that eliminates the production of swarf, which is metal debris generated during conventional milling operations. Instead of creating swarf, the tool used in Swarf-less Section Milling cuts and breaks the casing into small, easily removable pieces. This technique offers several advantages:[20]

1. Swarf elimination: Swarf-less Section Milling avoids the generation of metal debris, eliminating the need for swarf handling equipment and specialized milling fluids. This reduces both the cost and complexity of the operation.
2. Single trip completion: The Swarf-less Milling process can be completed in a single trip, which further reduces the time and cost involved compared to conventional milling methods that require multiple trips.
3. Reduced equipment and chemicals: Swarf-less Section Milling requires less equipment and chemicals compared to conventional milling operations, making it a more efficient and cost-effective option.
4. Innovative approach: Swarf-less Section Milling differs from conventional methods by milling the window from the bottom up instead of top down. This allows the use of a mechanical pump to drive all cuttings downhole. The cuttings can then be disposed of in the abandoned well below the caprock barrier, eliminating the need for surface disposal.

By evaluate the performance of Swarf-less Milling in comparison to Conventional Section Milling. They found that Swarf-less Milling was highly effective in this application, allowing them to install the required barrier with greater efficiency and at a lower cost. Table 3.1 shows a comparison of the operational times for the two methods, with Swarf-less Milling clearly demonstrating a significant advantage.



Operational Steps	Previous Averages Conventional Section Milling	Swarf-less Section Milling	Savings Time (hrs.)
	Time (hrs.)		
Rig Up Swarf Handling Equipment	4	-	-4
Pickup and Layout BHA	7.15	9.45	2.3
Tripping time for Milling	19.4	9.7	-9.7
Displace to and from Milling Fluid	2.5	-	-2.5
Flow Checks, and Hole Circulation	3.5	1.75	-1.75
Rig Up/Down Flow Head	5.5	-	-5.5
Section Mill 100 ft.	40	23	-17
Total Time	82.05	43.9	-38.15 (46.5%)

Table 3.1 Swarf-less Section Milling Time [20]

By using Swarf-less Section Milling instead of Conventional Section Milling, over 38 hours or 46.5% of rig time was saved, resulting in less use of CO2-emitting equipment. Additionally, there was no need for swarf handling equipment or specialty milling fluid, which removed the environmental cost of their development, transport, and use, as well as the need for handling, transport, and disposal of swarf. The use of Swarf-less Milling resulted in approximately 63% of CO2e emissions being avoided, by saving time on rig, pumping, operational, and transport activities.[20]

Swarfless section milling offers cost reductions by saving time and eliminating the need for equipment and services at the surface. The cost reduction can be estimated by multiplying the Hourly Rig Operating Cost (HROC) difference of 15 hours by the HROC itself. Additional cost reductions are achieved by eliminating milling fluid costs, swarf handling unit costs, swarf handling unit crew costs, swarf skip and disposal costs. The overall operation cost is reduced through savings in time, equipment, personnel, and services. Moreover, swarfless section milling brings about improved health, safety, and environmental conditions by eliminating manual cleaning, reducing lifts and well control risks, and eliminating the need for swarf, cement, and mud disposal associated with conventional section milling operations.[21]

3.3.3.2 Case study 2: Section Milling with Active Stabilization

Traditional methods of cutting and pulling casing may not be feasible, leading to increased costs and complexities. Milling the casing becomes necessary in such scenarios.

A conventional section mill has stabilization features close to the inside diameter of the milled casing, which reduces milling vibration. However, their gauge-diameter limits their ability to pass through restricted-diameter tubular. A new undersized section mill with active stabilization can be used to mill a section of casing string below a restricted-diameter tubular with similar performance and reliability to a conventional mill.[22]

The section milling process can be significantly enhanced by implementing active stabilization of the mill, which involves centralizing the mill within the casing before cutting commences. This can be achieved by expanding the stabilizer arms that are integrated into the mill prior to the knives expanding to cut the casing. The stabilizer arms help to reduce lateral vibration by keeping the mill centered within the casing, which in turn increases the longevity of the knives by several orders of magnitude. To ensure that the undersized mill operates with the same level of performance and reliability as a conventional mill, it must possess comparable features. Figure 3.14 provides a clear comparison between the conventional section mill and the actively stabilized section mill, including their knives and stabilization method.

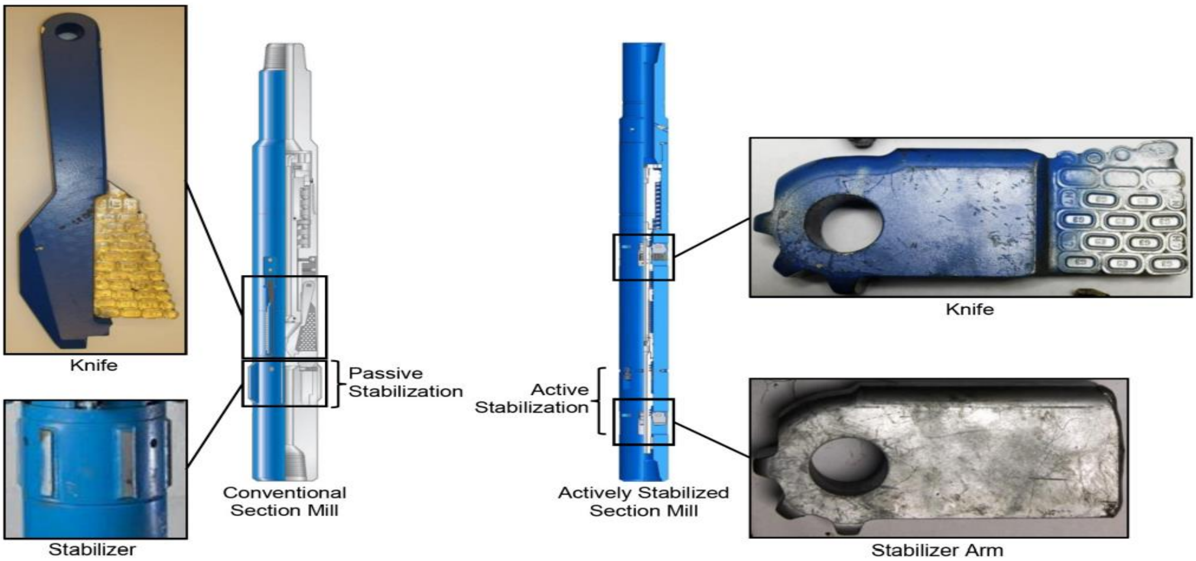


Figure 3.14 Conventional section mill and actively stabilized section Mill [22]

The actively stabilized section mill was used to mill a 70-ft section in 11-3/4 in. casing below a restricted-diameter production riser, saving the operator 3 days and USD 1 million by leaving the riser, BOP and surface equipment in place. Figure 3.15 shows the bottom hole assembly (BHA) with the actively stabilized section mill.

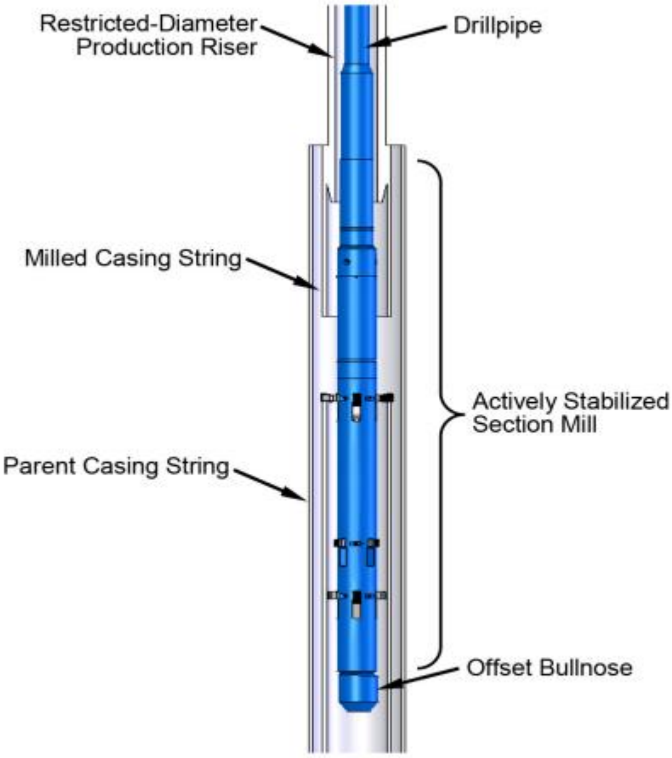


Figure 3.15 Actively stabilized section milling BHA [22]

The mill passed through the restricted inside diameter of the riser and BOP, expanded its stabilizer arms to centralize itself inside the casing, and then slowly expanded the cutting knives to begin the cut. The stabilizer arms kept the mill centered inside the casing, reducing lateral vibration, and increasing knife longevity. This undersized mill with active stabilization can be deployed through restricted-diameter tubulars to mill a section of casing string with similar performance and reliability as the conventional passively stabilized mill.

3.4 Perforate, Wash and Cement (PWC)

Plug and abandonment (P&A) is a crucial procedure in the oil and gas industry that involves permanently sealing a wellbore that is no longer needed for production. The key to a successful P&A operation is the proper placement of cement in the wellbore. Perforate, Wash and Cement (PWC) is a commonly used method that ensures the accurate placement of cement. Figure 3.16 illustrate PWC process.

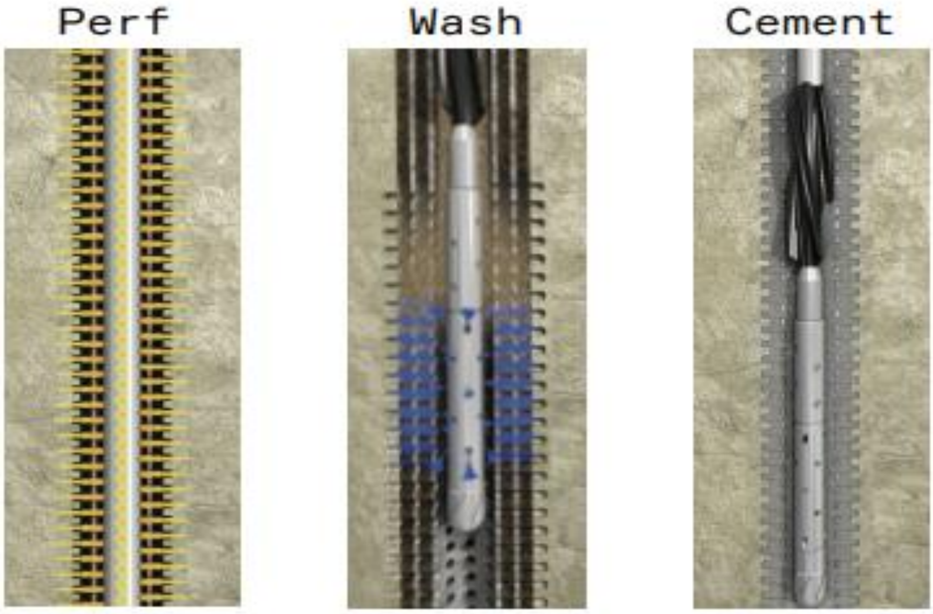


Figure 3.16 Perforate, Wash, and Cement process [23]

To ensure proper placement of cement in the wellbore during Plug and Abandonment (P&A) operations, the Perforate, Wash and Cement (PWC) process is commonly used, which involves two stages. In the first stage, the wellbore casing is perforated using a perforating gun, while in the second stage, the wellbore is washed and cemented. During the perforation stage, shaped charges are used to create holes of a specific size and shape in the casing, allowing the cement to flow into the wellbore and seal the annulus between the casing and the formation.[6]

In the second stage of the PWC process, the wellbore is first washed to remove any debris or drilling fluids that may be present using a circulating fluid. This step is essential because any debris or fluids left in the wellbore can prevent the cement from properly bonding with the casing and formation. Once the washing process is completed, cement is pumped down the wellbore and into the annulus between the casing and formation. The cement is designed to fill the annulus and bond with the casing and formation, creating a permanent seal. This step is critical in ensuring proper placement of cement to prevent any leakage or contamination of the surrounding environment.[6]

3.4.1 Operational Variables to Consider in PWC Operation Design

When designing a PWC operation, engineers have several variables that can be manipulated to ensure the success of the operation.

These variables include: [24]

1. Perforation Specification: The engineer must consider hole size and shot density to ensure proper fluid exchange. Typically, PWC perforations have an effective hole diameter (EHD) of 0.35-1.0" and a shot density of 12-18 shots per foot.
2. Flowrates: Sufficient flowrates in each phase are necessary to achieve fluid exchange throughout the annulus. Inadequate flowrates may result in bypassing certain areas. Fluid dynamic modeling helps determine required local fluid velocities based on rheological properties.
3. String Rotation: Rotation of the BHA aids in carrying solids to the surface in the return annulus. Sufficient annular velocity is crucial to transport debris and prevent the BHA from getting stuck during retrieval. String rotation also ensures fluid injection into all areas of the annulus, especially when using a jet-based BHA.
4. Pass Speed: The BHA must be passed slowly over the entire length of the perforations to ensure proper fluid mechanics in each section of the barrier location. Sufficient time at each point along the perforation length is necessary for complete fluid exchanges before moving to the next annulus section.
5. Fluid Choices: The choice of fluids is integral to the operation design. Selected fluids should control formation pressure and be compatible with the existing wellbore fluid. Proper engineering of yield strength differences prevents bypassing of the existing fluid. Maintaining density differences allows for effective separation after mixing and displacement of the old fluid from the annulus.

3.4.2 Failure Mechanisms in PWC Operations

When conducting PWC (Perforation, Wash, and Cement) operations, engineers need to be aware of potential failure mechanisms that can impact the effectiveness of the process. The principal failure mechanisms include: [24]

1. Insufficient Flowrate to Wash Effectively: If the gross flowrate during the washing phase is inadequate, the flow may not reach all parts of the annulus. Limited entry occurs when there is a pressure differential (dP) of approximately 50 psi across the perforations, ensuring effective washing. Insufficient pressure drop, caused by excessive exposed perforations or low flowrate, fails to clear the annulus of mud, settled barite, or loose cement. Higher flowrates are necessary for complete washing coverage, especially with lower shot densities and larger annuli.

2. Insufficient Washing Duration to Wash Effectively: Even with sufficient flowrates, a certain period of time is required to flush existing annular fluid from all areas of the annulus. The size of the annulus, solids content, and flowrate impact the minimum time needed for each section to be cleaned. Larger annuli or greater distances between perforations require longer residence times. CFD (Computational Fluid Dynamics) analysis helps model fluid behaviors and validate proposed washing durations.

3. Incompatible Wash or Spacer Fluid: When the existing fluid has a significantly higher yield point than the washing fluid, certain areas of the annulus may be bypassed due to insufficient energy to mobilize the existing fluid. Higher flowrates and increased fluid velocities from jet-based systems mitigate this issue. CFD analysis can assess the effectiveness of chosen fluids and operating parameters.

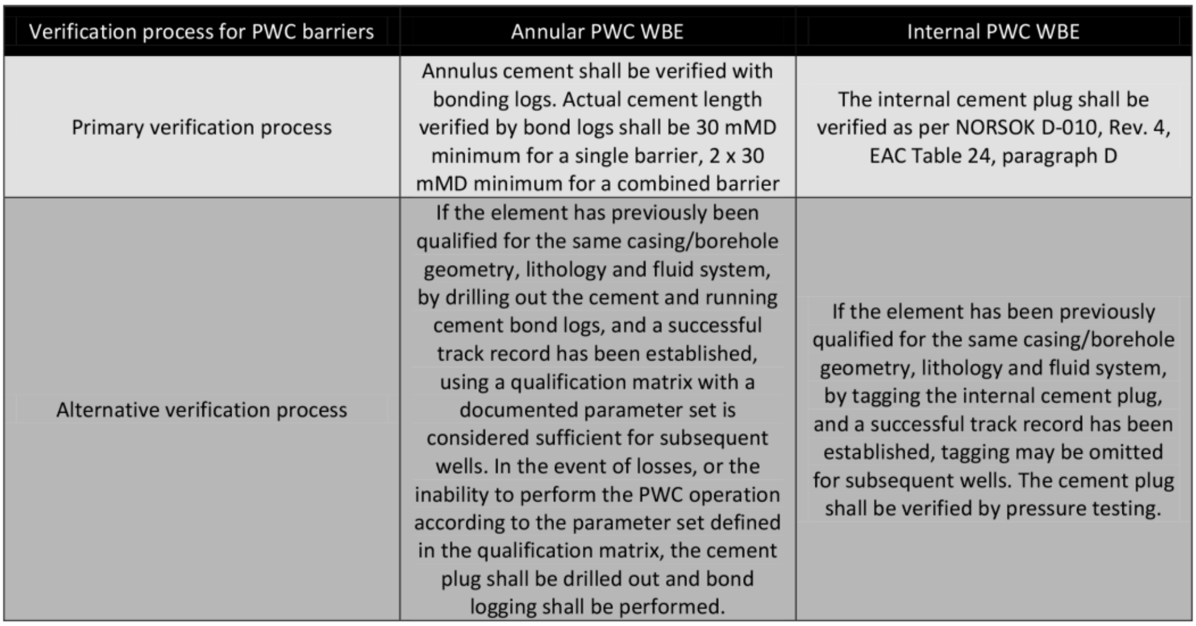
4. Gas Migration Through Cement During Curing: Proper placement of cement is crucial to avoid excess contamination, slumping, or boycotting. The curing process must prevent flow from below the cement, ensuring gas migration does not occur. Sealing barriers and appropriate placement techniques are essential.

5. Lack of Annulus Base for Cementing Operation: Cement placed in the annulus requires a stable base during the curing process. If no base is present, a PWC casing expander can be used to create an annulus base for the cement. The casing expander expands casing strings into the formation, preventing the cement from slumping down the hole.

Understanding and mitigating these failure mechanisms through careful planning, proper fluid selection, adequate flowrates, optimized washing durations, and appropriate cementing techniques contribute to the success and reliability of PWC operations.

3.4.3 Verification Criteria for PWC-installed Barriers

The table 3.2 presents primary and alternative verification criteria for barriers installed with the PWC method, including annular and internal well barrier



Verification process for PWC barriers	Annular PWC WBE	Internal PWC WBE
Primary verification process	Annulus cement shall be verified with bonding logs. Actual cement length verified by bond logs shall be 30 mMD minimum for a single barrier, 2 x 30 mMD minimum for a combined barrier	The internal cement plug shall be verified as per NORSOK D-010, Rev. 4, EAC Table 24, paragraph D
Alternative verification process	If the element has previously been qualified for the same casing/borehole geometry, lithology and fluid system, by drilling out the cement and running cement bond logs, and a successful track record has been established, using a qualification matrix with a documented parameter set is considered sufficient for subsequent wells. In the event of losses, or the inability to perform the PWC operation according to the parameter set defined in the qualification matrix, the cement plug shall be drilled out and bond logging shall be performed.	If the element has been previously qualified for the same casing/borehole geometry, lithology and fluid system, by tagging the internal cement plug, and a successful track record has been established, tagging may be omitted for subsequent wells. The cement plug shall be verified by pressure testing.

Table 3.2 Proposed primary and alternative verification criteria for barriers installed with the PWC method [25]

3.4.4 Advantages associated with PWC

Firstly, it saves time by minimizing tripping and reducing the number of runs required. The integration of perforation, wash, and cementing into a single operation streamlines the process and increases operational efficiency. Additionally, the use of PWC helps to eliminate errors that can occur when selecting the interval for perforation, ensuring accurate placement of perforations in the desired zones. Furthermore, PWC operations have the advantage of eliminating swarf handling issues, reducing the need for swarf management and disposal, which can be time-consuming and pose potential hazards.[6]

3.4.5 PWC Systems from HydraWell

The use of PWC technology negates the necessity for the three procedures. The process commences by puncturing the casing's desired segment, and then proceeding to perform a meticulous cleanse. Following that, the cement mixture is introduced into the annulus through the perforations. A number of corporations, such as the Stavanger-based firm HydraWell Intervention AS, offer this approach.

3.4.5.1 The HydraHemera System

In figure 3.17 HydraHemera System from Hydrawell. The system comprises two main components: the HemeraPoseidon and the HydraArchimedes cement assurance tool. This system is designed to handle more complex well conditions and increasing amounts of annular cement.[26]

Figure 3.17 The HydraHemera System from Hydrawell [26]

The Hemera Jet-washing Tool is utilized to effectively clean and remove movable debris, such as barite, formation materials, and traces of old cement, from the annuli behind the perforated casing(s). It features strategically positioned jet nozzles that are optimized for configuration and exit velocity, allowing them to thoroughly clean the areas behind the perforated casing(s).

By ensuring optimal conditions in the casing annuli, the Hemera Jet-washing Tool prepares the cross section for the placement of plugging material. It replaces debris, old mud, barite, and cuttings with clean wash fluid, such as mud or brine. After the washing sequence, the Hemera Jet-cementing Tool is activated using a ball drop mechanism. This tool is responsible for placing plugging material across the entire cross section of multiple annuli, creating a reliable barrier in the well for purposes like plug and abandonment (P&A) or sidetracking.

The HydraArchimedes Tool features twisted rubber blades that, when rotated during the cement job, force any wellbore fluid inside the casing to be expelled into the annuli. This rotation creates a slight pressure drop from the top to the bottom of the tool, facilitating the "flipping" of the hole. It helps push internal cement out to the annuli and allows in-situ fluid from the annuli to flow back into the wellbore.

3.4.5.2 The HemeraPoseidon system

The system includes a Hemera Jet-washing Tool and a Hemera Jet-Cementing Tool (fig. 3.18). The Jet-washing Tool is used to clean out movable debris in the annuli behind perforated casing, while the Jet-cementing Tool places plugging material in the entire cross section of multiple annuli to establish a proper barrier in the well for plug and abandonment or sidetrack purposes. The system is a better alternative to cup based PWC operations in low mud weight and low annular debris environments.

Figure 3.18 The HemeraPoseidon system from HydraWell [26]

3.4.5.3 The HydraTyphon system

The system combines the advantages of both jet-based and cup-based Perf, Wash, and Cement (PWC) systems, pushing the boundaries of the operating envelope (Figure 3.19). It enhances the efficiency of downhole hydraulic activities during the washing and cementing phases, providing a more successful barrier placement with increased certainty. The system expands the range of well geometries that PWC® can be applied to and offers opportunities to reduce costs through less expensive perforating specifications, reduced spacer and cement volumes, and shorter operational durations for effective washing. Additionally, HydraTyphon eliminates technical risks such as lost circulation, formation damage, and tool failure caused by high annular cement content, commonly associated with conventional cup-based systems.

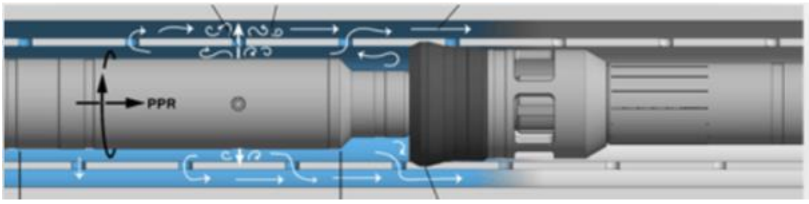


Figure 3.19 The HydraTyphon system from HydraWell [26]

3.4.5.4 HydraCT system

The system is an innovative Perf, Wash, and Cement system designed specifically for rigless abandonment operations. It utilizes a self-rotating, jet-propulsion tool, making it ideal for coiled tubing applications where rotation of the work string is not possible or where there are restrictions on internal diameter or limited load capacity (Figure 3.20). The HydraCT system offers increased efficiency and has the potential to significantly reduce costs by up to 60%. It also contributes to environmental sustainability by cutting CO2 emissions by 80%. By supporting operators to run solely on coil tubing, HydraCT eliminates the need for a rig or vessel, reducing reliance on rig intervention and associated costs. With no rig infrastructure required, operators can achieve substantial cost savings and enhance operational flexibility.

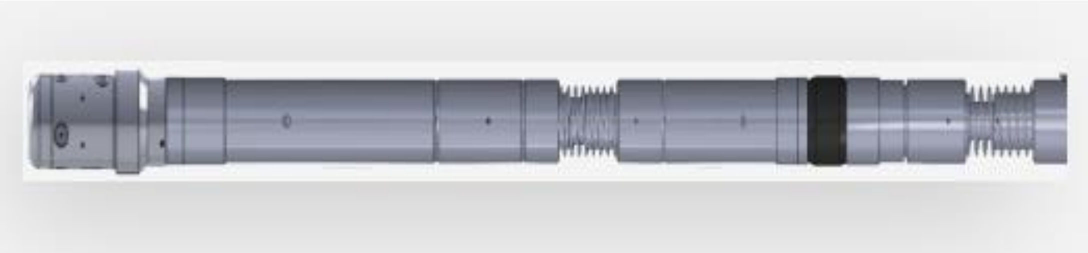


Figure 3.20 The HydraCT system from HydraWell [26]

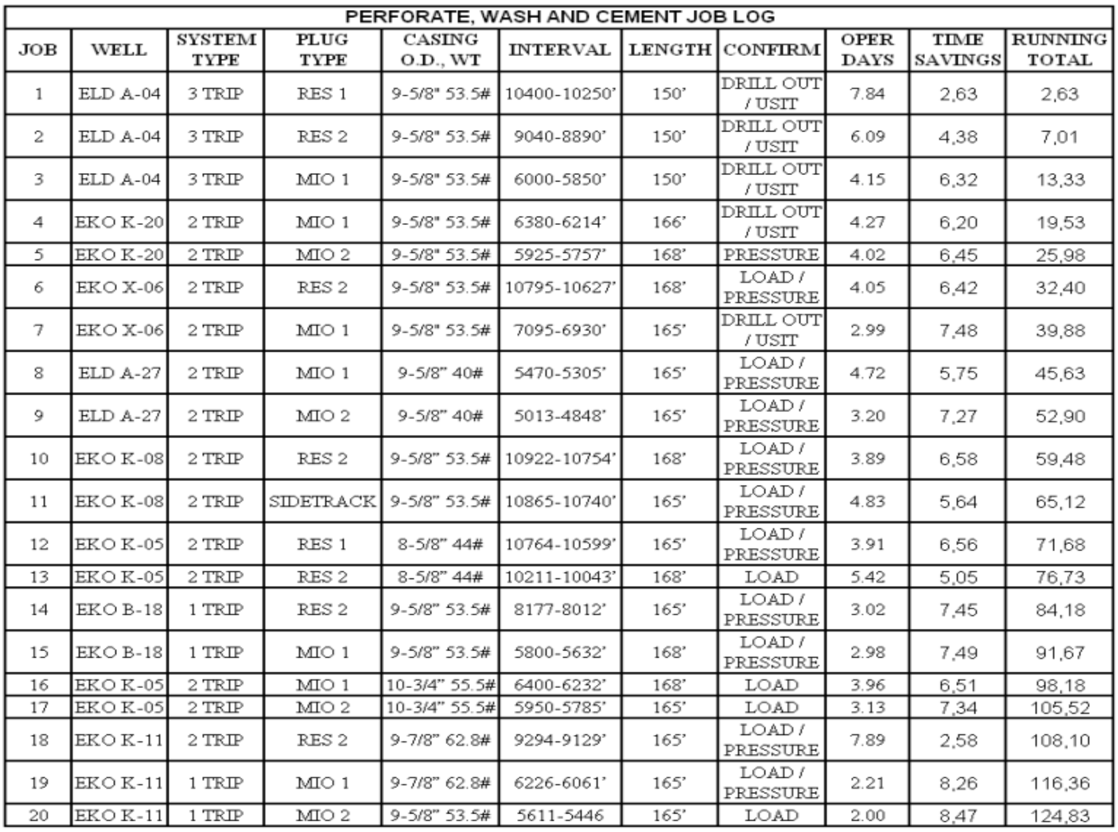
3.4.6 Perforate, Wash and Cement case studies

3.4.6.1 Case Study 1: Section Milling vs PWC

In 2008 and 2009, 6 wells were plugged using traditional section milling, with an average plug time of 10.5 days per well. However, one of the plugs took 20.4 days, which was excluded from the average due to its significant deviation from the rest. Table 3.3 presents the results of the section milling process. As of August 2011, 20 PWC plugs had been completed, and they all required one, two, or three runs and the operational time results have been compiled in Table 3.4, Perforate, Wash & Cement Job Log.

Well	Plug	Duration	
		Days	Days
X-09	Miocene	6.2	6.2
W-07	Reservoir 2	15.5	15.5
W-06	Reservoir 2	9.6	9.6
W-04	Reservoir 2	20.4	-
W-03	Reservoir 2	9.2	9.2
W-03	Miocene	10.9	10.9
W-01	Reservoir 2	8.1	8.1
W-01	Miocene	13.8	13.8
Average time per plug		11.7	10.5

Table 3.3 Time spent on each plug using traditional section milling [19]



PERFORATE, WASH AND CEMENT JOB LOG

JOB	WELL	SYSTEM TYPE	PLUG TYPE	CASING O.D., WT	INTERVAL	LENGTH	CONFIRM	OPER DAYS	TIME SAVINGS	RUNNING TOTAL
1	ELD A-04	3 TRIP	RES 1	9-5/8" 53.5#	10400-10250’	150’	DRILL OUT / USIT	7.84	2,63	2,63
2	ELD A-04	3 TRIP	RES 2	9-5/8" 53.5#	9040-8890’	150’	DRILL OUT / USIT	6.09	4,38	7,01
3	ELD A-04	3 TRIP	MIO 1	9-5/8" 53.5#	6000-5850’	150’	DRILL OUT / USIT	4.15	6,32	13,33
4	EKO K-20	2 TRIP	MIO 1	9-5/8" 53.5#	6380-6214’	166’	DRILL OUT / USIT	4.27	6,20	19,53
5	EKO K-20	2 TRIP	MIO 2	9-5/8" 53.5#	5925-5757’	168’	PRESSURE	4.02	6,45	25,98
6	EKO X-06	2 TRIP	RES 2	9-5/8" 53.5#	10795-10627’	168’	LOAD / PRESSURE	4.05	6,42	32,40
7	EKO X-06	2 TRIP	MIO 1	9-5/8" 53.5#	7095-6930’	165’	DRILL OUT / USIT	2.99	7,48	39,88
8	ELD A-27	2 TRIP	MIO 1	9-5/8” 40#	5470-5305’	165’	LOAD / PRESSURE	4.72	5,75	45,63
9	ELD A-27	2 TRIP	MIO 2	9-5/8” 40#	5013-4848’	165’	LOAD / PRESSURE	3.20	7,27	52,90
10	EKO K-08	2 TRIP	RES 2	9-5/8” 53.5#	10922-10754’	168’	LOAD / PRESSURE	3.89	6,58	59,48
11	EKO K-08	2 TRIP	SIDETRACK	9-5/8” 53.5#	10865-10740’	165’	LOAD / PRESSURE	4.83	5,64	65,12
12	EKO K-05	2 TRIP	RES 1	8-5/8” 44#	10764-10599’	165’	LOAD / PRESSURE	3.91	6,56	71,68
13	EKO K-05	2 TRIP	RES 2	8-5/8” 44#	10211-10043’	168’	LOAD	5.42	5,05	76,73
14	EKO B-18	1 TRIP	RES 2	9-5/8” 53.5#	8177-8012’	165’	LOAD / PRESSURE	3.02	7,45	84,18
15	EKO B-18	1 TRIP	MIO 1	9-5/8” 53.5#	5800-5632’	168’	LOAD / PRESSURE	2.98	7,49	91,67
16	EKO K-05	2 TRIP	MIO 1	10-3/4” 55.5#	6400-6232’	168’	LOAD	3.96	6,51	98,18
17	EKO K-05	2 TRIP	MIO 2	10-3/4” 55.5#	5950-5785’	165’	LOAD	3.13	7,34	105,52
18	EKO K-11	2 TRIP	RES 2	9-7/8” 62.8#	9294-9129’	165’	LOAD / PRESSURE	7.89	2,58	108,10
19	EKO K-11	1 TRIP	MIO 1	9-7/8” 62.8#	6226-6061’	165’	LOAD / PRESSURE	2.21	8,26	116,36
20	EKO K-11	1 TRIP	MIO 2	9-5/8” 53.5#	5611-5446	165’	LOAD	2.00	8,47	124,83

Table 3.4 Perforate, Wash & Cement Job Log [19]

Figure 3.21 shows the average time taken to complete these PWC plugs, including the average time for section milling as a point of comparison. The results indicate that PWC is much more efficient in terms of time than traditional section milling. The average time taken to complete a 50 m section using section milling was 10.47 days, whereas PWC was able to complete the same interval in a single trip, taking only 2.55 days, resulting in a savings of 7.9 days (70%) for a single section. Using PWC on all 20 plugs saved an estimated 124 rig days. [19].

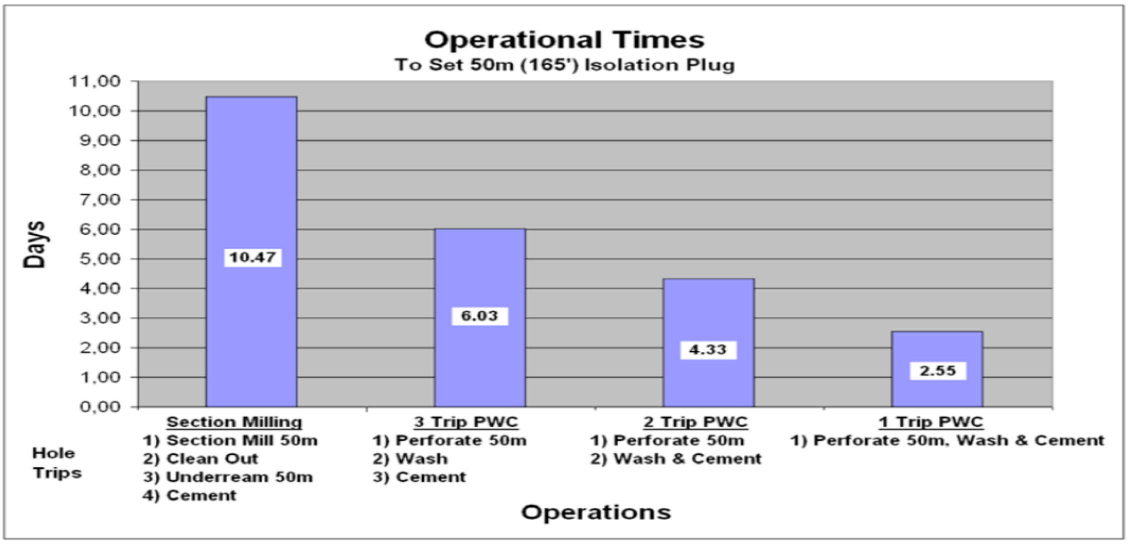


Figure 3.21 Field Operational Time Comparing Section Milling and PWC [19]

3.4.6.2 Case study 2: Comparison of the two main types of PWC tool concepts

There are two types of Perforate, Wash and Cement methods: the cup-type and jet-type (in the figure below). The selection of the PWC type is dependent on various factors, including the condition of the casing in the well to be plugged. The cup-type tool uses swab cups that are placed on either side of large nozzles, which circulate washing or cementing fluid into the annulus, and force the fluid to clean the annulus at high velocity. [27]

The cup-type tool shows in figure 3.22, is essentially a closed system, and hence, the standpipe pressure and return flow recorded at surface provide a clear and continuous feedback signal of washing effectiveness. In contrast, the jet-type tool in figure 3.23, employs small nozzles to jet fluid at high velocity through perforation holes into the annulus. However, the axial velocity declines rapidly with radial distance from the nozzle, and the lack of swab cups makes it an open system, allowing fluid to flow through the perforations and via the drill pipe/casing annulus. As a result, a continuous feedback signal at surface of washing effectiveness, degree of annular bond, or the perforation status of the casing is not provided. Additionally, the effectiveness of washing the annulus may be compromised in circumstances where the degree of annular bond to the casing is high, as the fluid may take the path of least resistance via the drill pipe/casing annulus.

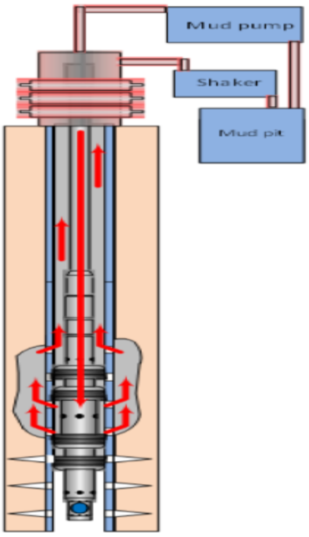


Figure 3.22 Closed system Cup type [27]

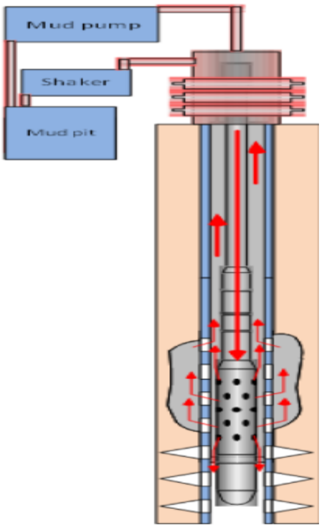


Figure 3.23 Open system Jetting type [27]

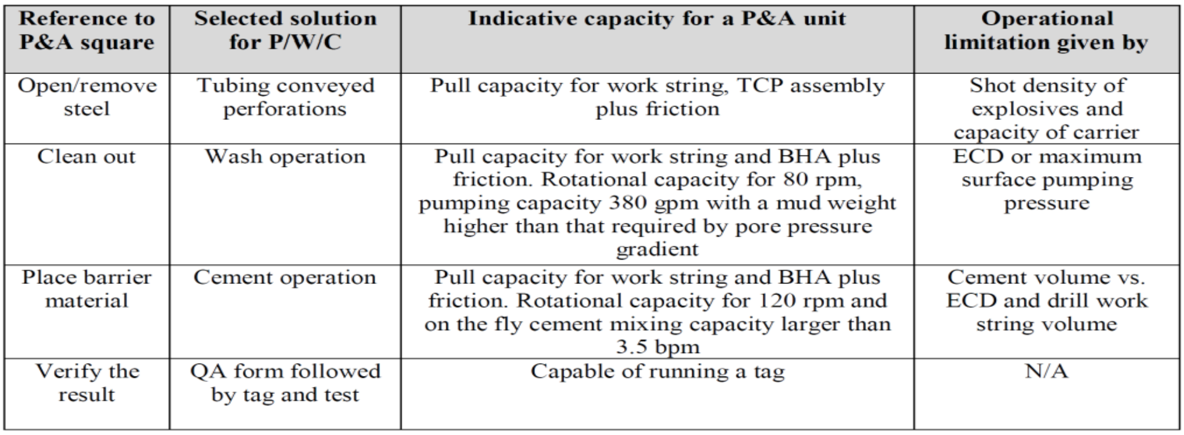
Table 3.5 summarizes the primary distinctions between the two tool types.[27]

	Closed system Cup type	Open system Jetting type
1	The cup-type tool employs double swab cups, one above and one below the nozzles.	Does not need swab cups.
2	Washing fluid is circulated through 6x0.906-inch nozzles located between the swab cups and into the annulus through the perforations.	Washing fluid is jetted out of, for instance, 30 x 1/8-inch nozzles in a tube that is about 2.5 feet long, at high velocity and impact force.
3	The cup-type tool is a "closed system," meaning the fluid can only go one way and must be forced into the annulus.	Fluid can flow through perforations to both the DP/casing annulus and the annulus behind it, making it a "open system."
4	The cup-type tool can rotate the string above the cups using a swivel.	Fluid can flow through perforations to both the DP/casing annulus and the annulus behind it, making it an "open system."
5	Cement is forced between cups and into annulus behind perforations.	A 3-foot-long cementing valve with four 1/8-inch nozzles sprays cement out of the nozzles.
6	Fluid bibass minimises surge/swab.	Using an "Archimedes" instrument, cement is pressed into perforations after spraying
7		Preferable is 18 spf with 1.1in EH or more.

Table 3.5 Comparison of the two main types of Perforate, Wash and Cement tool concepts [27]

In 2014, ConocoPhillips made the strategic choice to prioritize the Jet-type perforate, wash, and cement (P/W/C) technique as its main approach for permanently abandoning wells and establishing a comprehensive cement/steel barrier. In line with this decision, a project focused on enhancing quality was initiated to facilitate the shift from the Cup-type to the Jet-type P/W/C method, aiming to improve the overall quality of barrier plugs. [11]

In table 3.6, the required capacities for establishing a cross-sectional plug through the use of the Jet-type perforate, wash, and cement (PWC) method



Reference to P&A square	Selected solution for P/W/C	Indicative capacity for a P&A unit	Operational limitation given by
Open/remove steel	Tubing conveyed perforations	Pull capacity for work string, TCP assembly plus friction	Shot density of explosives and capacity of carrier
Clean out	Wash operation	Pull capacity for work string and BHA plus friction. Rotational capacity for 80 rpm, pumping capacity 380 gpm with a mud weight higher than that required by pore pressure gradient	ECD or maximum surface pumping pressure
Place barrier material	Cement operation	Pull capacity for work string and BHA plus friction. Rotational capacity for 120 rpm and on the fly cement mixing capacity larger than 3.5 bpm	Cement volume vs. ECD and drill work string volume
Verify the result	QA form followed by tag and test	Capable of running a tag	N/A

Table 3.6 Capacities required to set a cross-sectional plug using Jet-type P/W/C [11]

Due to closed system, standpipe pressure gives continuous clear feedback signal of washing effectiveness, washing data can be used to correlate vs. CBL data and de-risk chance of washing success. If annulus is plugged or perforation unsuccessful/blank section. Cannot circulate then tools provide diagnoses.

3.4.6.3 Case Study 3: The Hydrawell Solution

The Hydrawell solution is a development of the Perforate, Wash and Cement (PWC) technology, The Hydrawell system consists of two components, a HydraHemera Jetting Tool and a HydraHemera Cementing Tool. The HydraHemera Jetting Tool is a high-pressure jetting tool that is used to clean the inside of the wellbore before the cement plug is installed. The tool is lowered into the wellbore and uses a high-pressure water jet to remove any debris or residual fluids from the wellbore walls. The HydraHemera Cementing Tool is used to place the cement plug at the bottom of the wellbore. The tool is designed to mix and pump the cement slurry into the wellbore. Once the cement has been pumped, the HydraHemera Cementing Tool is used to verify that the cement has been properly set and is providing a reliable barrier. [26]

The solution is used to plug and abandon 10 well in Norwegian Continental Shelf and all 10 barrier plugs have been installed without incident, Savings of \$2.7 million for each barrier abandonment plug ≈ \$27 million totally, Time savings of 260 hours = 22 hours in average for each barrier abandonment plug. [28]

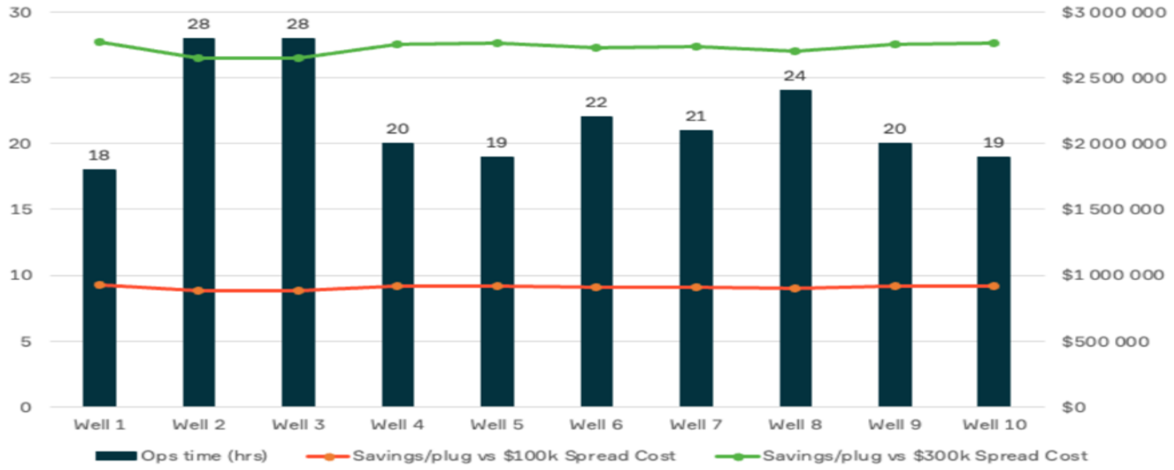


Figure3.24 operating time for Jet-PWC VS. saving for a 10-day benchmark Section Mill operation [28]

3.4.6.4 Case Study 4: PWC compared with Cut & Pull and Section Milling, (Value of PWC)

PWC avoids the technical hazards and potential price increases connected to stuck or parted casing, surface handling, and post-operational cleaning of components like BOPs. Also, PWC lowers the functional requirements. Table3.7 shows that, there is no longer a need for high hook loads, high torque capacities, and/or swarf management devices, which reduces the cost exposure of the "rig spread".

	PWC	**Section Milling**	**Cut and pull Casing**
Hook Load	150t	150t	250t
Torque capacity	2k ft.lbs	15k ft.lbs	15 ft.lbs
Swarf Handling	No	Yes	No

Table 3.7—Typical Rig Functionality Requirements for Annulus Remediation Methods [24]

PWC adds value by saving the total time required for procedures, as seen in the figure 3.25. When operational optimization has been effectively implemented, a typical one-trip operation may be expected to be completed in about 36 hours, with recent field performance comprising the installation and verification of 4 plugs in 8.8 days. [24] PWC has demonstrated significant time savings, reducing the operational time by 65% when compared to section milling and 70% when compared to cut and pull operations.

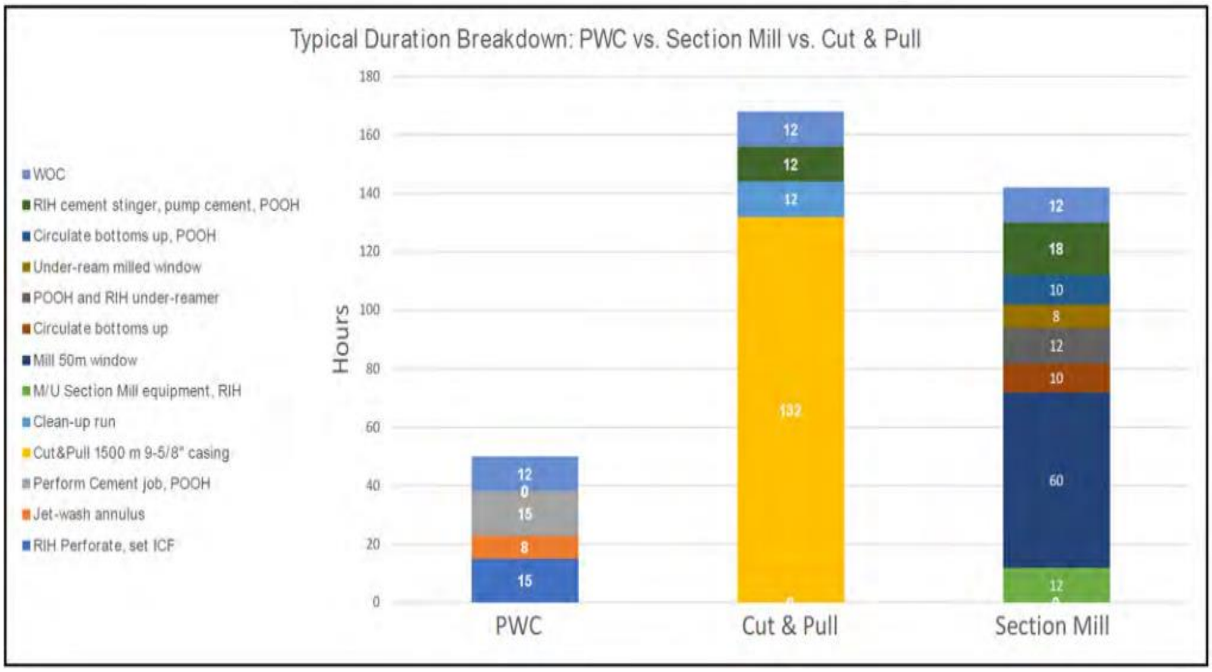


Figure 3.25—Typical Durations for Barrier Installation Operations.[24]

Costs are reduced as a result of this time savings. Figure 3.26 below demonstrates that, for normal charges and durations, the breakeven point is around a spread rate of US $50,000/day.

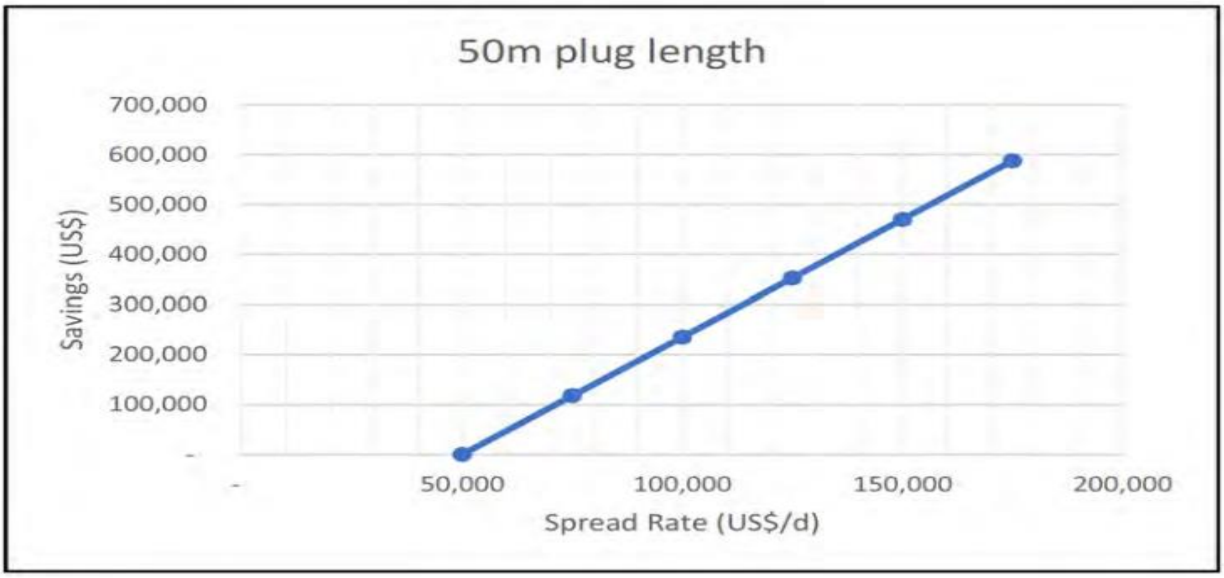


Figure 3.26—Typical Anticipated Savings using PWC compared with Section Milling as a function of Spread Rate (50m barrier length).[24]

4. Materials used in P&A

The P&A of well bores needs to be long-term sealed barriers with low cost. Simultaneously, as shown in the flow-chart Figure 4.1, geological conditions controlled by nature (geochemistry, geomechanics) should be included in the choice of P&A materials and designing placement processes, so that P&A last very long time (durable) without fail.

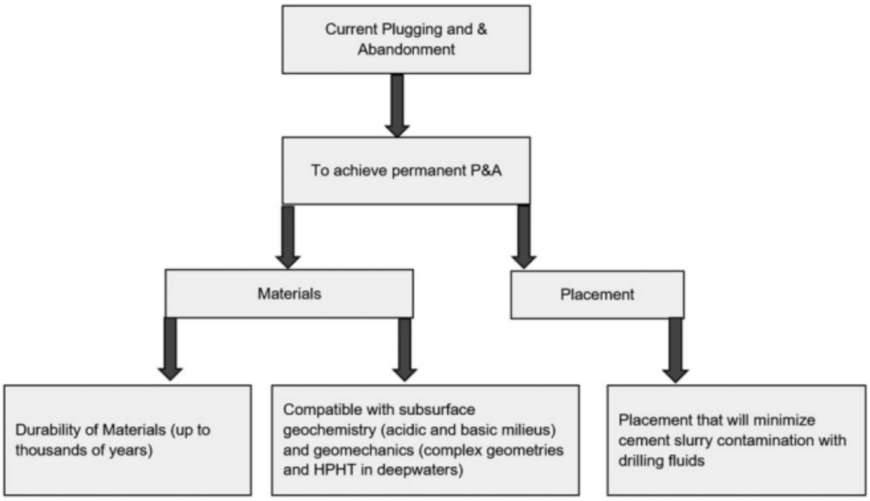
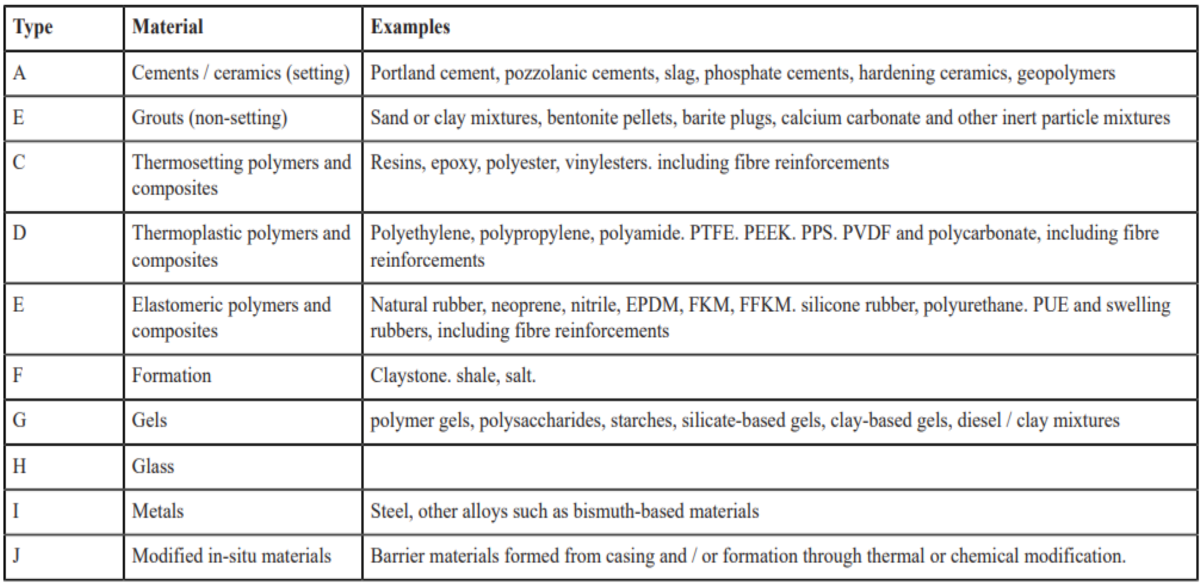


Figure 4.1 Flow-chart of design/choice of P&A materials and placement processes [29]

The lists of some alternatives available are presented in Table 4.1 Some have advantages over the cement and some fulfilling the minimum and functional operating requirements.



Type	Material	Examples
A	Cements / ceramics (setting)	Portland cement, pozzolanic cements, slag, phosphate cements, hardening ceramics, geopolymers
E	Grouts (non-setting)	Sand or clay mixtures, bentonite pellets, barite plugs, calcium carbonate and other inert particle mixtures
C	Thermosetting polymers and composites	Resins, epoxy, polyester, vinylesters. including fibre reinforcements
D	Thermoplastic polymers and composites	Polyethylene, polypropylene, polyamide. PTFE. PEEK. PPS. PVDF and polycarbonate, including fibre reinforcements
E	Elastomeric polymers and composites	Natural rubber, neoprene, nitrile, EPDM, FKM, FFKM. silicone rubber, polyurethane. PUE and swelling rubbers, including fibre reinforcements
F	Formation	Claystone. shale, salt.
G	Gels	polymer gels, polysaccharides, starches, silicate-based gels, clay-based gels, diesel / clay mixtures
H	Glass	
I	Metals	Steel, other alloys such as bismuth-based materials
J	Modified in-situ materials	Barrier materials formed from casing and / or formation through thermal or chemical modification.

Table 4.1 Well P&A Material Types [8]

4.1 Conventional P&A materials

Obtaining a satisfactory plug cement slurry is extremely important.

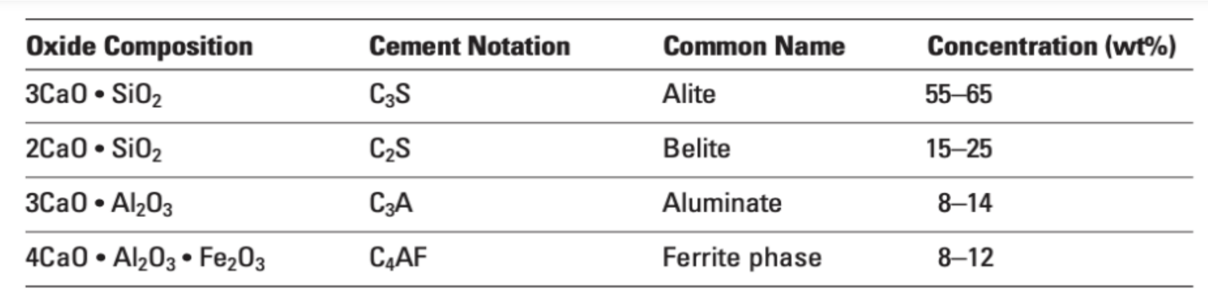
4.1.1 Cement slurry

Cement is the first material to be deployed for making cement plugs and placed in boreholes. Due to binding and sealing properties cement is used in constructional technology. It is one of the materials in plane concrete, RCC work, and mortar. Plane cement with water is used as a neat punning material. Being a good sealing agent, Portland cement or oil well cement is used as a plugging material to plug the abandoned well to stop the movement of fluids or gas from one level to another. Portland cement is a grey powder that has adhering properties and on mixing with water it forms a paste called as cement slurry which can seal the bore hole. Portland cement also called hydraulic is a desirable material for well cementing due to its ability to set in both air and water, predictable and quick strength development, low permeability, and insolubility in water. It is commonly used for sealing off annulus in a wellbore. [30]

According to NORSOK D-010, which outlines requirements for permanent well barriers in abandonment operations, cement plays a vital role as a barrier element. It must possess specific characteristics to be effective, including impermeability, long-term integrity, non-shrinking properties, ductility (non-brittleness), resistance to mechanical loads and impacts, and compatibility with various chemicals/substances such as H_2S, CO_2, and hydrocarbons. Additionally, cement should have wetting properties to ensure proper bonding to steel.

4.1.2 Portland cement

Portland cement is produced by grinding clinker, which refers to nodules of various sizes ranging from 5 to 25 mm in diameter. The clinker is formed by sintering material in a rotary kiln, which is commonly used in cement manufacturing plants. The clinker comprises four major minerals: Alite, Belite, Tricalcium Aluminate, and Tetra Calcium Aluminate Ferrite. This means that the production of OPC requires raw materials that contain specific amounts of calcium, silica, alumina, and iron compounds. As long as the raw materials meet these requirements, various materials can be used to produce OPC clinker. Table 4.2 displays the concentration of various oxides in a classic Portland cement clinker [30]

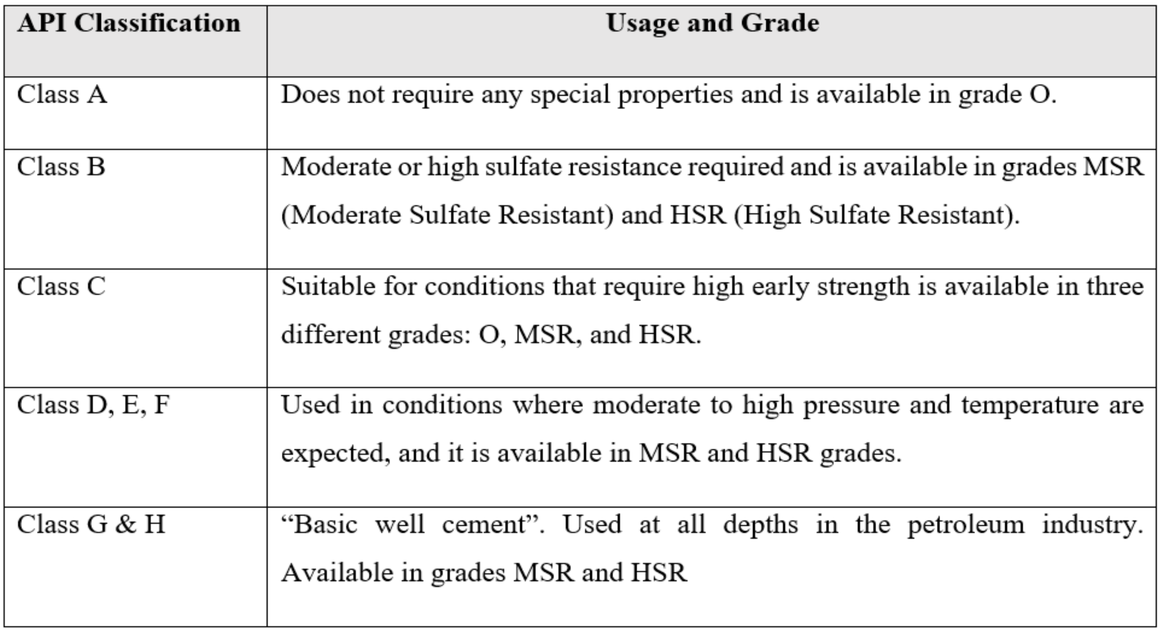


Oxide Composition	Cement Notation	Common Name	Concentration (wt%)
$3CaO \cdot SiO_2$	C_3S	Alite	55–65
$2CaO \cdot SiO_2$	C_2S	Belite	15–25
$3CaO \cdot Al_2O_3$	C_3A	Aluminate	8–14
$4CaO \cdot Al_2O_3 \cdot Fe_2O_3$	C_4AF	Ferrite phase	8–12

Table 4.2 composition of classic Portland cement clinker [30]

4.1.2.1 Classification of Portland cement

Portland cement is widely used in various industries, and they are manufactured with different properties depending on their intended application. To ensure consistency in performance and properties, and to distinguish between different types of cements, classification systems have been introduced. The API and ASTM classification systems are the most common for the petroleum industry. The API classification system is based on the ISO standard, and it provides specific criteria for cement manufacturers to meet based on the intended application.[30]. Table 4.3 shows the API classification system, which is used to classify cement based on their properties, such as sulfate resistance, early strength, and pressure/temperature requirements.



API Classification	Usage and Grade
Class A	Does not require any special properties and is available in grade O.
Class B	Moderate or high sulfate resistance required and is available in grades MSR (Moderate Sulfate Resistant) and HSR (High Sulfate Resistant).
Class C	Suitable for conditions that require high early strength is available in three different grades: O, MSR, and HSR.
Class D, E, F	Used in conditions where moderate to high pressure and temperature are expected, and it is available in MSR and HSR grades.
Class G & H	“Basic well cement”. Used at all depths in the petroleum industry. Available in grades MSR and HSR

Table 4.3 Classification of API Cement and usage [30]

The use of classes D, E, and F in cement production is limited due to the use of outdated additives for processing purposes. Classes G and H, on the other hand, do not allow for any additives to be used during production. This is to prevent interference with the later addition of cement additives, such as retarders or accelerators, which are used to obtain desired cement properties. The restrictions on additives and classifications are in place to ensure efficiency and stability in cement production.

4.1.2.2 Setting and hardening of Portland cement

Mixing water with cement initiates the setting process, where the cement forms a gel that binds together sand, stones, and other materials or creates a seal on their surfaces. This setting phase allows the cement mixture to be moulded into desired shapes. Concurrently, the hardening process takes place, characterized by the formation of crystalline products as a result of hydration. The entire setting and hardening process typically span around 20 days, during which various components like C_3A, C_3S, C_4AF, and C_2S are formed. These components contribute to the strength and structure of the cement. If the hydration process continues, the hardening process can persist for an extended period, even up to a year.[31]

The process of setting and hardening of cement can be observed in three stages:

1. Initial setting: When water is added to cement, the hydrolysis process does not immediately occur. As a result, the mixture can be moulded into various forms while still in a plastic state. However, over time, the mixture undergoes jellification.

2. The mixture is left undisturbed until it reaches a certain level of stiffness. At this point, a standard needle can penetrate the mixture to a specific depth.

3. Final setting: After approximately one hour, the cement mixture reaches a state of stiffness where it can no longer be moulded. The standard needle is unable to penetrate the mixture at all. Hardening of the cement involves further reactions through hydrolysis, which contribute to an increase in its strength.

The hardening process continues as long as the cement remains in a moist environment and may persist for several years. However, it is important to note that the rate of hardening decreases over time.

4.1.2.3 Hydration of Portland cement

Hydration of Portland cement involves a complex chemical reaction between the cement and water. The reaction produces several hydration products, including calcium silicate hydrate (C-S-H) and calcium hydroxide (portlandite). The silicates, C_3S and C_2S, are the most prevalent in the Portland cement mixture and react chemically in the following idealized manner [31]

$$2C3S \rightarrow C3S2H3 + 3CH$$

Equation 4.1

$$2C2S + 4H \rightarrow C3S2H3 + CH$$

Equation 4.2

The reaction begins with the dissolution of the cement particles in water, which releases calcium, silicate, and aluminate ions into the solution. The calcium ions combine with the water molecules to form calcium hydroxide, while the silicate and aluminate ions react with the water to form C-S-H and calcium aluminate hydrate (CAH).

The C-S-H phase is the most important product of Portland cement hydration, as it is the primary binder that gives cement its strength. The C-S-H phase has a variable composition, depending on factors such as calcium concentration, temperature, and the presence of additives. It typically makes up about 65% of fully hydrated Portland cement.

The Calcium hydroxide phase is highly crystalline and occurs as hexagonal plates. Its concentration in hardened cement is usually between 15% and 20%.

The hydration of C_3S (the principal constituent of Portland cement) is responsible for the beginning of the set and early strength development. The hydration of C_2S is significant only in terms of the final strength of the hardened cement. Figure 4.2 illustrates the variation in hydration time. [30], [31]

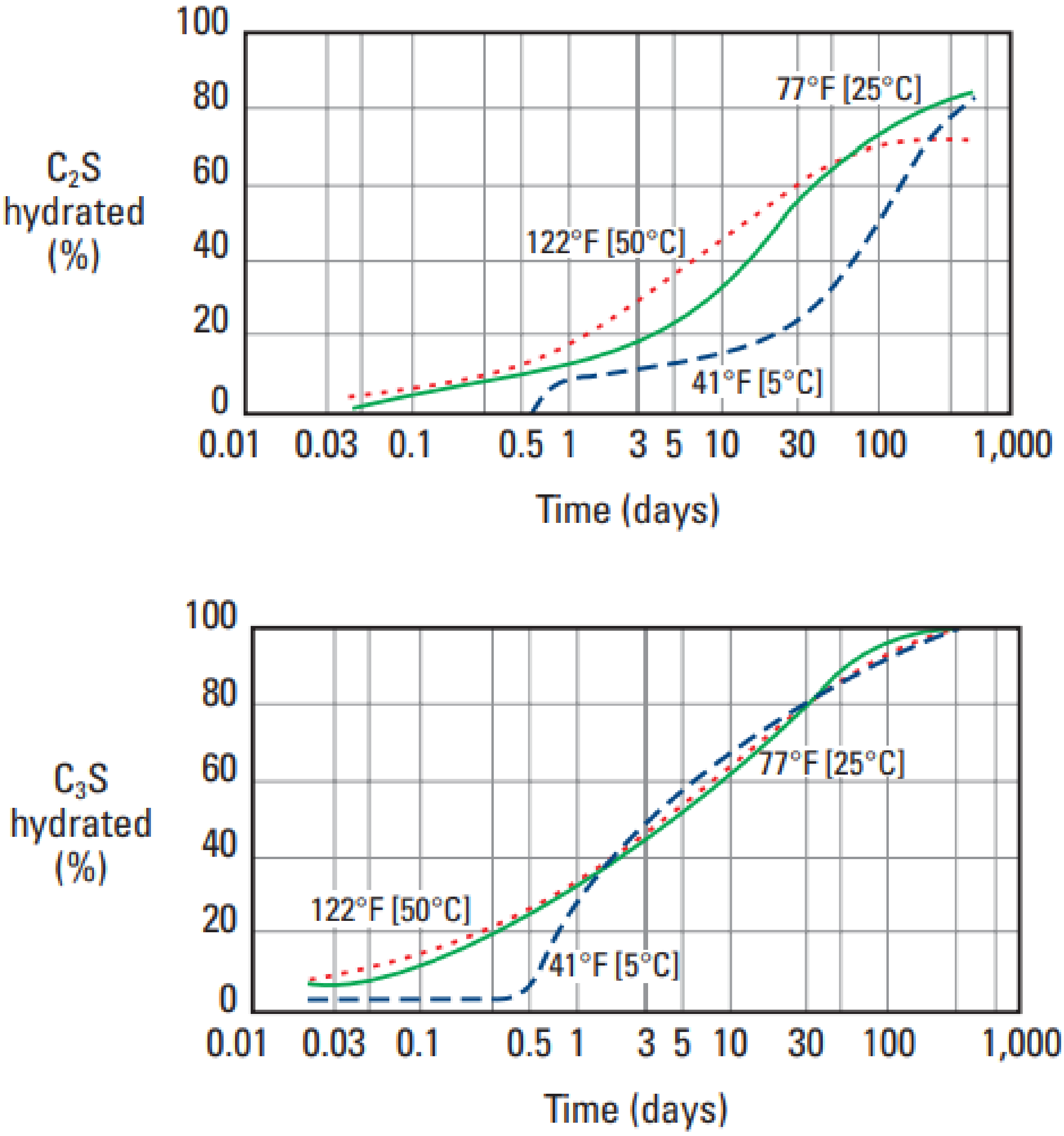


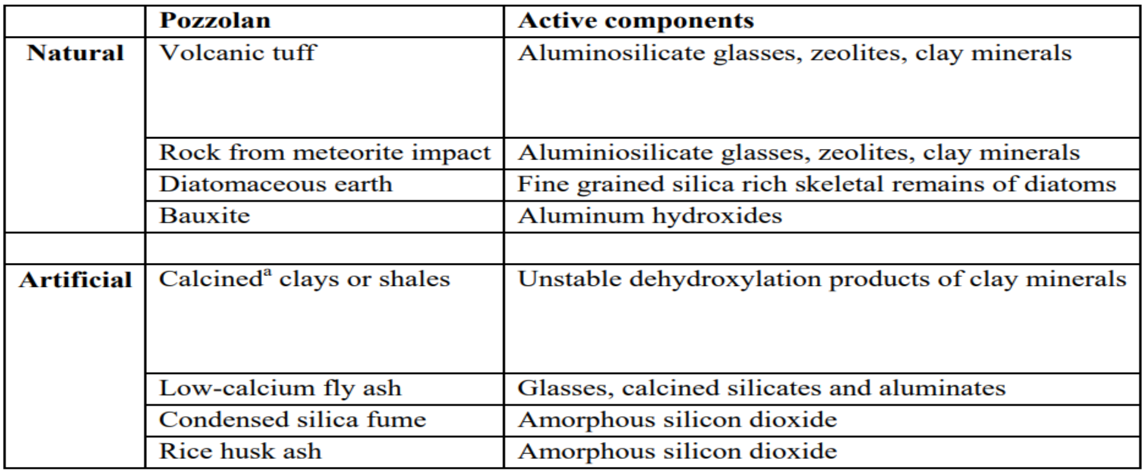
Figure 4.2 Hydration of C_2S and C_3S versus time [30]

4.2 Alternative and emerging plugging materials

This section focuses on presenting some alternative and emerging plugging materials specifically relevant to P&A operations in the field of the oil and gas industry. These materials offer unique properties and hold promise in addressing the challenges associated with sealing wells during the P&A process. The key materials discussed include Pozzolanic-Portland cement, Bismuth alloy, Geopolymers, Sodium bentonite, thermosetting resins, modified in-situ materials, and shale creep.

4.2.1 Pozzolanic cement

Pozzolanic-Portland cement is a type of blended cement that is produced through the intergrading of ordinary Portland cement clinker with gypsum and pozzolanic materials, or by separately preparing each component and then blending them. These cements adhere to the chemical composition requirements outlined in ASTM standard C618, with approximately 70% content of silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), and iron oxide (Fe_2O_3). The maximum allowed loss on ignition is 10%, as per the same standard. The content of acidic and amphoteric oxides (such as silica, alumina, and ferric oxide) can vary among different pozzolans. Silica is a significant component found in both natural and processed pozzolans. Pozzolans, whether natural or artificial, are reactive siliceous materials that can start to hydrate in the presence of lime and water, developing cementitious properties. The primary source of natural pozzolanic materials is volcanic ashes, while artificial pozzolans are created through the calcination of natural siliceous materials like clays, shales, rice husk ash, and certain siliceous rocks.[32] Examples of both types are given in Table 4.4.



	Pozzolan	**Active components**
Natural	Volcanic tuff	Aluminosilicate glasses, zeolites, clay minerals
	Rock from meteorite impact	Aluminiosilicate glasses, zeolites, clay minerals
	Diatomaceous earth	Fine grained silica rich skeletal remains of diatoms
	Bauxite	Aluminum hydroxides
Artificial	Calcined^a clays or shales	Unstable dehydroxylation products of clay minerals
	Low-calcium fly ash	Glasses, calcined silicates and aluminates
	Condensed silica fume	Amorphous silicon dioxide
	Rice husk ash	Amorphous silicon dioxide

Table 4.4 Example of pozzolans [32]

4.2.2 Bismuth alloy plug

Bismuth alloy is a unique metal with properties that make it ideal for plug and abandonment operations. No surface pumping equipment is needed for this type of plug. It is impermeable, heavy like lead, and flows like water when melted, allowing it to reach small spaces in the well. As it solidifies, it expands, providing a permanent seal. A 2.5-meter bismuth plug is sufficient for long-term isolation, unlike longer cement plugs. Although bismuth alloy is more expensive, reduced rig time lowers overall costs. It also minimizes the carbon footprint due to its instant solidification and impermeability, offering advantages over cement.[33] Bismuth alloy exhibits a comparatively lower melting point in comparison to other metals (273 °C). Due to this characteristic, it is employed in certain commercial applications as a substitute for lead, primarily because of its non-toxic nature. It is classified as a eutectic metal, transitioning swiftly from a liquid to a solid state upon cooling below its melting point, thereby bypassing the gel phase.[34]

According to Aker BP, the utilization of bismuth alloy for plugging wells on Valhall has proved to be a groundbreaking solution. Plugging wells on the Valhall field presents unique challenges, such as gas migration to the surface, subsidence, and compaction. These factors can potentially compromise the integrity of traditional cement barriers used for well plugging, allowing hydrocarbons to escape and potentially contaminate the surrounding environment.[33]

Recognizing the need for a more reliable and robust solution, Aker BP pioneered the use of bismuth alloy in the top section of the well. By implementing this technology, Aker BP ensures that the plug is 100 percent impermeable, effectively preventing gas leakage to the surface. The bismuth alloy plugs, measuring up to 2.5 meters in length and weighing 9 tonnes, have demonstrated their effectiveness in mitigating the risks associated with well plugging. One of the key advantages of using bismuth alloy plugs is their ability to withstand the stresses imposed by subsidence and compaction events. Unlike cement, which can fail under these conditions, the bismuth alloy maintains its integrity, providing a reliable barrier that prevents the migration of hydrocarbons. This innovation is particularly significant considering that the seabed around the Valhall field has sunk seven meters since the early 1980s, with the top of the reservoir dropping about 15 meters. Furthermore, the implementation of bismuth alloy plugs has yielded substantial operational benefits. Aker BP has streamlined the plugging process, significantly reducing the time spent per well. In fact, they achieved a record-low time of only 30 hours per well, cutting the previous duration in half. This improved efficiency has not only resulted in considerable cost savings but has also freed up several months of rig time that can now be allocated to new operations.

Bismuth is a metal with a specific gravity (SG) of 10, eliminating the need for squeezing. It boasts excellent corrosion resistance against commonly encountered downhole corrosive agents like CO_2 and H_2S. The alloy has a eutectic nature, melting or solidifying at a specific temperature lower than its constituent metals. It rapidly transitions from liquid to solid without a gel phase. Additionally, bismuth alloy exhibits minimal creep over time, depending on the specific alloy design.[35] Figure 4.3 pellet and solid bismuth.

Figure 4.3 Pellet and solid bismuth [35]

Melting bismuth downhole poses a challenge due to the high-power requirements and time constraints. Electric heaters were considered but proved impractical. Instead, thermite, a mixture of iron oxide and aluminum, is used to initiate a highly exothermic reaction. Once initiated, the heat from the thermite melts the bismuth alloy, which then flows and solidifies to provide permanent sealing in the wellbore. The molten alloy fills any gaps, including micro-annuli, and expands upon solidification.[35]

The Valhall field in Norway served as the first large-scale program for bismuth alloy abandonment applications. A successful trial in one well led to the expansion of the application to 30 wells. Different tool sizes were used, including the world's largest bismuth alloy plug, resulting in a solid barrier after melting the tools downhole.[35] Table 4.5 Time Analysis: Bismuth Plugs vs. Cement Plugs in Valhall's Seal 1 and seal 2. The use of bismuth plugs in the P&A campaign resulted in significant time savings compared to cement plugs. Bismuth was 73% quicker for Seal 1(30 wells) and 7% quicker for Seal

2 (5 wells), leading to a total time saving of 89.6 days. This reduced the abandonment schedule for the Valhall DP platform from 10 years to 4 years. In addition to environmental benefits, such as reduced energy consumption and emissions, the use of bismuth plugs provided premium-quality abandonments, simplified operational procedures and gained regulatory approval. The decreased need for section milling and cement usage further contributed to cost and time savings while protecting the environment.

RIG TIME (hrs)	BISMUTH	CEMENT
Dress off cement plug	6.1	6.1
Starter Cut / Initiate window	6.7	6.7
Section mill window	10.1	75.75
Scrub window	4.7	10
Cleaning BOP / cleanout run	1.9	4
Install and verify foundation	4.6	5
Place bismuth plug	6.8	
Place cement plug		4
Wait on bismuth and verify	offline	
Wait on cement and verify		offline
Additional (if applic)		
TOTAL (hrs)	40.9	111.55

RIG TIME (hrs)	BISMUTH	CEMENT
Starter Cut / Initiate window	6.7	6.7
Section mill window	7.5	15
Scrub window	4.7	10
Cleaning BOP / cleanout run	36	36
Install and verify foundation	4.6	4.6
Place bismuth plug	6.8	
Place cement plug	4	4
Wait on bismuth and verify	12	
Wait on cement and verify		12
Additional (if applic)		
TOTAL (hrs)	82.3	88.3

Table 4.5time Analysis: Bismuth Plugs vs. Cement Plugs in Valhall's Seal 1 (on left) and seal 2 (On right) [35]

Metals used in P&A operations, including bismuth-based alloys, have several key attributes:[36]

- They can create fast formation-to-formation barriers, ideal for uncemented annuli.
- They can be deployed with wireline during rig-less operations.
- They have a wide applicable range of melting points and can withstand various well fluids.
- They offer cost-effective solutions with low alloy volume requirements.
- They expand upon solidification, ensuring a tight seal and resistance to loads.
- They can generate heat to facilitate well-element removal.

However, there are some limitations:

- There may be thermal shrinkage during hardening.
- Liquid metal embrittlement can occur when introduced in a liquid state.
- Thermal shock during setting can affect integrity and isolation.
- Failure modes include corrosion, stress corrosion cracking, debonding, creep, and fatigue.
- Cement is still required for regulatory compliance, but bismuth alloys are being evaluated as alternatives.

4.2.3 Geopolymers

Geopolymers are man-made, rock-like materials that can be referred to as "artificial stone". They are composed of alkali-activated aluminosilicate with minimal calcium content. The type of raw material used, such as fly ash or kaolinite, determines the properties of the resulting geopolymer. By varying the precursor material, various types of geopolymers can be created with selected properties.[12]

There are three main mechanisms involved in the solidification of aluminosilicate materials: dissolution or depolymerization, transportation or orientation, and geopolymerization or polycondensation. In the dissolution process, the alkaline activator attacks the precursor materials breaks down the silicates, and forms small oligomers. These oligomers can be transported through the liquid phase and rearrange themselves. During the geopolymerization stage, the oligomers covalently bond to form long chains of molecules or geopolymers. This reaction is fast and difficult to control.[37]

Geopolymers have primarily been used as construction materials in civil engineering, but recent studies have shown their potential for use in well-cementing operations. Geopolymers offer advantages such as low shrinkage, low permeability, strength development, stability at elevated temperatures, and tolerance to contamination with oil-based mud, which make them a potential alternative to Portland cement for various well cementing applications, including P&A. However, questions remain about controlling pumpability and optimizing waiting on setting. Geopolymers have also been observed to have self-healing properties, which could be beneficial in the long-term.[38]

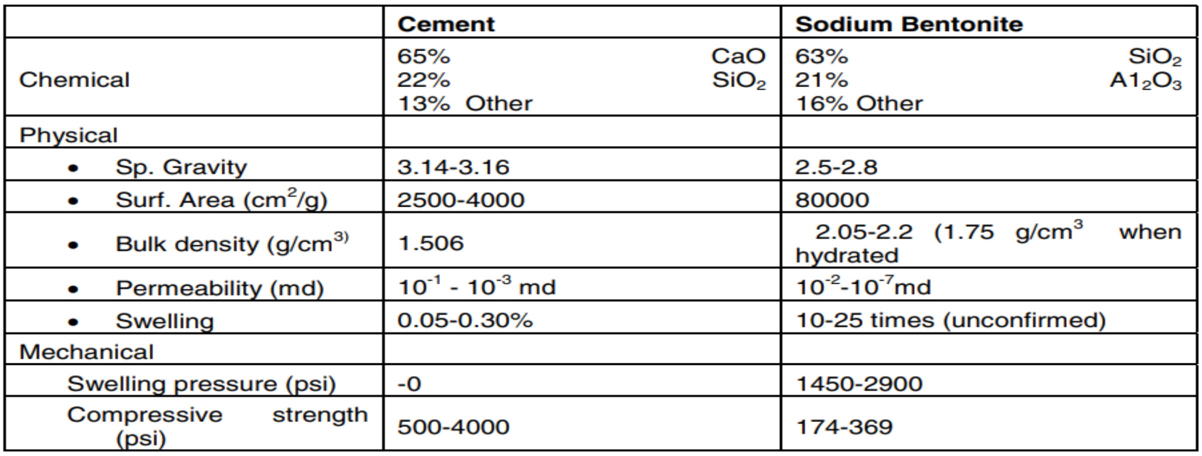
4.2.4 Bentonite plug

Sodium bentonite, a clay material primarily composed of sodium montmorillonite, is well-known for its exceptional plugging capability, low permeability, and hydration properties. It has been widely used in various applications, including monitoring wells, seismic shot holes, mining shafts, exploratory holes, water wells, and occasionally oil and gas wells.[39]

One significant challenge faced in utilizing sodium bentonite for well plugging is the occurrence of bridging during its placement at depth. To address this challenge, compressed sodium bentonite nodules were proposed as a potential solution. These nodules, when placed in wells, form impermeable plugs that create a reliable barrier. The dense and plastic nature of the material allows it to adapt to the changing formation environment through its latent hydration characteristics.

Extensive research was conducted to investigate the behavior of sodium bentonite under different conditions. This included examining its response to varying salinity levels, exposure to gases such as H2S, temperature fluctuations, and fluid conductivity. The study's conclusions yielded significant findings. Compressed sodium bentonite was successfully placed in wells, forming impermeable plugs with considerable latent hydration capability. It demonstrated its effectiveness in creating reliable plugs, even in challenging environments such as seawater and highly saline brines. The presence of oil or an oil column did not hinder its performance. Sodium bentonite remained stable at temperatures up to 170°C, and higher temperatures expedited its hydration process.[39]

In comparison to cement, sodium bentonite does have some limitations, as outlined in Table 4.6, which compares their physical and chemical characteristics [39]. Sodium bentonite has a lower specific gravity, potentially impacting its stability and sealing ability within the wellbore. Its higher surface area can lead to increased water absorption and swelling, which may result in pressure-related issues. Additionally, sodium bentonite exhibits lower compressive strength and higher permeability compared to cement, making it more susceptible to mechanical stresses and compromising its ability to isolate fluid flow pathways. The swelling behavior of sodium bentonite can also be uncertain or variable, posing challenges in accurately predicting and controlling its sealing characteristics.



	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

Table 4.6 comparison the physical and chemical characteristics of sodium bentonite with cement [39]

Understanding these limitations is crucial for the effective utilization of sodium bentonite in oil and gas plug and abandonment operations.

4.2.5 Thermosetting polymers and composite (resins)

It includes substances such as resins, epoxy, polyester, and vinyl esters, along with fiber reinforcements. Thermosetting polymers, which are particle-free fluid resins, transform into a solid state that is impermeable upon undergoing curing. The curing process is initiated by reaching a specific temperature. This type of material surpasses conventional Portland cement for the following reasons:

a) Unlike the setting process of Portland cement, where there is a "transition time," the formation of thermosetting polymers experiences continuous hydrostatic pressure from the solidifying resin during the transition from liquid to solid.

b) Before the resin sets, it possesses properties such as low viscosity, minimal shrinkage, a low yield point, low permeability, and excellent adhesion. After setting, the resin exhibits properties such as toughness, flexibility, and resistance to caustic and corrosive chemicals (such as CO_2, H_2S, hydrocarbons, brine) at high temperatures and pressures. Settled resins can endure impurities in the wellbore without significant degradation. Moreover, resins are compatible with numerous drilling fluids and can be pumped using conventional equipment.[40]

Resins or plastic cements are composed of a blend of API class A, B, G, or H cement, liquid resins, water, and a catalytic converter. These cements are utilized in limited quantities to seal open holes and compress perforations. The suggested temperature range for their application is 60 to 200 °F. [6] Thermosetting resins undergo a setting process when catalysts are present, typically achieved through the application of heat, pressure, or a combination of both. This setting process is permanent and irreversible, meaning that once the resin has set, it cannot be reheated and reshaped. The properties of thermosetting resins commonly employed for zonal isolation are outlined in Table 4.7.

Property	**Range**
Density	6.2–20.8 ppg
Viscosity	10–2000 cp
Right angle set	Yes
Target temperature	68–300 °F
Pumpable through pipe	Yes
Miscible with water or well fluids	No
Decomposition temperature	900 °F
Setting time	Depends on curing temperature

Table 4.7 The properties of thermosetting resins commonly employed for zonal isolation [41]

Resins offer several advantages over Portland G cement, including [42]

1. Compressive Strength: Resins can exhibit high compressive strength, providing reliable structural integrity.
2. Tensile Strength: Resins possess good tensile strength, enabling them to withstand tension forces.
3. Shear Bond Strength: Resins have strong shear bond strength, ensuring effective bonding to surfaces.
4. Flexibility: Resins are more flexible compared to cement, allowing them to accommodate slight movements or deformations.
5. Gas Tightness: Resins have excellent gas-tight properties, preventing gas migration or leakage.
6. Enhanced Penetration: Resins can penetrate deeper into formations, ensuring better sealing and isolation.

7. Adjustable Curing Time: Resins offer the advantage of a shorter, adjustable curing time, allowing for quicker operations.
8. Longer Service Life: Resins have a longer service life compared to cement, providing long-term integrity.

These advantages make resin-based materials more suitable for reservoir sections of wells. However, Thermosetting polymers, particularly resin, have certain limitations that should be considered when evaluating the use of resin-based materials in specific contexts. These limitations include:[36]

1. Unsuitability for Primary Cementing: Resins are not suitable as a direct replacement for primary cementing operations.
2. Rapid Hardening and Thermal Expansion: Resins undergo an exothermic reaction, leading to rapid hardening, thermal expansion, and shrinkage. This can impact the performance of the resin and surrounding materials such as casing, cement, or rock.
3. Heat Concentration and Trapping: Care should be taken to prevent heat concentration and trapping during the resin curing process, including cooling the casing. Large volumes of resin may pose a combustion or explosion risk.
4. Irreversible Setting and Curing Processes: Once the resin curing process is complete, it is challenging to modify the resin's shape or structure. The setting and curing processes are irreversible.
5. Limited Understanding of Seal Failure Mechanisms: The mechanisms causing seal failure and the properties necessary for seal durability with thermosetting polymers, like resin, are not fully understood.
6. Higher Cost: Thermosetting polymers, including resin, generally cost significantly more than cement on a volume basis, typically ranging from 15 to 50 times higher.
7. Lack of Universal Standards: There are no universally applicable standards for the use of thermosetting polymers as well sealants, and their application requires careful engineering.

Comparison of the Mechanical properties and Permeability between resin specifically formulated for zonal isolation and Neat G-cement in table 4.8 and table 4.9

Mechanical properties	Cement	Resin
Compressive strength (MPa)	58	77
Flexural strength (MPa)	10	45
E-modulus (MPa)	3700	2240
Failure flexural strain (%)	0.32	1.9

Table 4.8 Mechanical Properties of resin designed for zonal isolation versus Neat G-cement [42]

Permeability	Cement	Resin
Water permeability (mD)	0.0016	< 0.0000005
Lamp oil permeability (mD)	n/a	< 0.0000005

Table 4.9 Permeability of resin designed for zonal isolation versus Neat G-cement [42]

In a case study, the well presented numerous challenges for plugging and abandonment due to a compromised tubular, a depleted reservoir, and previous failed remediation attempts. Cement plugs were unsuccessful as they disappeared into the reservoir before hardening, exacerbating the well's downhole complexity. Additionally, a prematurely set rigid liquid in the tubing prevented tool access to the well. Lost circulation materials and $CaCO_3$ pills were also used but may have restricted flow.[42]

Resin application proved to be an ideal solution due to its ability to be formulated solids-free and its post-set resilience. A 94.4-barrel resin pill was engineered with a density matching that of seawater and a curing time of 30 minutes at reservoir temperature. The resin's Newtonian fluid profile and tuned viscosity allow it to be easily circulated through the narrow restrictions of the side pocket mandrel and displaced to the perforations. Partial success was confirmed through increased differential across the perforations. A second 94.4-barrel resin pill was then pumped, achieving the objective of sealing the reservoir, as confirmed by positive and negative pressure testing of the set plug.[42] Figure 4.4 provides a visual representation of how the resin applications were carried out, showcasing the execution process.

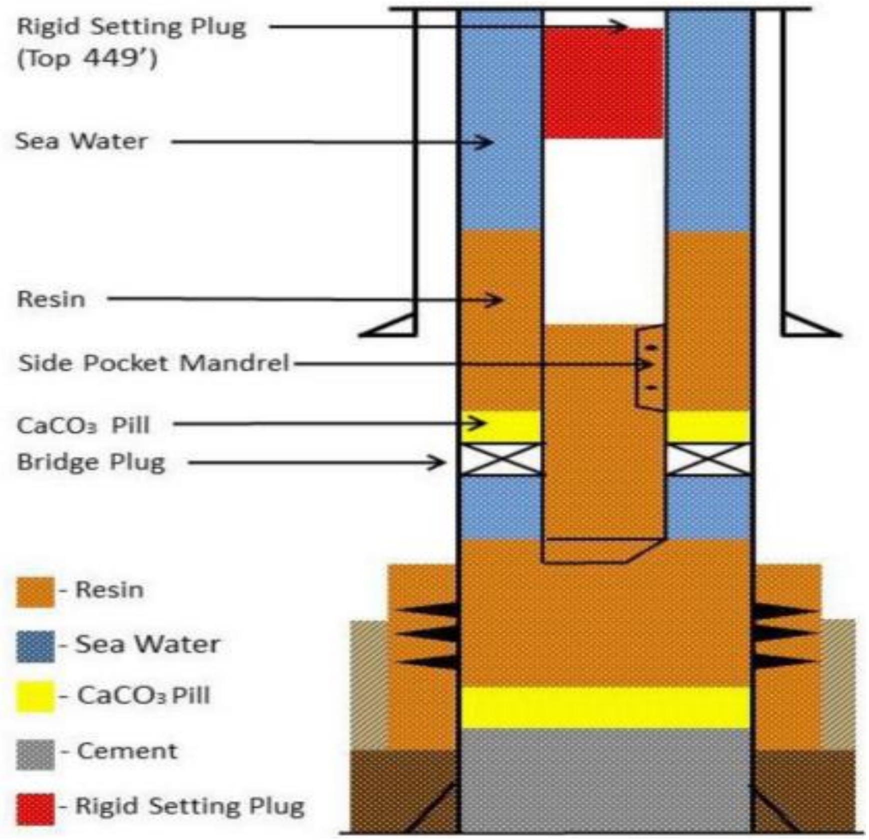


Figure 4.4 Execution Process of Resin Applications for Well Remediation [42]

4.2.6 The modified in-situ materials (group J)

Group J barrier materials are created by modifying the casing or using thermal or chemical processes to alter the formation (e.g., thermite plug). These materials are also known as "Melting the cap-rock" because the thermite melts and recreates the cap-rock formation, effectively sealing the well. Centrica has claimed that this innovative material and process for well plug and abandonment (P&A) has the potential to reduce costs by over 50%.[43]

4.2.7 Shale formations/shale creep

Shale is a broad term that refers to clay-rich rocks, which are abundant sediments found on Earth. These rocks, comprising more than 50-75% of the geologic column, exhibit diverse petrophysical and mechanical properties. While shale typically acts as a barrier or seal for hydrocarbon migration, it has recently been explored as a potential reservoir in certain basins. In some instances, cement bond logs have shown that uncemented shale intervals have migrated and closed the annulus of wells. Pressure communication testing has been conducted on these sections, establishing them as effective well-barrier elements for plug and abandonment (P&A) operations. Shale creep is considered to be the primary mechanism driving this deformation process.[44] Shales are composed of various clay mineral groups, such as Kaolinite, Halloysite, Vermicullite, Illite, Smectite, Chlorite, Mixed-layer, and Palygorite. These minerals, along with other components in shales, greatly influence the rock's permeability and mechanical properties. Clay particles possess a large specific surface area and intricate interactions with water and dissolved chemicals, involving colloidal and surface chemistry. The tiny pore apertures in shales, as small as 1 nanometer, coupled with surface charge effects, lead to extremely low permeability. Core measurements and log-driven models are used to estimate permeability. Natural clay media exhibit varying matrix permeability, ranging from 10 micro-Darcy for surface glacial till to 0.1 micro-Darcy for typical over-consolidated clay, and even as low as 0.1 Nano Darcy for oil-field shale. In the North Sea field, specific shale formations were found to have permeability levels spanning from 21 Nano Darcy to 6.6 micro-Darcy, enabling long-term retention of gas and oil. [45]

Creep refers to the time-dependent deformation that occurs when a material is subjected to constant loading and elevated temperatures. The extent of creep in shale formations is influenced by factors such as the applied load, shale properties, and the interaction between annular fluids and the shale conducted a numerical simulation study that demonstrated the impact of temperature on the wellbore, resulting in a reduction in wellbore size and the closure of the annular gap between the shale formation and casing.[46] Generally, it is observed that as the loading and temperature increase, the initial elastic deformation, transient creep deformation rate, and steady-state creep deformation all increase, while the time to creep failure decreases [47]. Figure 4.5 provides a conceptual illustration of the creeping process in shale formations. Initially, drilling activities disrupt the equilibrium of in-situ stresses around the wellbore (Figure

1a). If the well pressure is insufficient to counteract the stress from the shale formation, the shale will deform, flow, and come into contact with the casing (Figure 1b), influenced by the applied overburden rock mass stress and the interaction between annular fluids and the shale. Over time, the deformation eventually seals the annular gap, creating an effective barrier that prevents the passage of fluids (Figure 1c).[47]

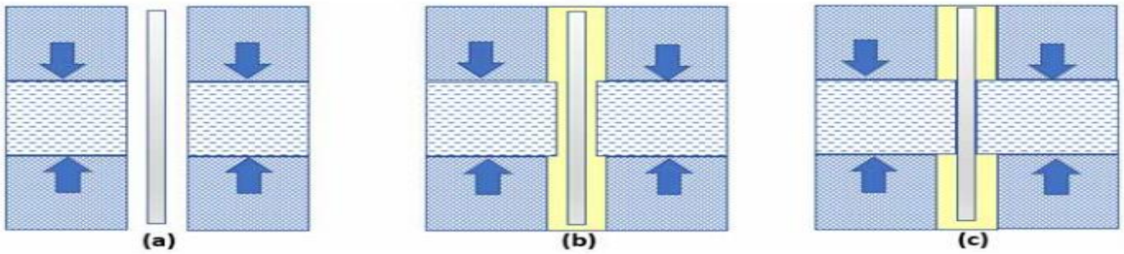


Figure 4.5 Conceptual illustrations of shale creeping in the uncemented annulus [47]

Shale serves as a highly effective annular barrier, similar to the reasons outlined in the NORSOK standard D-010, making it an excellent cap rock. These reasons include its long-standing ability to provide sealing over extended periods, its chemical inertness, and its extremely low permeability. To confirm the potential of shale as an annular barrier, the NORSOK regulations mandate the use of bond logs, which involve the following procedures: [48]

- Utilizing two independent logging measurements/tools.
- Acquiring logging measurements that offer azimuthal data.
- Interpretation and verification of logging data by qualified personnel, with proper documentation.
- Establishing criteria for log response prior to commencing logging operations.
- Ensuring a minimum contact length of 50 m MD (measured depth) with 360 degrees of qualified bonding.

Once the shale annular barrier has been verified through bond logging, a suitable pressure test is conducted to officially qualify the shale as an effective annular barrier. Following the completion of this process, subsequent wells can rely solely on logging procedures for assessment purposes.

The desired properties for candidate shale properties in relation to barrier formation are as follows:[49]

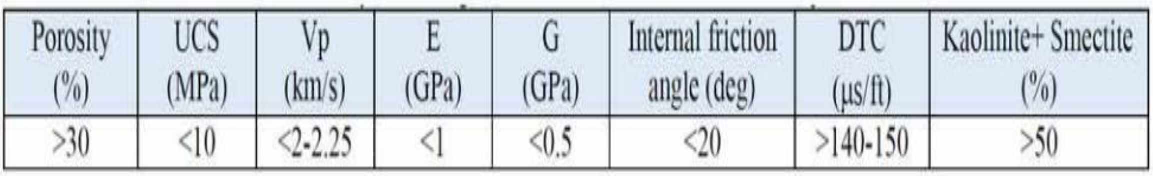
1. High Clay Content and Particularly High Smectite Content: Shale formations with high clay content, especially high smectite content, are advantageous for barrier formation. The presence of high smectite content contributes to ductility and results in low permeability in the nano-darcy range, which is beneficial for effective barrier performance.

2. High Porosity: Candidate shale properties with high porosity are desirable as they are indicative of low rock strength properties. Higher porosity allows for better fluid flow control and can enhance the barrier's effectiveness.

3. Low Acoustic Velocity: Shale formations characterized by low acoustic velocity are correlated with low rock strength properties. Lower acoustic velocity indicates a more ductile shale, which can contribute to the formation of robust and reliable barriers.

4. Low Content of Cementing Minerals like Quartz and Carbonates: Shale formations with lower content of cementing minerals such as quartz and carbonates are favorable for barrier formation. A reduced presence of these minerals promotes ductile deformations and creep, which can enhance the integrity and stability of the barrier.

When searching for shale barrier candidates, it is important to consider the properties listed in the Table 4.10. These properties outlined, both from laboratory data and field data, align with each other and provide consistent information.



Porosity (%)	UCS (MPa)	Vp (km/s)	E (GPa)	G (GPa)	Internal friction angle (deg)	DTC (µs/ft)	Kaolinite+ Smectite (%)
>30	<10	<2-2.25	<1	<0.5	<20	>140-150	>50

Table 4.10 Properties for good shale barriers based on laboratory and field data from Kristiansen et el. (2023) [47]

In Case Study, a well was drilled in 2017 using a drilling liner in a depleted reservoir. Following losses encountered during drilling, standard procedures were followed to secure the well using a drilling liner, but no cement was pumped. Instead, a bond log was conducted six days after the liner was drilled to confirm the presence of a shale barrier.[49]

Figure 4.6 shows the bond log results, indicating a good shale barrier with a "High to Moderate" bond quality observed in the Horda interval. Above and below this interval, there are also shale barriers with a "Moderate" bond quality, which is of lower quality compared to the tested pressure tests. However, further investigation is required through a pressure test when the opportunity arises, as other operators have successfully tested shale barriers of similar quality.

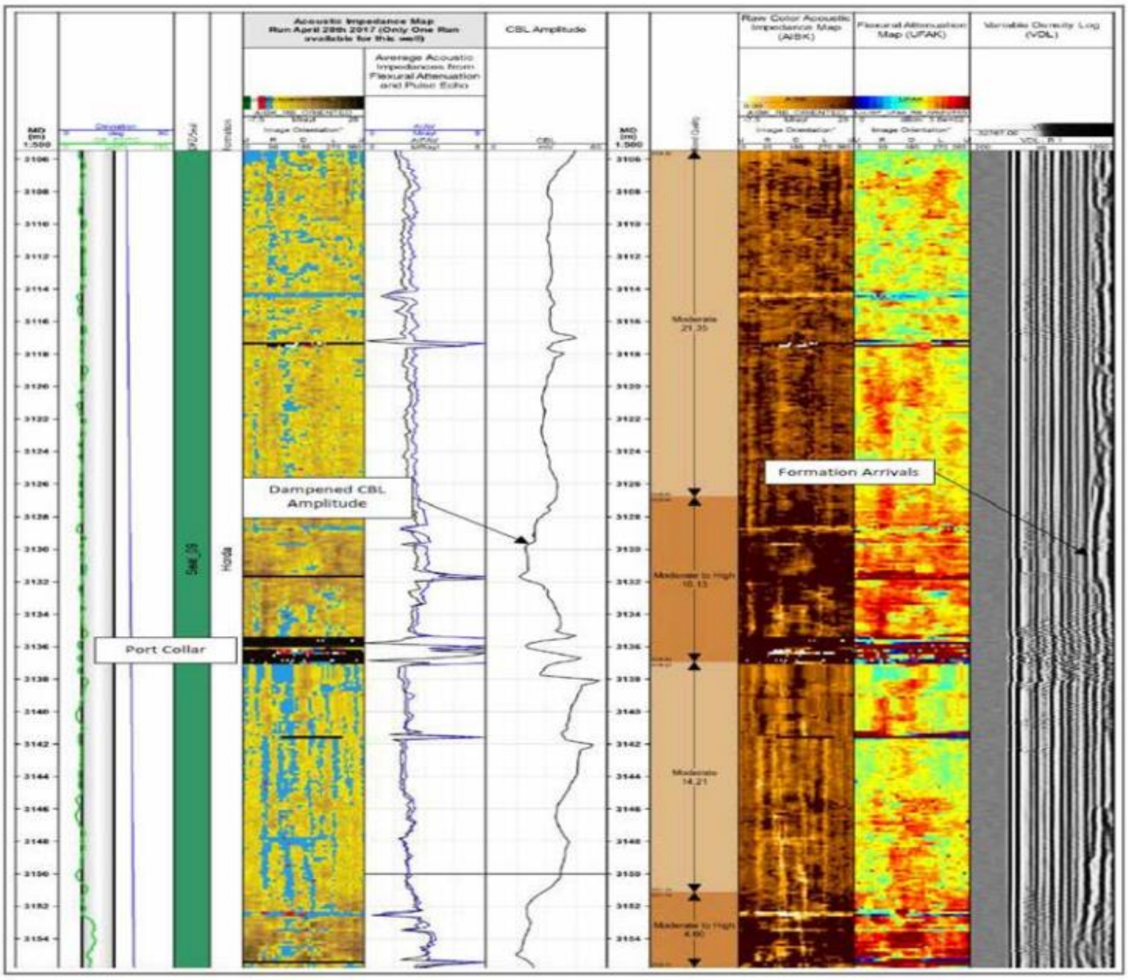


Figure 4.6 Bond log in Horda1[49]

To verify the integrity of the shale barrier in Horda 1, a pressure verification test was conducted through a port collar placed in that interval. The pressure test was performed in an extended leak-off mode to ensure communication with the rock. Figure 4.7 illustrates the test results, showing the pressure versus injected volume relationship behaving as expected with a linear and straight pattern. The leak-off pressure, break-down pressure, fracture propagation pressure, and closure stress align with offset data and the field stress model. Two cycles of the pressure test were conducted, with the latter one being notably larger in volume compared to an extended leak-off test.

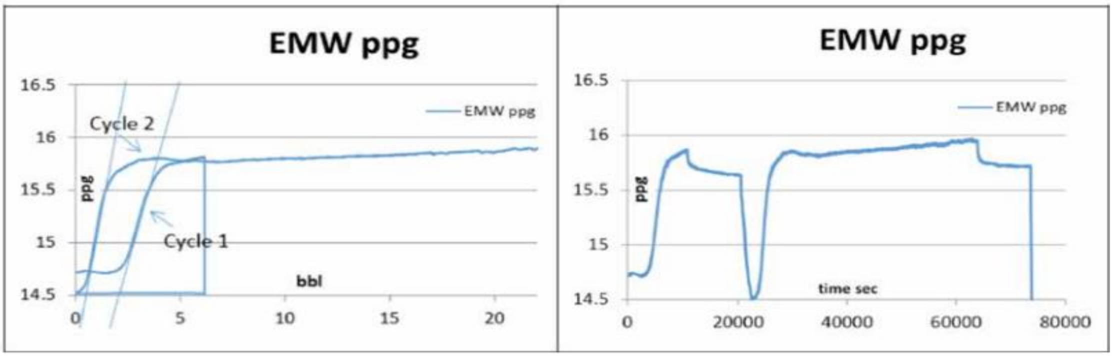


Figure 4.7 Extended leak-off test in Horda1 [49]

4.3 Nanotechnology

Nanotechnology offers a promising avenue for enhancing cement performance during Plug and Abandonment (P&A) operations. By incorporating nanomaterials into cement formulations, it becomes possible to improve various aspects of P&A processes. This study focuses on understanding the specific impact of nano-SiO_2 on the cement's properties and performance.

4.3.1 Enhancing Oilwell Cementing with Nanosilica

Nanosilica, owing to its higher surface area, presents a promising solution for improving oilwell cementing operations. One notable benefit is its ability to expedite the cement hydration process. Additionally, nanosilica is required in small quantities, making it a cost-effective option. Its application in oilwell cementing contributes to enhancing final compressive strength and effectively controlling fluid loss. By carefully determining the appropriate dosage of nanosilica, it becomes feasible to design cement slurries with desirable low rheology, optimal mechanical properties, and efficient fluid loss control. The incorporation of nanosilica in oilwell cementing demonstrates its potential to optimize cement performance and overall operational efficiency.[50]

4.3.2 Influence of nanosilica on the hydration process

When nano-silica is introduced as a pozzolana, it effectively reduces the concentrations of hydroxyl and calcium ions in the surrounding pore fluid. This reduction creates favorable conditions for the development of abundant calcium silicate hydrate (CSH) seeds on the surface of the nano-silica particles. These seeds act as pure seeds of calcium-silicate-hydrate, characterized by poorly crystalline sheets of calcium and oxygen surrounded by chains of tetrahedral silica, with water interlayers separating the main layers.

The presence of these CSH seeds accelerates the hydration process of tri-calcium silicate and di-calcium silicate, the primary components of a cement. This combined effect of the pozzolan reaction, whether the pozzolana is siliceous or both siliceous and aluminous, and the seed influence of nano-silica leads to the rapid completion of the initiation phase of hydration. As a result, the binder achieves a higher rate of hydration compared to the reference sample during the early stages of the hydration process. [51]

4.3.3 Recent application of Nanomaterials on cement and geopolymer

4.3.3.1 Justin Montgomery study et al. (2016)

Justin Montgomery et al. (2016) conducted a study on the compressive strength of hardened cement paste and the formation of Calcium Silicate Hydrate (C-S-H) by adding nanosilica (SiO2). The study involved performing compressive strength testing using MTS and Forney testing machines. Four different percentages (control 0, 1, 3, and 5%) of nanosilica were used in the experiment. Figure 4.8 displays the average compressive strengths of water-cured testing cylinders. It compares the control group with 1% and 3% nanosilica replacements for cement, over testing periods of 3, 7, 14, 28, and 56 days.[52]

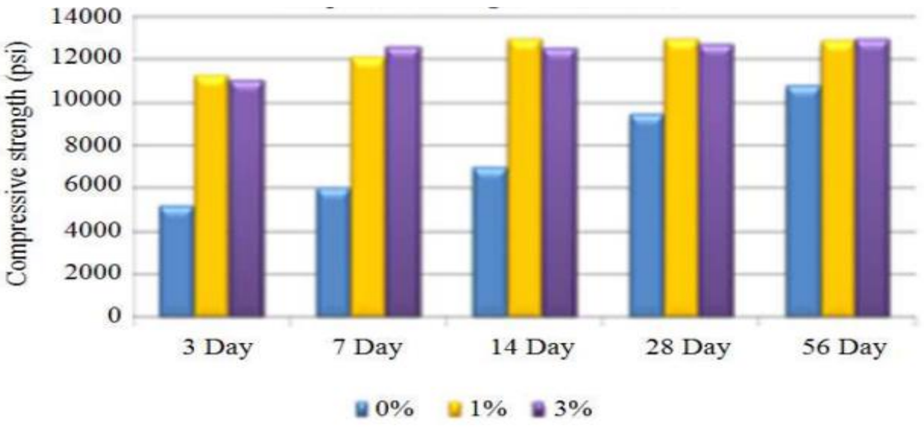
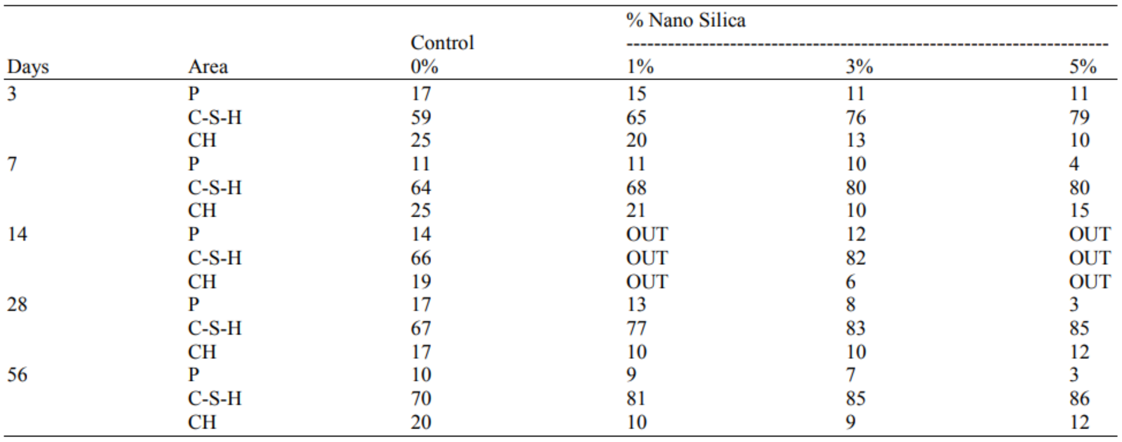


Figure 4.8 Compressive strength results from the study by Justin Montgomery et al. (2016) [52]

The control samples exhibited a continuous increase in strength over time. The compressive strength for the control mix increased from 5,219 psi at 3 days to 10,842 psi at 56 days. When nanosilica was added, the compressive strength significantly improved compared to the control concrete throughout all testing stages. Water-cured samples with 1%, 3%, and 5% nanosilica replacements for cement demonstrated approximately double the compressive strength of the control mix at 3 days. However, the 5% nanosilica samples performed relatively poorly compared to the 1% and 3% nanosilica concretes in most testing stages. The peak compressive strength for the 5% nanosilica samples was observed at 14,182 psi in the 56-day water-cured test. Nonetheless, during the 3, 7, 14, and 28-day tests, the compressive strength of the 5% nanosilica water-cured samples was consistently lower than that of the 1% and 3% nanosilica samples.

As demonstrated in Table 4.11, the study revealed also that the addition of nanosilica to the cement mixture led to increased formation of calcium silicate hydrate (C-S-H). The 5% nanosilica samples exhibited the highest C-S-H formation compared to the 1% and 3% samples. Overall, the results from the table confirmed that the nanosilica mixtures outperformed the control samples in terms of C-S-H formation and potentially improved strength development.



		Control	% Nano Silica		
Days	Area	0%	1%	3%	5%
3	P	17	15	11	11
	C-S-H	59	65	76	79
	CH	25	20	13	10
7	P	11	11	10	4
	C-S-H	64	68	80	80
	CH	25	21	10	15
14	P	14	OUT	12	OUT
	C-S-H	66	OUT	82	OUT
	CH	19	OUT	6	OUT
28	P	17	13	8	3
	C-S-H	67	77	83	85
	CH	17	10	10	12
56	P	10	9	7	3
	C-S-H	70	81	85	86
	CH	20	10	9	12

Table 4.11 SEM chemical area results from the study by Justin Montgomery et al. (2016) [52]

4.3.3.2 Jalal et al. study (2011)

Another study by *Jalal et al. (2011)* investigated the effect of nano-SiO2 on high-performance self-compacting concrete (HPSCC). The study analyzed the mechanical, rheological, durability, and microstructural properties of the concrete. Nano-SiO2 was used at 2%bwoc, and three different binder contents were utilized (400 kg/m3, 450 kg/m3, and 500 kg/m3). The amount of added silica was subtracted from the binder content to maintain a constant w/b ratio of 0.38. The samples were cured for 3, 7, 28, and 90 days and tested. The study found that the addition of nano-SiO2 improved the mechanical, rheological, and durability properties of the concrete. [50]

Compressive strength (Mpa)			
No	Concrete ID	3 days	28 days
1	HPSCC400	27.8	51.8
2	HPSCC450	27.8	52
3	HPSCC500	32.5	52.5
4	HPSCC400NS2%	29.2	71.3
5	HPSCC450NS2%	31.8	80.4
6	HPSCC500NS2%	36.2	82.1

Table 4.12 Compressive strength results from the study by Jalal et al. (2011) [50]

From the table 4.12 the addition of 2%bwoc nano-SiO2 led to remarkable improvement in the mechanical properties of the concrete, with the improvement attributed to accelerated C-S-H gel formation and found that the compressive strength increased by 37.6%, 54.6%, and 56.3%, respectively, after 28 days of curing compared to the reference with no additive of Nano-SiO2.

4.3.3.3 Patil and Deshpande research (2012)

Different research by *Patil and Deshpande (2012)* investigated the effect of SiO2 nanoparticles as additives in cement. The nanoparticles had a size of 5-7nm and were dispersed. The study found that the addition of nano-SiO2 significantly improved the compressive strength of cement, particularly in terms of early strength. The cement tested was premium H-class cement, and the slurries were mixed based on API classifications.[53]

Effect of nanosilica on compressive strength					
Latex (gal/sk)	Silica	Retarder (gal/sk)	Time to 500 psi (hr: min)	UCA Strength Rate of Strength Development (psi/hr)	24-hr Strength (psi)
1.5	0	0.05	23:05	172	690
1.5	Nanosilica	0.05	13:29	460	2203

Table 4.13 Compressive strength from the study by Patil and Deshpande (2012) [53]

As displayed in table 4.13, the mixture with no additives Compared to the mixture with nanosilica has a significantly higher rate of strength development, with a psi/hr of 460 compared to 172. Additionally, the time to reach 500 psi is significantly reduced from 23 hours and 5 minutes to 13 hr and 29 min, indicating a faster setting time. It was also found that Nanosilica may accelerate C-S-H gel formation and fill voids between cement particles, resulting in a denser matrix and improved compressive strength, especially early strength.

Overall, the study suggests that the use of nanosilica can improve the strength development and setting time of the mixture. This could help to reduce wait on cement time (WOC), and normal well operations could commence quicker.

4.3.3.4 Li et al. study (2003)

Finally, in *2003 Li et al.* conducted a study where they use nano-SiO2 as an additive to cement mortar. The addition of nanoparticles was found to fill and block some of the pore spaces in the cement mortar, resulting in an improvement in its structural integrity. The study used OPC as the binder, a water-reducing agent, a defoamer, and sand, and tested different concentrations of nanoparticles as shown in Table 4.14. The cubes of cement mortar were cured for 7 and 28 days, and the results indicated that adding 0.5 wt% SiO2 significantly improved the cement's performance.[54]

Mix no.	W/b	Mix proportions (kg/m^3)					
		Water	Cement	Sand	NanoSiO2	NF	Defoamer
A-1	0.5	230	460	1380	–	–	–
A-2	0.5	230	446.2	1380	13.8	6.9	0.5
A-3	0.5	230	437	1380	23	11.2	0.5
A-4	0.5	230	414	1380	46	23	0.5

Table 4.14 Mix proportions of the specimens from the study by Li et al. (2003) [54]

Table 4.15 displays the compressive strength results after 7 and 28 curing ages. The study found that the addition of nanosilica to concrete mixes resulted in improved compressive strength. Mix A-2 showed a 5.7% increase in strength at the 7th day and a 13.8% increase at the 28th day compared to the reference mix. Mixes A-3 and A-4 exhibited even greater enhancements, with a 20.1% increase in strength at the 7th day and a 17.0% and 26.0% increase, respectively, at the 28th day. These findings suggest that nanosilica can effectively enhance both early-age and long-term compressive strength in concrete.

Mix no.	Compressive strength on the 7th day		Compressive strength on the 28th day	
	Target (Mpa)	Enhanced extent (%)	Target (Mpa)	Enhanced extent (%)
A-1	17.6	-	28.9	-
A-2	18.6	5.7	32.9	13.8
A-3	21.3	20.1	33.8	17.0
A-4	21.3	20.1	36.4	26.0

Table 4.15 Compressive strength results from the study by Li et al. (2003) [54]

5. Experimental works

5.1 Materials

This section will focus on the materials used to conduct the experimental program.

5.1.1 Cement

The cement used in the experimental program was an MSR/HSR API G-class Portland provided by Norcem located in Lilleaker, Norway.

5.1.2 Water

Regular water from the laboratory is used during the experimental program to synthesize cement slurries.

5.1.3 Nano-Silica SiO2

The nano-silica used in the experimental program was a colloidal mixture of 50 wt% silica suspended in H_2O. The nanoparticles used in the experiment were supplied by Sigma Aldrich Norway, but no information about their size was available. The dispersion had a pH of 9.0 and a density of 1.4g/ml at a temperature of 25ºC. [55] The color of the SiO_2 nanoparticles was transparent/it tends to be white.

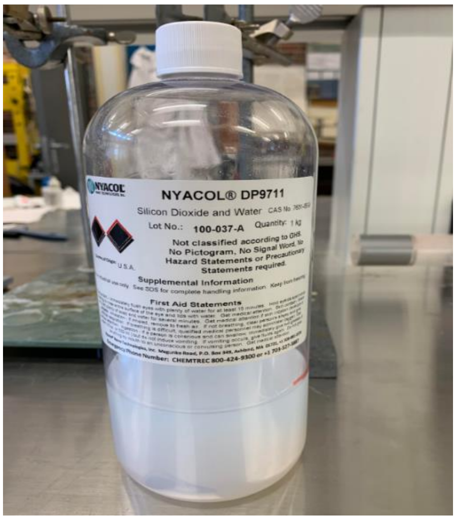


Figure 5.1 Nano-SiO2 aqueous solution

5.1.4 Cement Mould

Plastic cylinders with dimensions of 69mm in height and 34mm in diameter were used as moulds for curing the specimens. To ensure that the plug could be removed from the mould without suffering any structural damage, a thin layer of oil was applied to the mould as a lubricant. The purpose of this was to make sure that the retrieval of the plug from the mould was successful and safe.

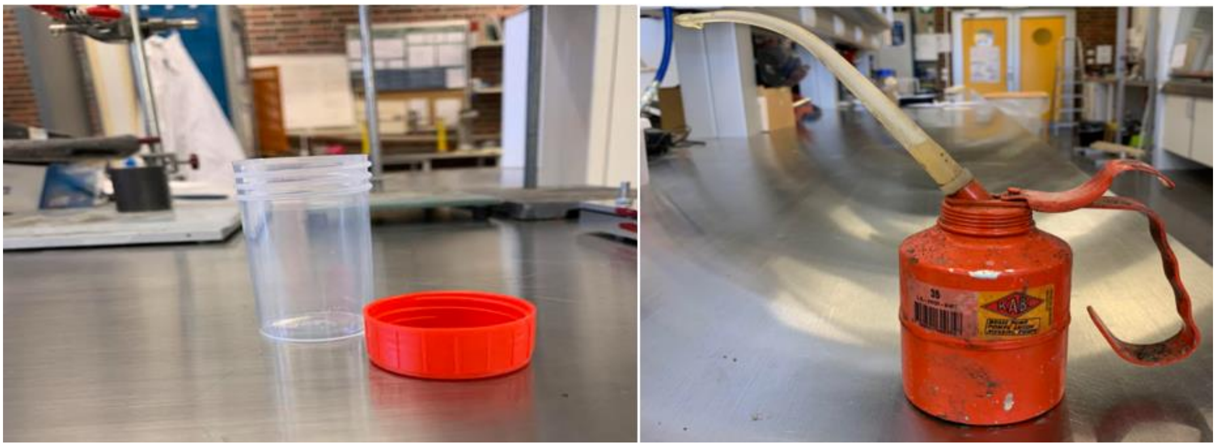


Figure 5.2 A cement mold used for curing the specimens (on the left), the oil for lubrication (on the right)

5.2 Test design

This section will present details about the test batch that were designed. And the components of each patch, and the purpose behind the test

5.2.1 Test batch

The purpose of this thesis is to investigate the effect of nano-SiO_2 on 0,44 WCR G-class cement for different curing ages of 3 days and 28 days and to find the ideal quantity of silica to be added to achieve the maximum increase in compressive strength. Four test patches (a total of 40 cement plugs) were created, consisting of four reference plugs with no addition of nano-Silica and four plugs for each concentration. Furthermore, the compositions of the test batch are shown in Table 5.1.

PLUG	Cement (g)	Water (g)	Nano-SiO2 (g) (aq)
1	227,2	100	0
2	227,2	100	0
3	227,2	99,65	0,35
4	227,2	99,65	0,35
5	227,2	99,45	0,55
6	227,2	99,45	0,55
7	227,2	99,25	0,75
8	227,2	99,25	0,75
9	227,2	99	1
10	227,2	99	1

Table 5.1 The compositions of the test batch

5.2.2 Slurry synthesis procedure

The process for creating cement plugs involved measuring 227.2 ± 0.05g of dry G-class cement and mixing it with 100 g of liquid, resulting in a water-cement ratio (WCR) of 0.44. The liquid component was made up of water and added nano-$SiO2$ in different dosages (0g, 0.35g, 0.55g, 0,75g, 1g).

To prepare the cement mixture, dry cement was first placed in a mixing container, followed by the addition of a liquid mixture of water and nanosilica. The mixture was stirred until smooth before being poured into moulds, with care taken to avoid air bubbles. The cork was placed lightly on top of the mould to prevent damage to the specimen.

The cement plugs were left to cure for 3, and 28 days at room temperature and atmospheric pressure. After the curing period, the cork was removed, and the top of each sample was smoothed to prevent point loading during compression testing. Length, weight, and sonic velocity were measured before the samples were crushed to determine their UCS. All samples were tested on their final curing day.

5.3 Characterization methods

Figure 5.3 provides a summary of the experimental section of this thesis. This section provides information about the procedure and the process of determining parameters for both non-destructive and destructive testing carried out on the cement specimens.

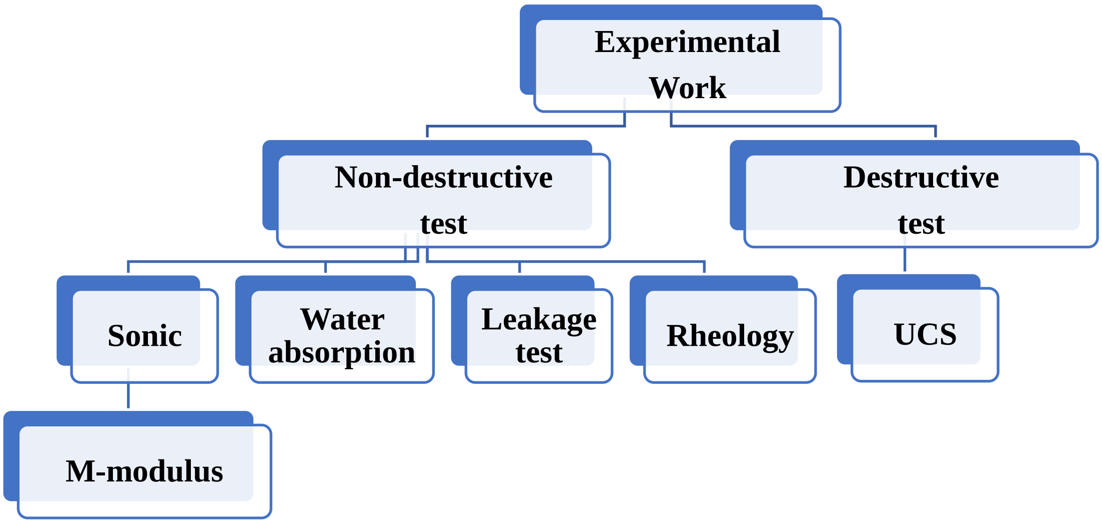


Figure 5.3 Experimental portion of the thesis

5.3.1 Non-Destructive Testing

5.3.2 Ultrasonic velocity measurement

Ultrasonic velocity can be measured by placing the plug to be tested between an ultrasonic emitter and receiver. The emitter sends out an ultrasonic pulse that travels through the specimen and is detected by the receiver on the other side.

The time it takes for the ultrasonic pulse to travel through the specimen and the distance between the emitter and receiver are recorded. Using this information, the velocity of the ultrasonic pulse can be calculated using the formula:

$$Vp=L/t$$

Equation 5.1

Where Vp is compressional wave velocity (m/s), L is the length of the plug (m), and t is the sound travel time (ms)

Figure 5.4 shows the CNS Farnell Pundit-7 which typically consists of a transducer, which includes an emitter and a receiver, a hydraulic switch, a control unit, and various accessories. The transducer should be positioned at a right angle to the surface of the plug, with the emitter and receiver facing each other. Before taking any measurements, the instrument should be calibrated according to the manufacturer's instructions to ensure accurate readings, this could be done by using a homogenous plug with a known travel time of 25,2 μs.

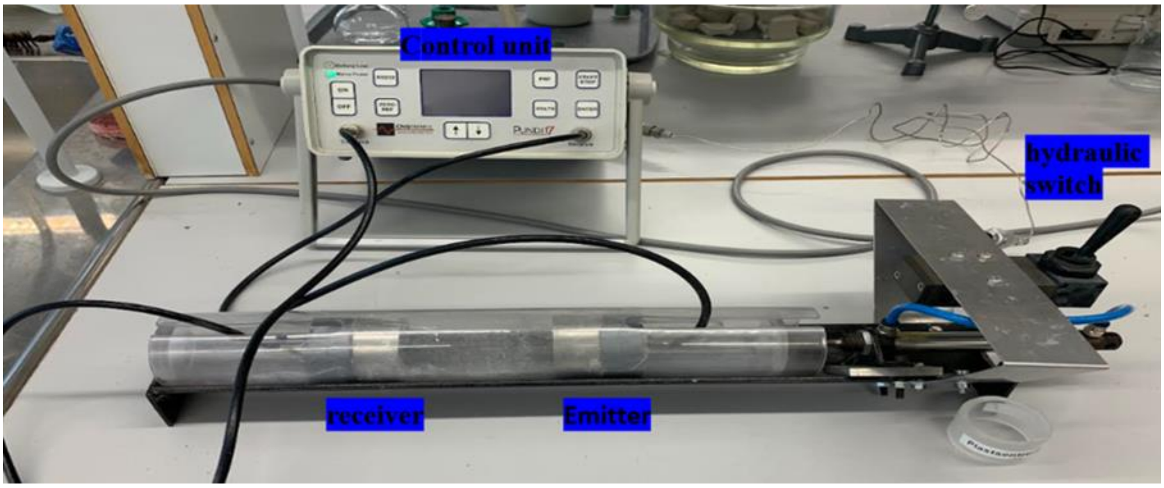


Figure 5.4 The CNS Farnell Pundit-7 used in Ultrasonic velocity measurement.

After completing the calibration of the machine, the next step is to measure the test samples. To ensure accuracy in measuring the cement plugs, which have smaller diameters than the test tube, the samples are placed inside a plastic ring with an inner diameter equal to that of the test tube. This step ensures that there is full contact between the plug surface and the emitter/receiver, which results in more reliable measurements. To further enhance reliability, a hydraulic press is used, which activates a small press to apply pressure to the emitter and receiver, securely holding the sample in place between the two units. This process guarantees that the emitter is correctly positioned against the sample, thus producing more reliable measurements.

5.3.3 M-modulus (Modulus of Elasticity)

The P-wave modulus (Modulus of Elasticity), also known as the M-modulus, is one of the elastic moduli that can be used to describe isotropic and homogeneous materials. It is defined as the ratio of axial stress to axial strain in a uniaxial strain state.[56]

The following relationship is utilized when expressing the P-wave modulus in terms of the bulk modulus (K) and shear modulus (G).[56]

$$M = \mathrm{K} + \frac{4\mathrm{G}}{3}$$

Equation 5.2

Where G is the shear modulus (GPa), and K is the bulk modulus (GPa) of the material. Finally, M is the P-wave modulus (GPa).

Additionally, the P-wave modulus can be expressed in terms of the velocity of a P-wave and the density of the medium through which it travels.

$$Vp^2 * \rho = \mathrm{K} + \frac{4\mathrm{G}}{3}$$

Equation 5.3

$$M = \frac{Vp^2 * \rho}{10^9}$$

Equation 5.4

Where M is P-wave-modulus (GPa), ρ is the density of the cement plug (kg/m3), and Vp denotes compressional wave velocity (m/s)

5.3.4 Water absorption

Water absorption data can provide information about the microstructure of a cement sample. When a cement sample is submerged in water for a period of time, the water can penetrate the pores and voids within the cement matrix, leading to an increase in weight due to water absorption. The extent of water absorption can provide insights into the porosity and permeability of the cement sample, which are important microstructural properties that can affect the performance of the cement in P&A operations. A cement sample with a high degree of water absorption may have a more porous microstructure, which could make it more susceptible to cracking and failure over time. On the other hand, a cement sample with low water absorption may indicate a more compact and less permeable microstructure, which could be more effective at preventing fluid migration and providing a long-lasting seal. From the review of the literature, it is thought that silica nanoparticles can improve cement by acting as fillers in the matrix, which should lead to reduced water absorption. [50]

The procedure for measuring water absorption was simple, the cement plugs cured for approximately, 28 days, then they were de-moulded, and their dry weight was measured. Then immersed in water for 24 hours, after the immersion period, the sample is removed from the water. The surface is carefully dried with a paper towel and weighed immediately after it is removed from the water to determine its wet weight. The amount of water absorbed by the sample is calculated using the following formula:

$$\Delta M = \frac{M_t - M_0}{M_0} * 100$$

Equation 5.5

Where M_w (g) is the weight of the specimen after 24 hours of submersion in water, M_d (g) is the dry weight before being immersed and ΔM (%) is the percentage change in mass.

5.3.5 Water Leakage and absorption

The leakage of the plug used in plug and abandonment (P&A) operations refers to the undesired flow of fluids or gases around or through the cement plug which can compromise the effectiveness of the well isolation and pose environmental or safety risks. The main reason behind the leakage is the failure of the cement plug to create a complete and effective seal between the formation and the wellbore.[29]

To prevent leakage, it is important to design and execute the cementing job properly, using the appropriate cement slurry and additives to achieve good bonding [29]. Additionally, various testing methods, such as leakage tests, can be used to evaluate the quality and integrity of the cement plug and identify potential issues before they lead to leakage.

Figure 5.5 Oven used to store samples during heat cycles of approximately 105°C

A standard cement batch was prepared, incorporating various amounts of nano silica additives (0g, 0.35g, 0.55g, 0.75g, and 1.0g). The cement was then filled into a steel pipe with a plug on one end, allowed to dry for 24 hours at room temperature, and then put into an oven heated to 105°C.

To determine leakage and absorption rates, the sample was then being quickly cooled under running water. The leakage, water absorption, and water evaporation were all calculated using a variety of measurements. Figure 3.7 shows the heating cycle.

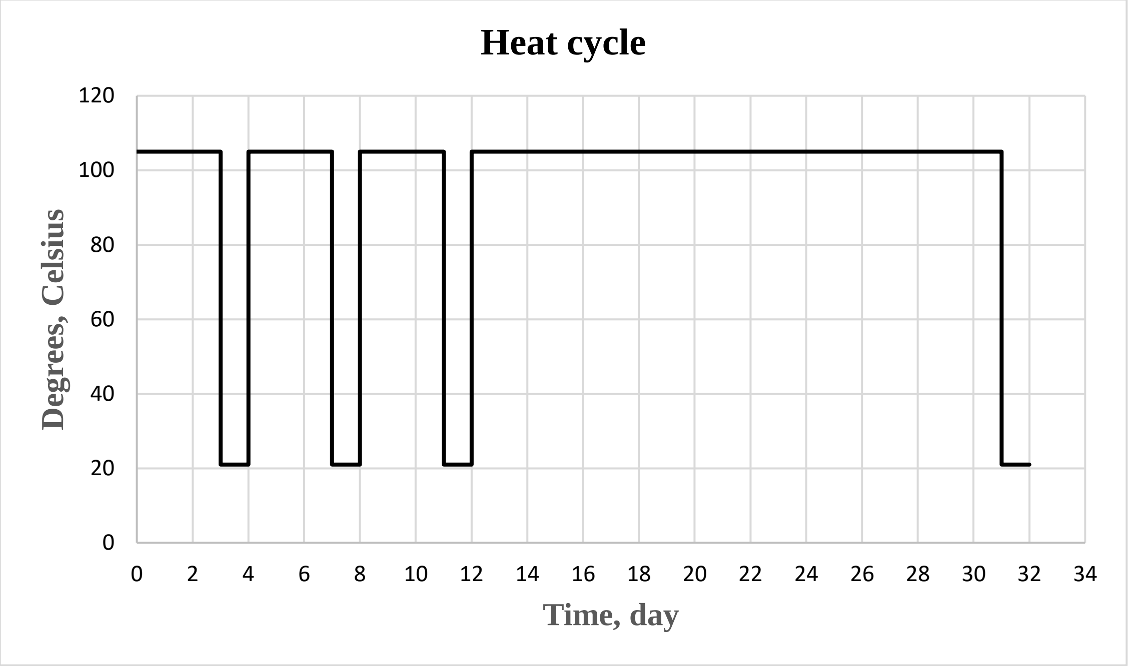


Figure 5.6 Heat vs duration for testing of leakage

The Heat cycle is shown in Figure 5.6 as being as follows:

1. 72 hours in the oven at 105°C,
2. Pipe is removed from the oven and briefly cooled under running water, waiting until the pipe reaches room temperature.
3. Pipe is filled with water and left at room temperature (roughly 21°C) for 24 hours to measure the amount of water leakage, water absorption and evaporation.
4. 72 hours in the oven at 105°C,
5. repeat 2&3,
6. 72 hours in the oven at 105°C
7. repeat 2&3.
8. 19 days in the oven at 105°C
9. repeat 2&3

Totally 28 days in the oven. To reduce water evaporation, aluminum foil is placed over the pipe's top and the location where it enters the cup, where the leaked water accumulates, during the testing interval.

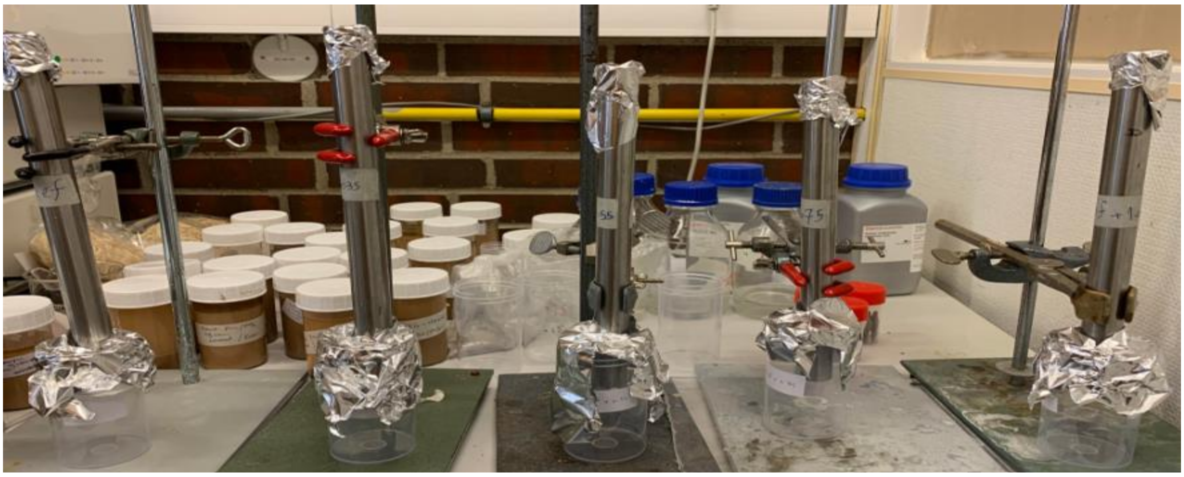


Figure 5.7 Leakage test showing aluminum foil to reduce water evaporation.

5.3.6 Rheology

Rheology is the study of the flow and deformation of matter, including liquids, solids, and semi-solids. It is a branch of physics that deals with the mechanical properties of materials, especially in response to applied forces or stresses.

Rheological measurements, such as viscosity, shear stress, and yield stress, can be used to optimize the design of cement slurries. By conducting rheological measurements on cement slurries used in the P&A process, engineers can gain insights into the slurry's flow behavior, adjust its properties to meet specific requirements and optimize the design for successful well sealing and long-term integrity.

There are many developed models that describe the rheological properties of cement slurries; However, this thesis will utilize the Casson rheological model, The Casson model describes the rheological properties of a material using two parameters: the yield stress and the Casson plastic viscosity. The model is based on the idea that the material has an apparent yield stress that must be exceeded for the material to begin flowing, and the plastic viscosity is the measure of the material's resistance to flow. [57]

Casson model can be represented by the following equation:

$$\tau^{0,5} = \tau_c^{0,5} + \mu_c^{0,5}\gamma^{0,5} \quad For\ \tau < \tau_c$$

Equation 5.6

$$\gamma = 0 \quad For\ \ \tau \geq \tau_c$$

Equation 5.7

Where:

γ = Shear rate [Sec^{-1}]

τ = Shear stress [$\text{lbf}/100\text{ft}^2$]

τ_c = Casson yield stress [$\text{lbf}/100\text{ft}^2$]

μ_c = Casson plastic viscosity [$\text{lbf-s}/100\text{ft}^2$]

For testing the rheological properties of the cement slurries, an O-Fite 8-Speed viscometer, as shown in Figure 5.8 was employed.

The measuring cup was set in place, and the cement was made in accordance with usual practice. Afterward, readings for RPM (Revolutions Per Minute) were taken at 300, 200, 100, 60,30,6, and 3.

Figure 5.8 O-Fite 8-Speed viscometer used for rheology testing

5.3.7 Destructive testing - Uniaxial Compressive Strength (UCS)

The damaging aspect of the tests will be covered in this section. The plug is subjected to mechanical load till failure, as the title suggests. Max mechanical load and specimen deformation data are the results of a destructive test. This can be used to determine the specimens' elastic, mechanical, and energy absorption properties.

5.3.7.1 Destructive Measurement Procedure

The modified hydraulic hand-operated press was used during destructive testing (Figure 5.9). All the cement plugs were crushed using a hydraulic press that was manually controlled. The installation of a load cell in this press allows for the recording of deformation data and ensures the reliability of the output data. Using data-gathering software, the computer on the right side of the press gathered all load and deformation readings (DAQ). With this hydraulic workshop press, all test batches were put to the test.

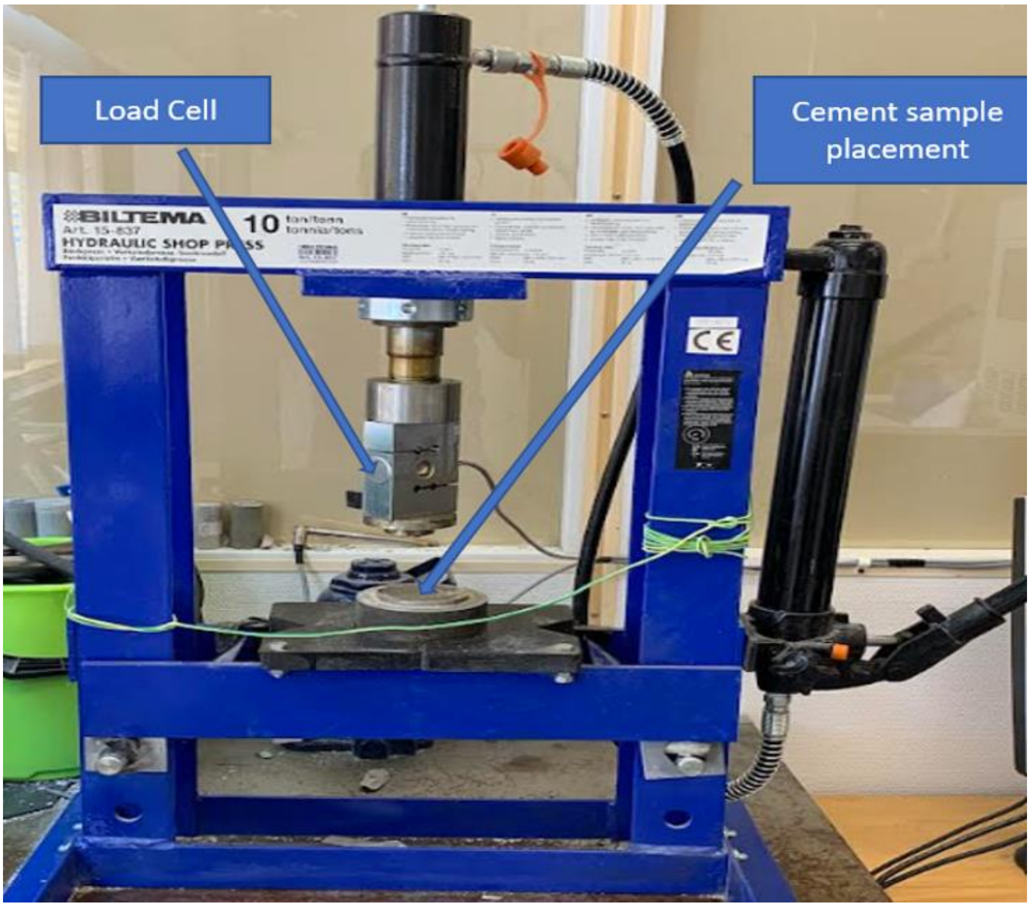


Figure 5.9 Modified hydraulic hand-operated press

The plug needs to be flat on both sides prior to any testing to avoid point loading. The samples were positioned in the center, beneath the load cell, after this was confirmed using a spirit level. Next, a small distance above the cementitious plug, the load cell was lowered.

To ensure that deformation data would be accurately collected, some tiny metal plates were inserted under the deformation pin before the load cell was lowered any further. The cement plug was then manually loaded until mechanical failure was reached. After that, a plastic protective cover was placed in front of the cement plug to protect against cement splinters. The loading speed was maintained as consistently as feasible. In addition to the software plainly displaying the load difference once failure had been reached, failure could also be seen visually. The thousands of cells of data from the DAQ program were exported last to an excel spreadsheet for further calculations.

5.3.7.2 UCS

The plug's maximum load-carrying capacity during the uniaxial compressive test is known as UCS.

UCS stands for the uniaxial compressive strength and is typically expressed in units of pressure, such as pounds per square inch (psi) or megapascals (MPa).

The equation for calculating the UCS (σ):

$$\sigma = \frac{Fmax}{A}$$

Equation 5.8

where σ is the uniaxial axial compressive strength in psi or MPa, F_{max} is the maximum load applied to the specimen during the test, and A is the original cross-sectional area of the specimen.

6. Results and Discussion

In this section, the thesis presents the outcomes of the technologies and the case studies related to P&A technologies. Furthermore, it encompasses all the results obtained through the experimental works conducted, comprising both destructive tests (such as UCS) and non-destructive tests (such as p-wave modulus, water absorption, Leakage, and rheology).

6.1 P&A Technologies with case studies

6.1.1 Cut and pull

The cut and pull technique is often used in well plug and abandonment operations. However, there are several challenges associated with this technique, such as the risk of the casing and tubing getting stuck, which can cause delays and increase costs. This is especially true if the casing is cut too deep. The deeper the cut, the more casing needs to be handled on the surface, increasing tripping time and the potential for complications. Therefore, it is essential to carefully plan and execute cut-and-pull operations to minimize the risks and ensure successful results. However, the development of new tools such as the Lock & Load System, Hydraulic Pulling Tool, hydraulic cutting, and the Harpoon spear has significantly improved the reliability of the cut and pull method.

The hydraulic cutting operation proved highly efficient in removing a partially stuck 13⅜-inch, 72 lb./ft. N-80 casing from a challenging well scenario. With 30 individual cuts performed over a depth range of 1,283 ft. (391 m) down to 190 ft. (57.9 m) in just 18 hours, the process demonstrated the effectiveness of advanced cutting technology. The operation achieved a remarkable average cut time of 8.4 minutes per cut, resulting in precise and efficient extraction while minimizing operational time. Despite operational constraints and high over-pulls, the successful completion of the 36 cuts within 144 operational hours showcases the effectiveness of the chosen approach. Furthermore, the utilization of advanced cutting technology reduced the need for extensive surface handling, optimizing productivity throughout the hydraulic cutting operation.

The Archer Lock & Load System is a versatile and efficient tool for well interventions. It offers flexibility in plug selection, compatibility with different casing sizes, and on-site redressing capability. The system saves time, reduces equipment inventory, and improves operational efficiency, making it a valuable tool for enhancing well-intervention processes.

The Harpoon spear allows for the casing to be cut at a shallower spot, reducing the amount of casing that needs to be handled on the surface, and minimizing the tripping time. Additionally, the Harpoon spear can be repositioned if the casing becomes stuck, improving the number of successful runs and making the operation more consistent. The implementation of the Harpoon spear in a Norwegian Sea well intervention operation resulted in significant cost savings and improved efficiency compared to traditional methods. The new spear allowed the intervention team to perform a slot recovery operation in a deviated well, removing the upper section of 9 5⁄8-in., 53.5-lb/ft casing and enabling a planned open hole sidetracking operation. This was achieved in a single trip, saving 19.5 hours of rig time and an estimated $650,000 compared to traditional methods that required two separate runs and would have taken an estimated 36 hours.

The utilization of a **hydraulic pulling tool** proved crucial in safely and successfully removing 9⅝-inch and 13⅜-inch casings from challenging platform wells in the North Sea. The tool provided significant downhole pulling force and interchangeable anchors, allowing for efficient casing extraction in varying depths. When necessary, the tool facilitated the cutting and removal of stuck casing sections. Overall, the hydraulic pulling tool enabled the operator to overcome limitations and achieve successful casing removal, ensuring operational efficiency and safety.

The "Tubing partly retrieved" method developed by Statoil is a modification of the traditional cut-and-pull method for plugging a well. In traditional cut and pull, the entire tubing and packers are removed from the well before the cement plug is placed. However, if the tubing or packers are stuck, they need to be cut first, which can be challenging and time-consuming.

The new method involves lifting the tubing only to the height of the cement plug, which eliminates the need to remove and handle the entire tubing on the surface. The cement is then pumped through the tubing and allowed to harden, after which the tubing is lowered and left on top of the cement plug. The advantage of this method is that it saves time and reduces the risk of complications that may arise from handling the entire tubing on the surface. The method has been estimated to save an average of 12.8% of time compared to traditional methods.

6.1.2 Section milling

Section milling is a commonly used alternative method in cases where cut & pull cannot be used to remove the casing. The practice of section milling during P&A activities has been viewed negatively within the industry due to its time-consuming that can only be carried out using a rig, not a vessel, and the potential for equipment failures and hole-cleaning issues. Additionally, the lack of new technology in this area has contributed to its negative perception. However, with the introduction of new technology such as Swarf less and Section Milling with Active Stabilization, these issues have been addressed, leading to significant improvements in section milling operations.

The section milling operations were often hampered by two main issues: swarf and worn-out knives. Swarf, which is the debris generated by the milling process, can cause a range of problems in the well, such as pack-offs and equipment damage. Meanwhile, worn-out knives can lead to inconsistent plugging operations that require multiple runs to complete. Overall, these issues can make section milling a challenging and time-consuming process. To improve the efficiency and consistency of section milling, it may be necessary to address these underlying issues through improved tool design and operational techniques.

some suggestions to improve the use of section milling and address the issues of swarf and worn-out knives could include:

1. Regular maintenance and inspection of milling equipment to ensure that knives are not worn out and are sharp enough to effectively mill the casing.
2. Implementation of effective swarf management strategies, such as using debris catchers or magnets in the milling assembly to collect swarf and prevent it from circulating in the wellbore.
3. Utilization of real-time downhole monitoring and data analysis to detect and mitigate issues such as pack-offs and damaged equipment as soon as they occur.
4. Development of new technologies that are specifically designed to address the challenges of section milling, such as cutters that are more resistant to wear and tear and swarf management systems that are more efficient.

By implementing these suggestions, the plugging operations could become more consistent and efficient, ultimately reducing costs and downtime associated with milling operations.

Swarf-less Section Milling is a relatively new technology that helps reduce or eliminate the generation of swarf during section milling operations. This is an important development because swarf can create several problems in the well, like pack-offs and damaged equipment, leading to inconsistent plugging operations in terms of time and cost.

The successful implementation of Swarf-less Section Milling technology in the North Sea P&A campaign resulted in significant environmental and cost savings. The technology not only saved over 38 hours or 46.5% of rig time but also eliminated the need for swarf handling equipment and specialty milling fluid, leading to reduced environmental impact and cost. The avoidance of CO_2 emissions amounted to approximately 63%, which is a substantial reduction in emissions resulting from reduced rig time, pumping, operational, and transport activities. The success of this technology suggests that it could be adopted in other P&A operations to achieve similar environmental and cost savings. Furthermore, continued research and development in this area can lead to further improvements and efficiencies in well-plugging and abandonment operations. Additionally, it may be useful to explore the potential for combining Swarf-less Section Milling with other new technologies, such as downhole optimization systems or real-time data monitoring, to further improve the consistency and efficiency of P&A operations. Overall, the successful application of this technology in the North Sea is a promising development for the industry, and further exploration and refinement of Swarf-less Section Milling could lead to significant benefits for future P&A activities.

The implementation of **section milling with active stabilization** offers a viable solution for scenarios where traditional casing cutting and pulling methods are impractical. By using an undersized section mill with active stabilization, the milling process can be enhanced, allowing the mill to pass through restricted-diameter tubular while maintaining performance and reliability similar to conventional mills. The active stabilization involves centralizing the mill within the casing using expanded stabilizer arms, reducing lateral vibration and significantly extending the longevity of the knives. This technology has been successfully utilized to mill a 70-ft section in 11-3/4 in. casing below a restricted-diameter production riser, saving the operator time and costs by avoiding the removal of surface equipment. The undersized mill with active stabilization demonstrates its capability to efficiently mill casing strings in restricted-diameter tubular, providing comparable performance and reliability to conventional mills.

6.1.3 Perforate, wash and cement (PWC)

The traditional methods of plug and abandonment, such as section milling and cut and pull casing, come with several challenges such as risk of casing and tubing getting stuck, generated swarf, high hook loads, high torque capacities, and swarf management devices, which can lead to potential price increases and additional operational cleaning of components. To address these challenges, new methods and technologies have been developed, one of them being the Perforate, Wash, and Cement (PWC) technology.

The PWC technology eliminates many of the challenges associated with section milling operations by perforating the casing rather than milling it. The swarf generated during section milling is eliminated, and the time taken to complete a 50m section is reduced from 10.47 days with section milling to a single trip taking only 2.55 days with PWC. This results in a savings of 7.9 days (75%) for a single section and using PWC on all 20 plugs can save an estimated 124 rig days.

The Hydrawell solution is a development of the PWC technology, consisting of two components, a HydraHemera Jetting Tool, and a HydraHemera Cementing Tool. The HydraHemera Jetting Tool is used to clean the inside of the wellbore before the cement plug is installed, and the HydraHemera Cementing Tool is used to place the cement plug at the bottom of the wellbore. The solution is used to plug and abandon 10 wells in the Norwegian Continental Shelf, and all 10 barrier plugs have been installed without incident, resulting in savings of $2.7 million for each barrier abandonment plug and time savings of 260 hours or 22 hours in average for each barrier abandonment plug.

PWC avoids technical hazards and potential price increases associated with stuck or parted casing, surface handling, and post-operational cleaning of components like BOPs.

PWC also reduces the functional requirements such as high hook loads, high torque capacities, and/or swarf management devices, thereby reducing the cost exposure of the "rig spread". PWC has demonstrated significant time savings, reducing the operational time by 65% when compared to section milling and 70% when compared to cut and pull operations.

PWC technology has proven to be a highly efficient and effective method for plug and abandonment operations, providing significant time and cost savings while eliminating many of the challenges associated with traditional methods. The success of the PWC technology highlights the importance of continued development and innovation in the oil and gas industry to address challenges and improve operational efficiencies.

6.2 Experimental work

This section will focus on the results of investigating the impact of using nano-SiO_2 as the sole additive in dosages of 0.35, 0.55, 0.75, and 1.0 grams on 0.44 water-to-cement ratio (WCR) neat G-class cement.

6.2.1 Effect of nano-SiO2 on UCS

UCS (Uniaxial Compressive Strength) is a significant factor because it indicates the strength of the cement. A higher UCS value signifies that the cement can withstand greater loads in a challenging well environment, such as higher pressures and harsher conditions.

The method for obtaining the destructive test results is described in Section 5.3.7.1 and involves using *Equation 5.8* (More details in Appendix 3). The presented results are based on the average values obtained from four plugs. Specifically, this means that the reference values obtained after 3 and 28 days of testing were collected for all four plugs in the test batches, and the average reference value was calculated and displayed in the diagrams. The same process was followed for the other plugs with the addition of SiO_2.

We know from other experiments that incorporating nano-silica has a beneficial impact on the cement paste. [50], [52], [53], [54]

Figure 6.1 shows a straight line representing the UCS value of the reference, which helps to visualize the strength increase resulting from different additives of the SiO_2 nanoparticle. Figure 6.1 illustrates that the nano-SiO_2 result in enhanced UCS in comparison to the reference value. After a curing age of 3 days, the results of UCS demonstrate that nano-SiO_2 displays significant improvement in comparison to the reference value, with the plugs containing 0.55g and 0.75g of nano-SiO2 attained average compressive strengths of 18.0 Mpa and 16.6 Mpa, respectively, resulting in a 39.53% and 28.68% increase in UCS compared to the reference. Therefore, 0.55g of nano-SiO_2 appears to be the most effective and optimal dosage for enhancing the strength characteristics of the plugs. Meanwhile, the 0.35g and 1.0g nano-SiO_2 plugs achieved compressive strengths of 16.8 MPa and 15.7 Mpa, respectively. This corresponds to a 30.23% increase for 0.35g and a 21.7% increase for 1.0g of SiO_2.

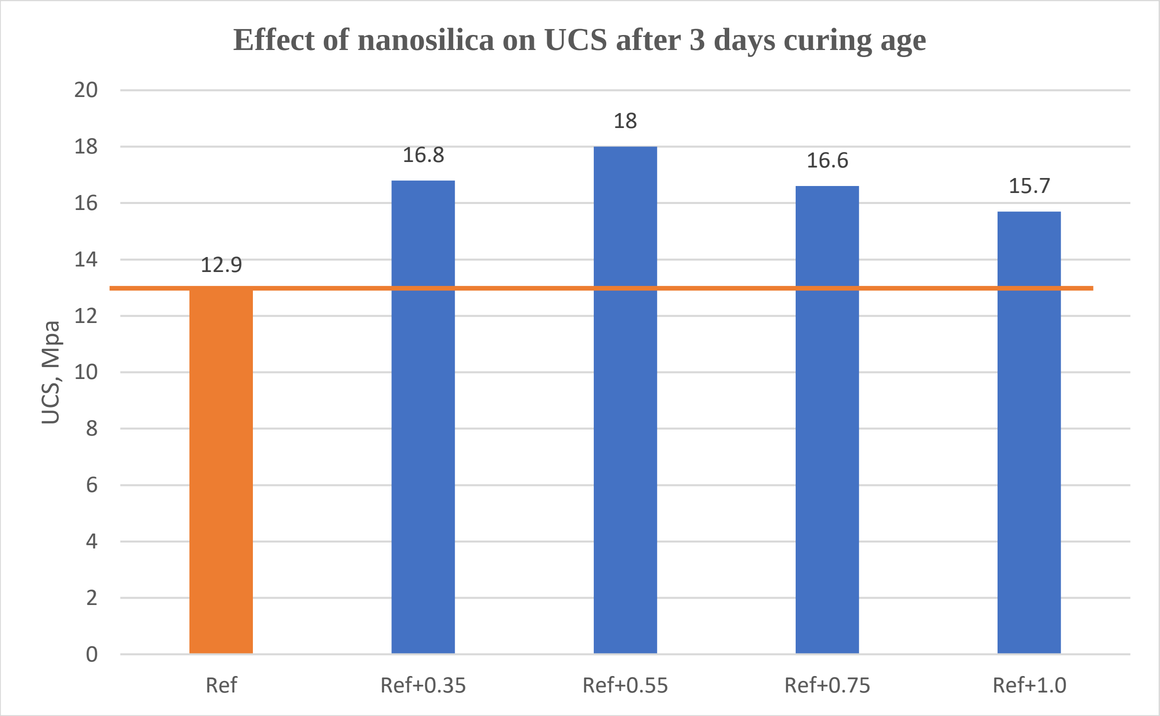


Figure 6.1 UCS for different dosages of nano-silica after 3 days of curing age

After 28 curing age as displayed in Figure 6.2, the addition of SiO_2 at all concentrations results in an increase in uniaxial compressive strength (UCS) over the reference value. The graph shows that the extent of the strength increase varies for different concentrations of SiO_2.

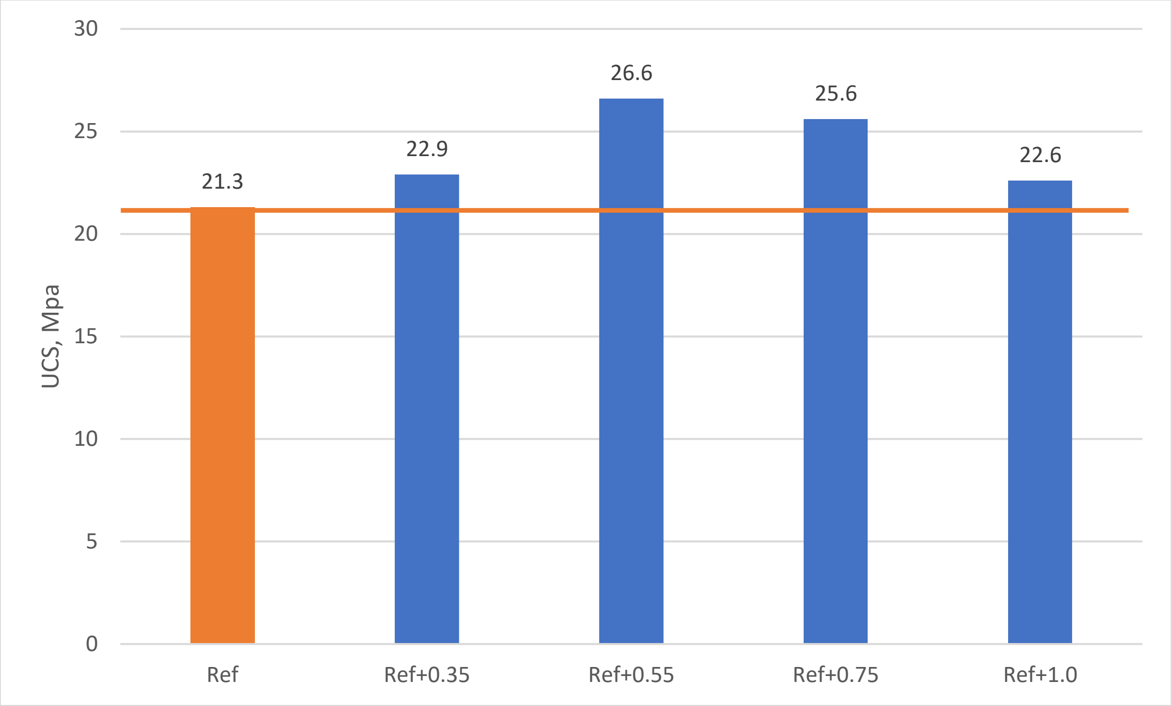


Figure 6.2 UCS for different dosages of nano-silica after 28 curing ages

The plugs with 0.55g and 0.75g of nano-SiO_2, had average values of 26,6 MPa and 25,6 MPa. When compared with the reference value cured for 28 days, they had the highest improvements of 24.88% and 20.19% respectively. However, the plugs containing 0.35g and 1.0g of nano-SiO_2 demonstrated compressive strengths of 22.9 MPa and 22.6 MPa, respectively, after 28 days of curing. This represents a 7.51% improvement for the 0.35g concentration and a 6.1% improvement for the 1.0g concentration compared to the reference values.

During the process of cement hydration, the inclusion of nano-silica may expedite the generation of C-S-H gel, ultimately enhancing the strength of the cement. Moreover, the small size of the silica particles may enable them to fill the spaces between the larger cement particles, resulting in a more compact structure. This phenomenon could elucidate the findings obtained from the destructive testing. [50][52][53] The presence of silica particles in the cement hydrate products inhibits the growth of crystals like Ca(OH)2 and AFm, which is beneficial for the strength of cement. Additionally, the nanoparticles are evenly distributed throughout the cement paste, serving as nuclei that form strong bonds with cement hydrates and promote cement hydration due to their high reactivity.[54]

The presence of nanosilica in the cement mixture likely contributed to the accelerated hydration process and the formation of CSH seeds, resulting in improved strength development. The experimental findings confirm that the incorporation of nanosilica in the cement mixture positively influenced the compressive strength of the plugs, supporting the potential benefits discussed in section 4.3.1 and 4.3.2

6.2.2 Effect of nano-SiO2 on M-modulus

The process for obtaining the M-modulus is presented in Section 5.3.3 which is calculated using *Equation 5.4* based on data measured at 3 and 28 curing days, just prior to the samples undergoing destructive testing. The presented results are based on the average values obtained from four plugs (More details in Appendix 2)

When the M-modulus is high, it indicates a low ultrasonic travel time, which in turn suggests that the medium through which the pulse travels is sufficiently dense. A dense medium is an indicator of a well-maintained microstructure, without any significant cracks or pore spaces. Therefore, a high M-modulus is often considered to be correlated with high UCS values, as it signifies a more intricate microstructure.

After 3 days curing age, Figure 6.3 "the M-modulus for NS after 3 days curing age" shows that the average modulus of elasticity of the zero-additive plugs is approximately 15.3 GPa and that the 0.35g and 0.75 of NS plugs lie above that value which corresponds with UCS presented in figure 6.1. One can observe that the highest M-modulus is the 0.75g of NS plug with a 7.84% increase compared to the zero-additive plug. Furthermore, the second highest M-modulus is observed to be the 0.35% of NS plug, which also had the highest UCS value.

Both the M-modulus and the UCS are functions of the velocity of sound in the plugs. However, for plugs (3 days curing age), we can observe the inverse relation of the UCS with the M-modulus. For example, 0.55g and 1.0g of SiO2 in (3 days), have significantly higher UCS than the reference value, while also having reduced M-modulus.

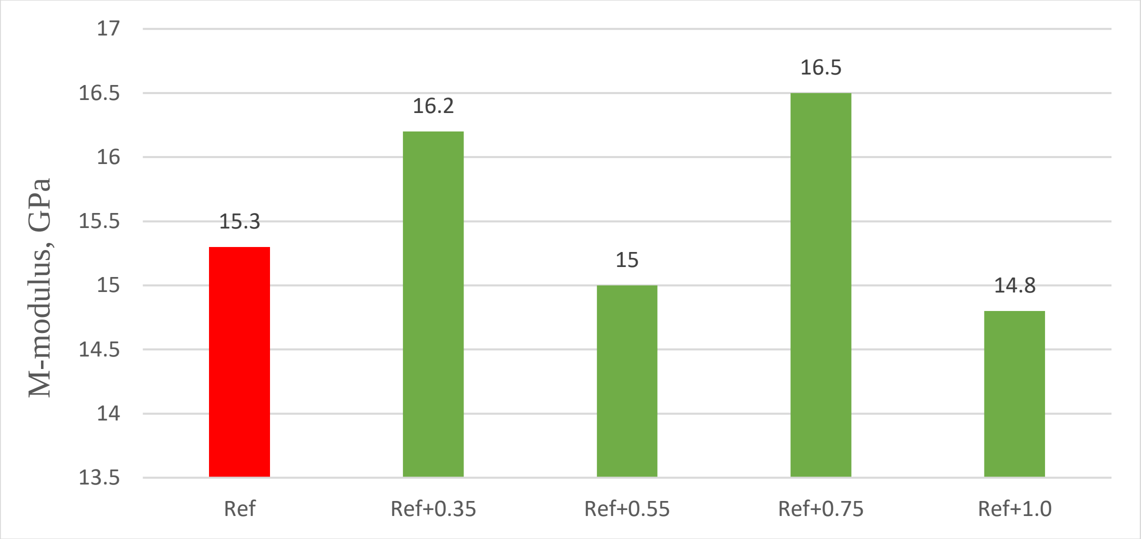


Figure 6.3 M-modulus of NS after 3 days of curing age

After 28 days curing age: Based on the data presented in figure 6.4, it can be observed that the average modulus of elasticity for the zero-additive plugs is approximately 20.8 GPa. Among the nano-plugs, two of them have values higher than 20.8 GPa, while the other two have values lower than that. The nano-silica plugs with 0.55g and 0.75g exhibit the highest M-modulus of 21.0 GPa, corresponding to the highest UCS (after 28 curing age) results of 26.6 and 25.6, MPa respectively. On the other hand, the plugs containing 0.35g and 1.0g of nanosilica have M-modulus values of 19.8 and 19.5 GPa, respectively, slightly lower than the reference sample with no additive.

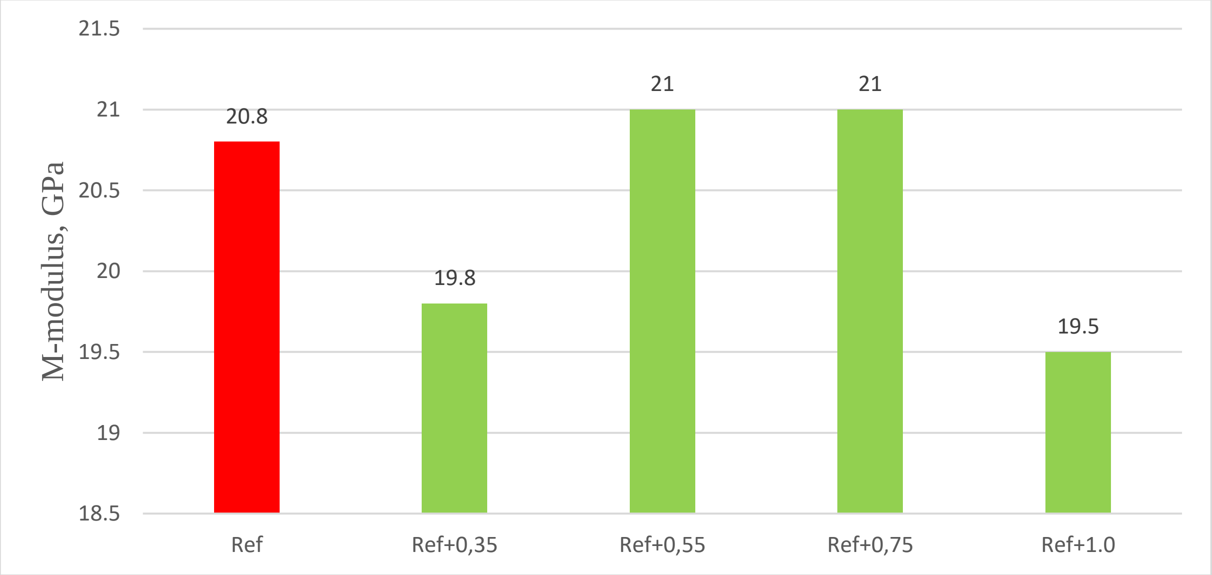


Figure 6.4 M-modulus of NS after 28 days curing age

The M-modulus is calculated based on the sonic travel time through the test sample, which is influenced by the internal structure of the sample. Higher M-modulus values (indicating lower sonic values) are associated with an intact inner structure characterized by minimal cracks or large pore spaces. A higher modulus of elasticity corresponds to a denser material, which logically leads to a higher compressive strength.

While the plugs with nanosilica additives may have slightly lower M-modulus values compared to the reference sample, indicating a slightly less rigid structure, the UCS results show that they possess higher compressive strength.

This apparent discrepancy can be attributed to the fact that the M-modulus is based on the sonic travel time through the sample, which provides information about the internal structure, such as the presence of cracks and pore spaces. The plugs with nanosilica additives may exhibit a slightly lower M-modulus due to their internal structure, but the presence of nanosilica particles can enhance the interparticle bonding and overall strength of the material, resulting in improved UCS values. Therefore, even though the M-modulus values may be slightly lower, the plugs with nanosilica additives demonstrate a notable improvement in compressive strength compared to the reference sample, as indicated by the UCS results.

6.2.3 Water leakage and absorption

The theory and procedure behind fluid leakage and absorption through/around cement is covered in Section 5.3.5 and Section 5.3.4

The results from the leakage and absorption test are presented in tables 6.1, 6.2, and 6.3 (3 days,6 days, and 9 days respectively) (More details in Appendix 4)

	water added	**Leakage**	**absorbed**	**Leakage%**	**absorbed%**
Ref	24.28	0	9.48	0	39.04
Ref+0.35	22.98	0	7.59	0	33.03
Ref+0.55	23.31	0	5.09	0	21.84
Ref+0.75	21.29	0	5.52	0	25.93
Ref+1	24.52	0	8.02	0	32.71

Table 6.1 Leakage and absorption test results after 3 days in oven

	Water added	Leakage	absorbed	Leakage%	absorbed%
Ref	22.02	0	8.81	0	40.01
Ref+0.35	23.03	0	7.58	0	32.91
Ref+0.55	23.88	0	6.03	0	25.25
Ref+0.75	22.27	0	6.28	0	28.20
Ref+1	25.16	0	8.65	0	34.38

Table 6.2 Leakage and absorption test results after 6 days in oven

	water added	Leakage	absorbed	Leakage%	absorbed%
Ref	23.98	0	8.9	0	37.11
Ref+0.35	23.03	0	7.43	0	32.26
Ref+0.55	23.95	0	5.8	0	24.22
Ref+0.75	21.75	0	5.92	0	27.22
Ref+1	25.9	0	8.69	0	33.55

Table 6.3 Leakage and absorption test results after 9 days in oven

We know from previous research, such as the study conducted by Jalal et al. (2011) [50], that the incorporation of nano-SiO2 has a beneficial effect on water absorption. This study examined the effect of incorporating SiO2 into cement on its water and capillary absorption, as well as its microstructure. The findings indicated that the addition of SiO2 resulted in a decrease in both water and capillary absorption, implying an enhancement in the cement matrix's microstructure with reduced pore size. As a result, the research concluded that adding SiO2 has a beneficial impact on cement's water and capillary absorption.

In the post-test analysis, multiple measurements were conducted (see Appendix 4 for more information), with a specific focus on the amount of water leakage through the cement plug, and the amount of water absorbed by the cement matrix. The findings revealed that, regardless of the number of heat cycles endured, the reference sample containing no additives and all samples containing nanosilica demonstrated zero water leakage through or around the cement plug. This suggests that the reference sample itself was capable of providing a reliable barrier against water leakage. Additionally, the inclusion of nanosilica additives did not compromise the sealing properties of the cement matrix. This finding demonstrates the compatibility of nanosilica with the cement matrix and implies that nanosilica can potentially enhance the material's sealing properties without causing any detrimental effects.

It is important to mention that the results for water absorption were obtained through a leakage test, as described in section 5.3.5, rather than by immersing the samples directly in water. From figure 6.5 After 3,6- and 9-days heat cycle, the results show that the addition of nanosilica positively affected water absorption compared to the reference sample with no additive.

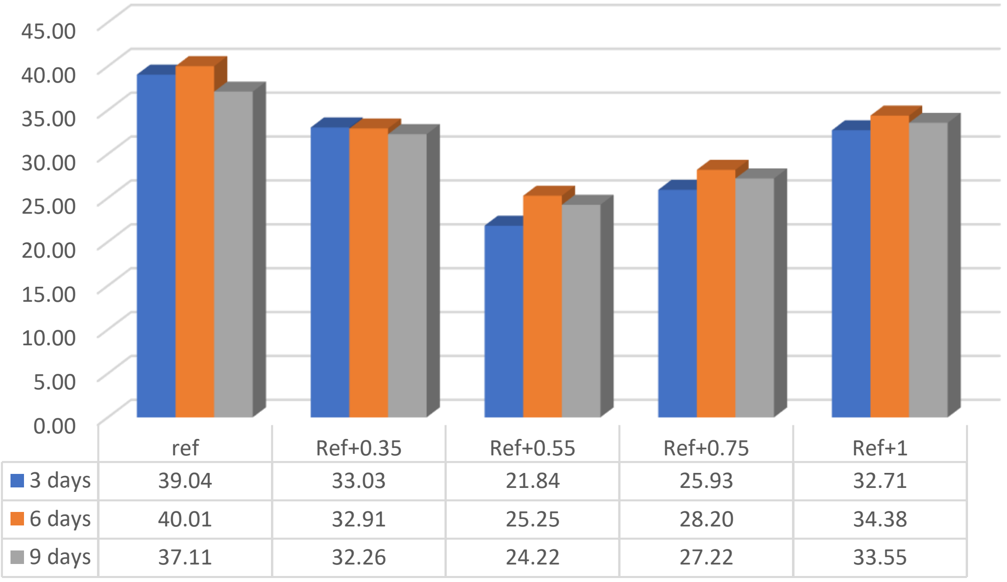


Figure 6.5 water absorption after 3,6- and 9-days heat cycle

One can observe that all concentrations of nanosilica positively affect water absorption after each heat cycle compared to zero additives of nanosilica called the reference. The examination of the literature shows that silica nanoparticles act as fillers in the matrix and can enhance cement performance by reducing water absorption. Therefore, it can be inferred that the inclusion of silica nanoparticles in the cement matrix positively impacts its microstructure and reduces water absorption, leading to improved properties and performance to cement samples.

The greatest reduction in water absorption was observed with the addition of 0.55g of SiO2, which resulted in a 17.2% decrease compared to the reference sample. Adding 0.75g, 1.0g, and 0.35g of SiO2 also resulted in reduced water absorption of 13.1%, 6.4%, and 6%, respectively.

An interesting note is that the water absorption capacity of the cement matrix remained relatively stable after each heat cycle for all concentrations of nanosilica. The amount of water absorption for 0.35g, 0.55g,0.75g, and 1.0 was around 33.03%, 21.84%, 25.93% and 32.71% compared to 39.04% with no additive. The fact that the amount of water the cement matrix was able to absorb remained almost stable after each heat cycle with all concentrations of nanosilica indicates that the addition of nanosilica can help to improve the durability and reduce the permeability of the cement matrix to water. This is due to the fact that the addition of nanosilica particles helps to fill in the gaps and spaces within the material, resulting in a more densely packed structure that is less permeable to water. As a result, the amount of water that can be absorbed by the material is reduced, and this effect is maintained even after exposure to heat cycles.

This stability in water absorption after heat cycles with nanosilica also indicates that the nanosilica is able to maintain its beneficial effects on the material properties even under challenging conditions. This could be important in applications where the material is exposed to high temperatures that could impact its performance over time.

The results showed also a relatively constant amount of water evaporation in each heat cycle but with some variation between heat cycles, which could indicate that the nanosilica additive has a limited effect on the moisture content of the material during curing. However, the variation between heat cycles may indicate that other factors such as temperature, humidity, and airflow are influencing the moisture content of the material and may need to be controlled more closely to achieve more consistent results.

It is worth noting that the amount of cement added to the pipe is almost the same for the control sample and the nano-sample. To ensure accurate and consistent results, a cement plastic mould was used to precisely measure the amount of cement added to the pipe for both the control sample and the nano-samples. Additionally, the pipes used for the samples were the same length to minimize any differences in the test conditions. However, it is important to point out that there was little variation in the amount of water added during each heat cycle across all samples.

After 28 days of heat cycle, the results are displayed in Table 6.4. The findings indicated that all samples, including the reference sample, still demonstrated an absence of water leakage through or around the cement plug.

	water added	Leakage	absorbed	Leakage%	absorbed%
Ref	23.1	0	14.78	0	63.982684
Ref+0.35	22.78	0	12.81	0	56.2335382
Ref+0.55	26.62	0	11.67	0	43.8392186
Ref+0.75	22.38	0	10.27	0	45.8891868
Ref+1	23.79	0	11.9	0	50.0210172

Table 6.4 Leakage and absorption test results after 28 days in the oven

However, water absorption percentages after 28 days increased in both the reference sample and nano silica-containing samples compared to earlier heat cycle durations (3, 6, and 9 days). Notably, samples containing nanosilica additives exhibited a significant reduction in water absorption compared to the reference sample. This indicates that nanosilica additives positively influenced the water absorption characteristics of the cement plug, potentially enhancing its long-term durability and performance.

As illustrated in figure 6.6 Among the tested dosages, the greatest reduction in water absorption was observed with the addition of 0.55g of SiO_2, resulting in a decrease of 20.14% compared to the reference sample. This suggests that 0.55g of SiO_2 is the optimum dosage for minimizing water absorption in cement plugs during heat cycles.

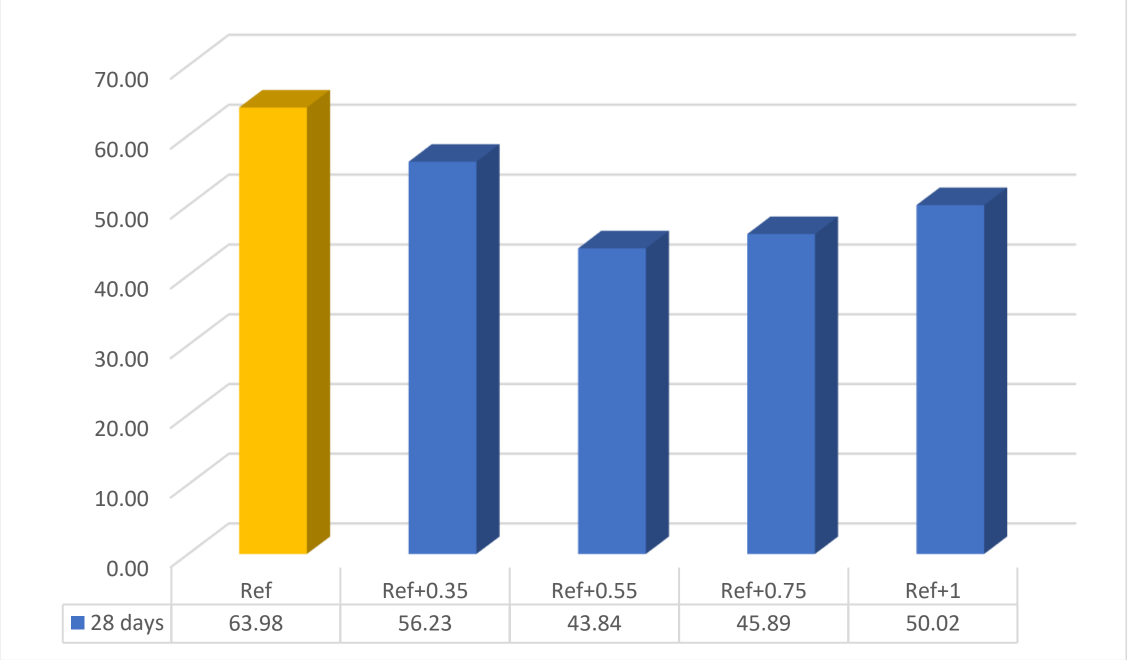


Figure 6.6 water absorption after the 28-day heat cycle

Additionally, adding 0.75g, 1.0g, and 0.35g of SiO_2 also led to reduced water absorption of 18.09%, 13.96%, and 7.75%, respectively, compared to the reference sample.

Although these dosages exhibited lower effectiveness than 0.55g of SiO_2, they still demonstrated considerable reductions in water absorption, indicating their potential as alternative options for improving cement plug performance.

The observed reductions in water absorption can be attributed to the nanosilica additives, which likely enhanced the microstructure of the cement plug matrix, resulting in improved water resistance. The presence of nanosilica particles may have filled the pores and voids within the cement matrix, limiting water ingress and subsequent absorption.

6.2.4 Rheology

In the petroleum industry, fluid transport is prevalent, making rheology crucial. It provides critical information on how flowing materials deform and move. During the construction of a well, the initial cementing operation is crucial to get right, and understanding the rheological properties is essential in designing and executing it properly. Knowing the rheological properties of a cement slurry helps in determining the required pump pressure and rate to pump it downhole. Additionally, rheology is valuable in identifying the frictional pressure in the wellbore during the cement pumping process, and it assists in optimizing the placement of the cement slurry. [30].

From M. Jalal et al. Research, the Rheological properties of high-performance self-compacting concrete (HPSCC) incorporating SiO_2 nanoparticles have been investigated. In general, the data suggests that adding 2% NS to concrete mixtures did not significantly affect their workability or rheological properties, with mixtures containing 2% NS performing similarly to those without any admixtures. However, Increasing the binder content from 400 to 500 kg/m3 also improved the rheological properties of the concrete, likely due to an increase in paste volume which led to a more uniform flow and reduced segregation. Overall, the study suggests that increasing binder content can improve the rheological properties of concrete. [50]

The procedure for determining the rheological properties is outlined in Section 5.3.6, which includes the utilization of *Equation 5.6* and *Equation 5.7* (More details in Appendix 5)

Figure 6.7 presents the shear stress of different concentrations of nano-SiO_2. Seemingly when 0.35g of nanoparticles are added to neat G-class cement, the shear stress had the same values or little improvement compared to the control system for some measured points. While the opposite can be said when for other concentrations ((0.55g, 0.75g and 1.0g) of nano-SiO_2, as it reduces shear stress.

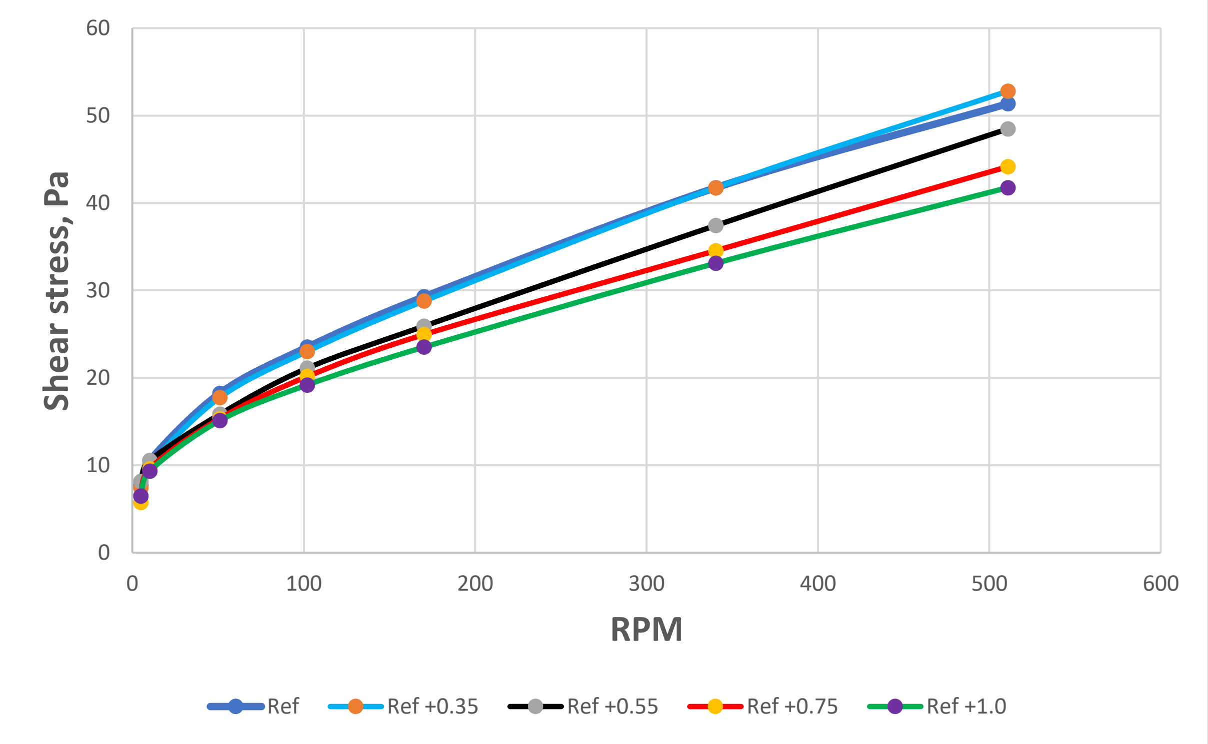


Figure 6.7 the shear stress for different concentrations of nano-SiO_2

Furthermore, figure 6.8 displays the Casson yield stress of the slurries, it is apparent that the slurries with nanoparticles have a lower yield stress compared to the reference. This indicates that less force is required to initiate movement of the cement slurry containing nanoparticles, which could be advantageous when setting a cement plug. Lower yield stress also implies that more of the available pump power can be utilized for other purposes, making it a desirable characteristic.

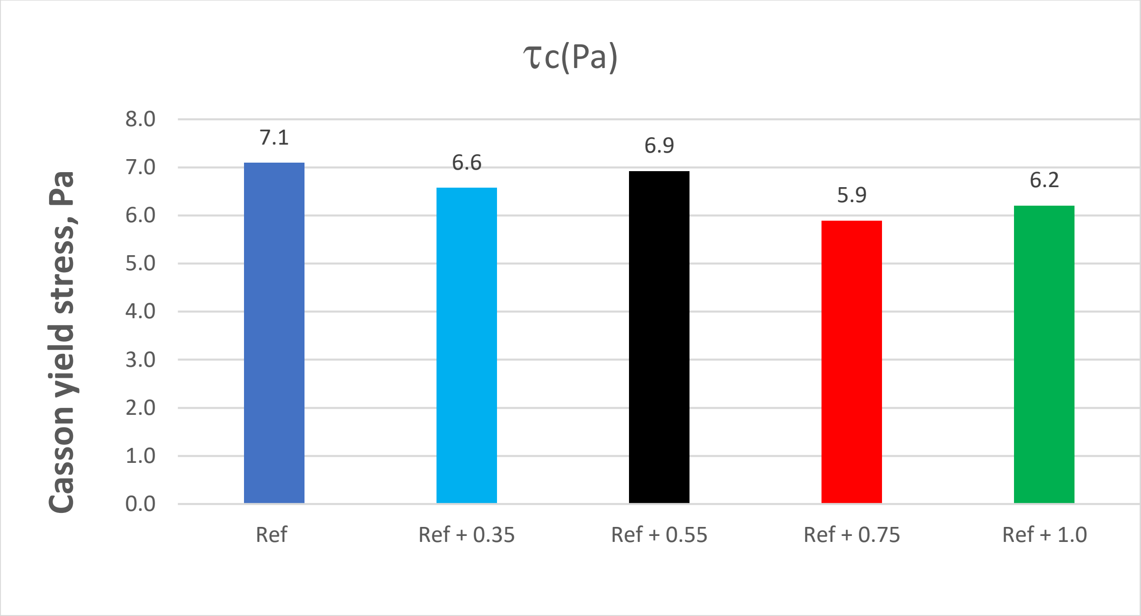


Figure 6.8 Casson yield stress for different concentrations of Sio_2

Also, the Casson plastic viscosity is displayed in Figure 6.9. One can observe that the slurry with 0.35g additive of Sio2 experienced higher PV than the reference slurry, whereas, for other concentrations of nanosilica (0.55g, 0.75g, and 1.0g), there is a significant reduction in PV. A high PV means a higher resistance to flow. This equates to larger friction in the pipe and thus it requires more pumping power.

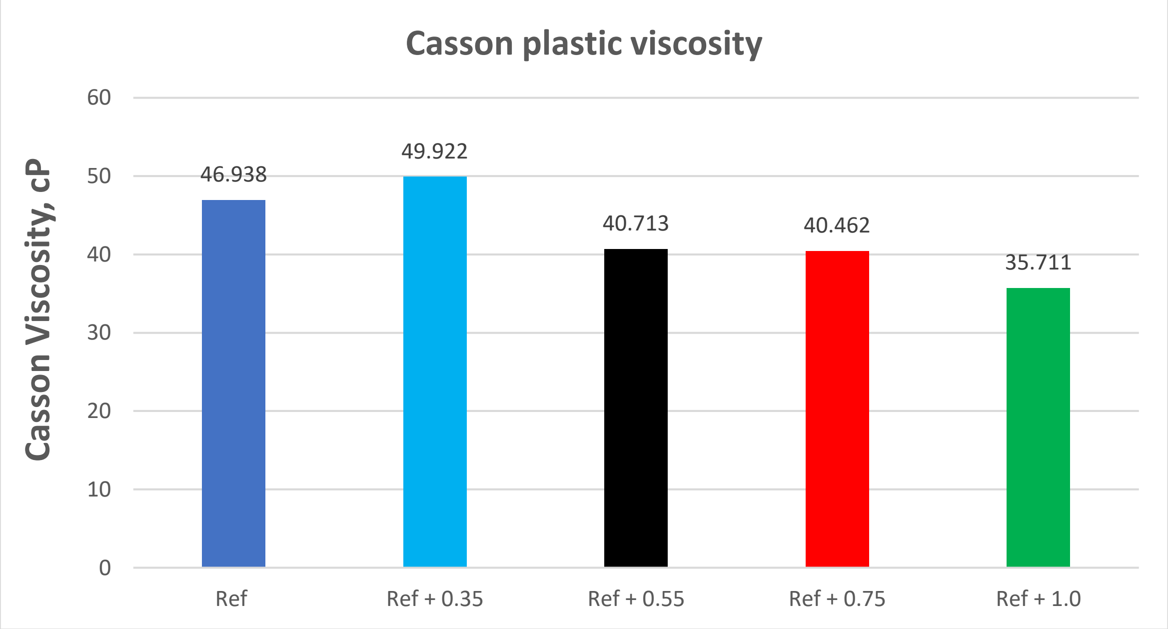


Figure 6.9 Casson plastic viscosity for different concentrations of Sio_2

Conversely, if the plastic viscosity (PV) of slurries is lower than the reference value, they will produce notably lower frictional forces and necessitate less pump pressure to pump them downhole. This property can be advantageous in certain applications, where lower frictional forces and pump pressure requirements can reduce equipment wear and operational costs.

It's worth noting that the specific concentrations of nanosilica used in this study (0.55g, 0.75g, and 1.0g) demonstrated a notable decrease in PV, implying a potential for optimizing the nanosilica concentration to achieve the desired flow properties and reduce pump pressure in practical applications.

7. Summary and Conclusion

There are no commercial beneficiaries involved in P&A activities; the only concerns are the costs and who is responsible for them. Despite the absence of direct advantages, it remains the government's duty to safeguard the environment through P&A activities in this situation.

Plug & Abandon (P&A) activities must be conducted in compliance with the regulations of respective countries. Each country has its own set of rules, regulations, and recommended practices for carrying out P&A procedures. Despite the variations in these guidelines, the fundamental objective shared by different countries is to restore the cap-rock to prevent the harmful release of gases and fluids, including oil, brine, or other chemical substances from abandoned wells and protect the environment.

Conventional Plug and Abandonment (P&A) technologies have certain limitations that can impact their performance and effectiveness. However, the development and implementation of alternative P&A technologies, solutions, and tools have shown promise in addressing these limitations. Case studies have demonstrated that these alternative approaches have the potential to improve the overall P&A process by enhancing efficiency, reducing costs, and ensuring long-term well integrity. By exploring and adopting innovative techniques, the industry can overcome the limitations of conventional P&A technologies and achieve more effective and efficient well abandonment operations.

Casing cut and pull operations for permanent well abandonment can be challenging due to limitations in platform load capacities, rig pulling capacity, and workstring capabilities. Stuck casing adds to the difficulties. However, there are multiple solutions available, and the best one depends on the specific scope of work, downhole tool selection, and surface equipment capabilities. Customized approaches are necessary for each application.

At times, section milling may be necessary for annular integrity remediation during well abandonment, but it can raise concerns due to the associated swarf, risks, and costs. However, active stabilization of an undersized section mill can minimize the number of trips needed for milling, reducing intervention costs and HSE risks. Alternatively, the "swarfless" approach provides a viable alternative that reduces the risks, time, and cost related to section milling. By implementing the swarf-less milling technology, significant savings of 46.5% in rig time can be achieved. This reduction in rig time directly translates to less utilization of pumps, engines, and other equipment that emit CO_2. As a result, the implementation of Swarf-less Section Milling technology has the potential to reduce emissions in decommissioning operations by over 70%.

Perforate, Wash & Cement (PWC) has become increasingly popular as an alternative to traditional methods like section milling and cut and pull. PWC offers several advantages, including the elimination of technical risks and potential cost escalations associated with stuck or parted casing, as well as simplifying surface handling and post-operational cleaning of elements like BOPs. Furthermore, PWC reduces functional requirements. In terms of time savings, PWC has shown remarkable results, reducing the operational time by 65% compared to section milling and 70% compared to cut and pull operations.

Another vital aspect to consider is the choice of plugging material, with cement traditionally being the preferred option. The NORSOK D-010 standard specifies certain requirements for cement, such as impermeability, resistance to corrosive substances, and the ability to retain its size without shrinkage. Although cement continues to be widely utilized for plugging and abandonment procedures, ongoing research and development are exploring alternative materials and techniques that offer enhanced and dependable sealing properties.

The future of P&A operations is expected to embrace new materials, with solutions like bismuth and thermite resin technology showing early promise. Activated shale as a barrier also holds potential as a sustainable alternative. Geopolymers shows promise as a potential alternative to Portland cement in P&A operations, providing advantages such as low shrinkage, low permeability, and high-temperature stability. However, despite these advancements, it should be noted that cement-based slurries, specifically Portland cement, often fail to meet certain requirements. While cement-based solutions have been widely used and are considered the most cost-effective choice, there are limitations due to factors such as shrinkage, well integrity issues, fluid leakage, and the risk of long-term degradation. Consequently, the industry recognizes the need for alternative materials and continues to explore innovative options to overcome the shortcomings of cement-based slurries. Emerging technologies like nanosilica can enhance engineering seals; however, to ensure their long-term effectiveness, it is essential to design seals that gradually adopt geological characteristics as part of a transition process.

The inclusion of nanosilica in G-class cement has demonstrated enhancements in various aspects such as strength and resistance to fluid migration. The experimental results consistently show that the addition of various dosages of nano-SiO_2 (0.35g, 1.0g, 0.55g, and 0.75g) to the cement mixture leads to significant improvements in compressive strength throughout the curing process compared to the reference value, both after 3 days and 28 days of curing. Notably, the plugs containing 0.55g of nano-SiO_2 demonstrate the highest improvements, with a remarkable 39.53% increase in compressive strength after 3 days of curing and a 24.88% increase after 28 days of curing, compared to the reference value. These results indicate that the optimal dosage for enhancing compressive strength in cement plugs is 0.55g of SiO_2.

The leakage test results showed no water leakage in both the reference sample and the samples with nanosilica, regardless of the heat cycles endured. This indicates that the inclusion of nanosilica did not compromise the cement plug's sealing properties. It demonstrates the compatibility of nanosilica with the cement matrix and suggests its potential to enhance sealing without detrimental effects. Additionally, the results emphasize the importance of optimizing the dosage of nanosilica additives to minimize water absorption in cement plugs during heat cycles. Among the dosages tested, the incorporation of 0.55g of SiO_2 exhibited the most reduction in water absorption, with a decrease of 15.00% after 3 heat cycles and 20.14% after 28 heat cycles, compared to the reference sample. Nevertheless, alternative dosages such as 0.75g, 1.0g, and 0.35g of SiO_2 also demonstrated reductions in water absorption, indicating their potential as viable options for enhancing the performance of cement plugs.

The addition of nanosilica in cement slurries results in lower yield stress, requiring less force to initiate movement. This can be advantageous when setting a cement plug and allows for efficient utilization of pump power. Additionally, the presence of nanosilica reduces the Casson plastic viscosity, lowering resistance to flow and decreasing pump pressure requirements. This property can reduce equipment wear, and operational costs, and may allow for the optimization of nano-silica concentration for desired flow properties.

8. Future work

In this thesis, ***literature studies*** on plug and abandonment (technologies, alternative materials, field cases) are presented. Moreover, the impact of nanoparticles on cement was experimentally investigated. The author proposes the following possible future work.

In plug and abandonment

- Investigate P & A operation evaluation based on expert opinion. Here, prepare interviews and perform surveys to gather experts' experience who are involved in the different P & A operations to investigate the challenges and performance of the P & A technologies.
- Study P & A operational data obtained from different operators to evaluate the performance of the different P & A technologies implemented in the North Sea.

By doing so, one can come up with more information about conventional technologies.

In the experimental part

The authors also propose the following future works on the experimental part:

- Expand the number of cement specimens for each nano-SiO_2 dosage and reference. Consider using a larger number of specimens, such as 10 or more, to increase the statistical power of the study. This will help ensure that any observed effects are not due to chance variations.
- Exploring the long-term performance and properties of the cement with nano-SiO2 additive by investigating the effects of extended curing periods, such as 60, and 90 days. This will provide valuable insights into the behavior of the cement over a longer duration and allow for a comprehensive assessment of its long-term performance and properties.
- Larger-sized moulds can better represent the real-world conditions and dimensions encountered in practical applications. This can enhance the relevance and applicability of the findings to actual construction scenarios. This can reduce the potential for errors and ensure a more consistent and reliable experimental procedure.
- Performing SEM (Scanning Electron Microscopy) analysis of the microstructure in the tested cement specimens with nanoparticles is an excellent suggestion for

future work. SEM analysis can provide detailed and high-resolution images of the microstructure, allowing for a deeper understanding of the effects of nanoparticles on the cement matrix.

- Investigating the impact of more realistic well conditions, specifically High-Pressure High Temperature (HPHT) conditions, on the performance of the cement samples can provide valuable insights into their behavior in realistic oil and gas well environments.
- Investigate the combined effects of nanosilica with chemical admixtures (e.g., superplasticizers, accelerators, retarders, air-entraining agents) and assess their influence on workability, setting time, strength development, and other relevant properties of the cement.
- Explore the synergistic effects of nanosilica with mineral admixtures (e.g., fly ash, slag, silica fume) and evaluate their impact on hydration kinetics, strength development, pozzolanic activity, and durability characteristics of the cement.

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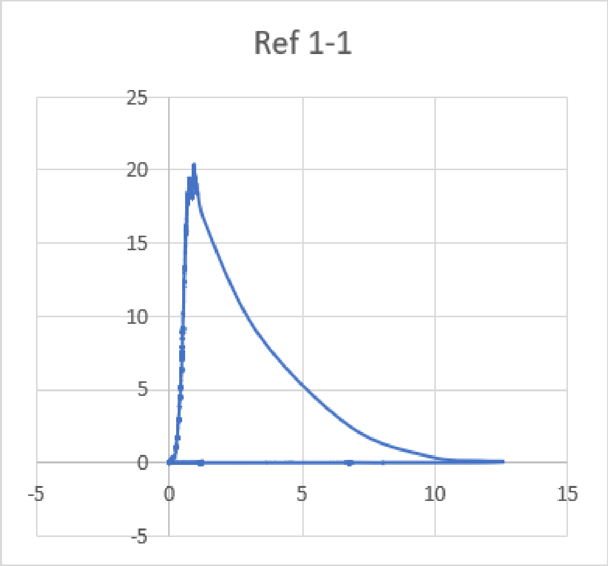
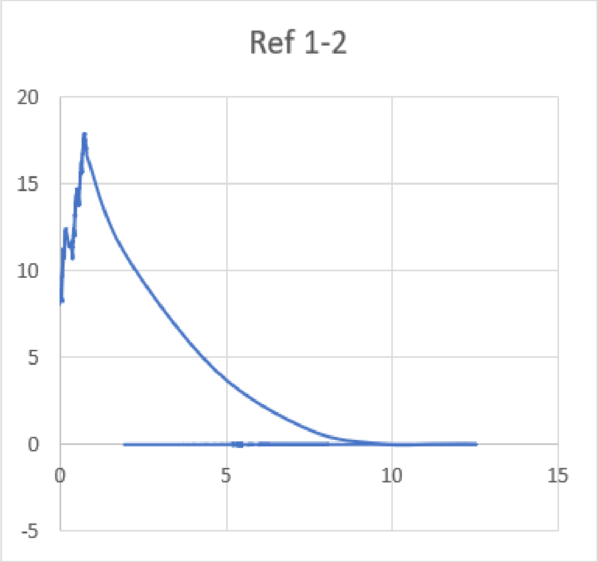
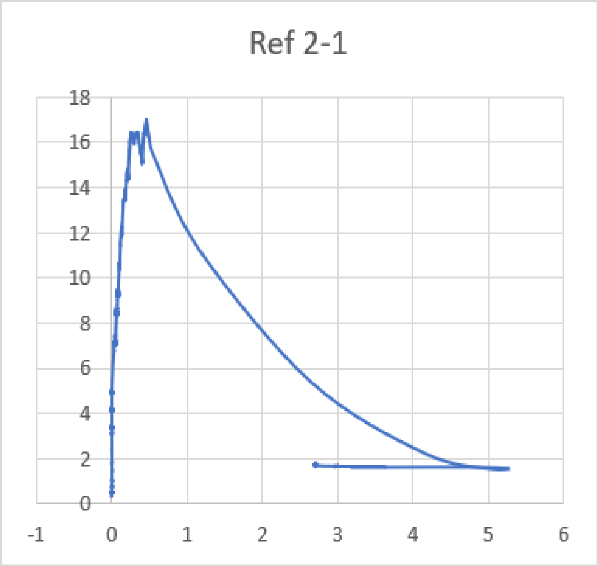
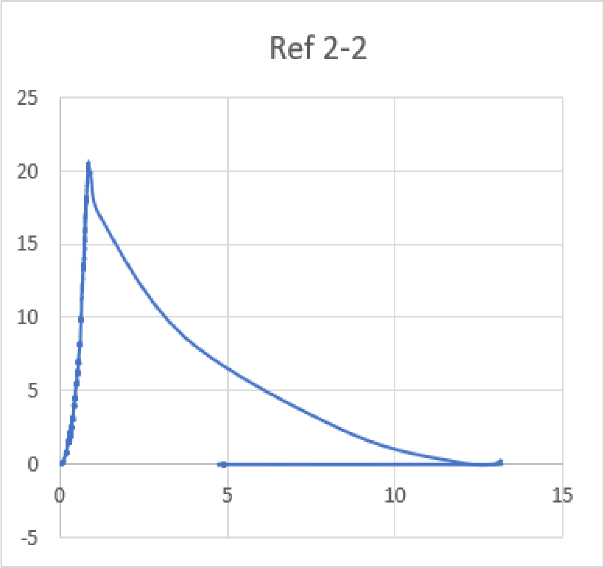
Appendix 1- Load vs deformation

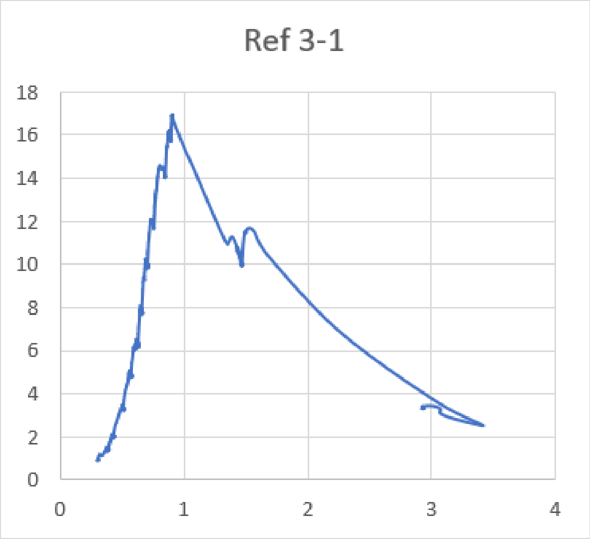
Displays the relationship between deformation (mm) on the x-axis and load (kN) on the y-axis for all cement plugs.







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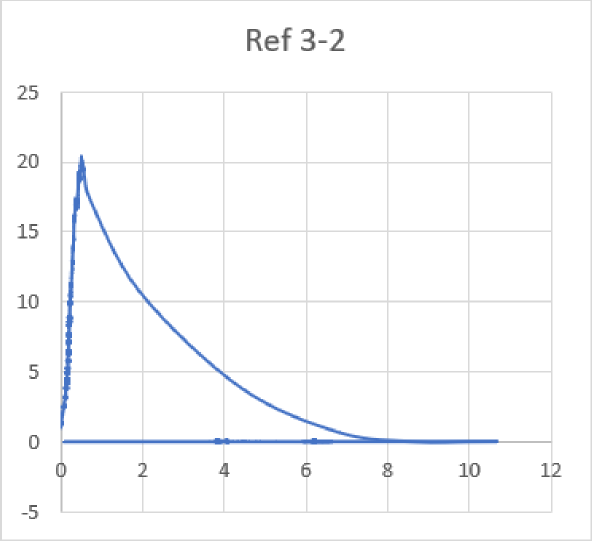
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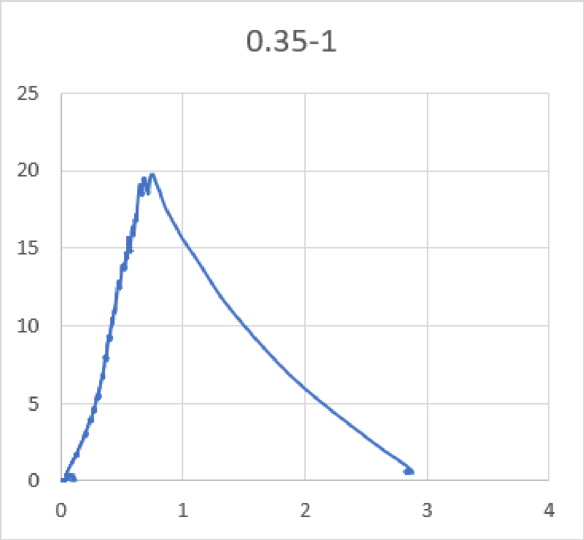
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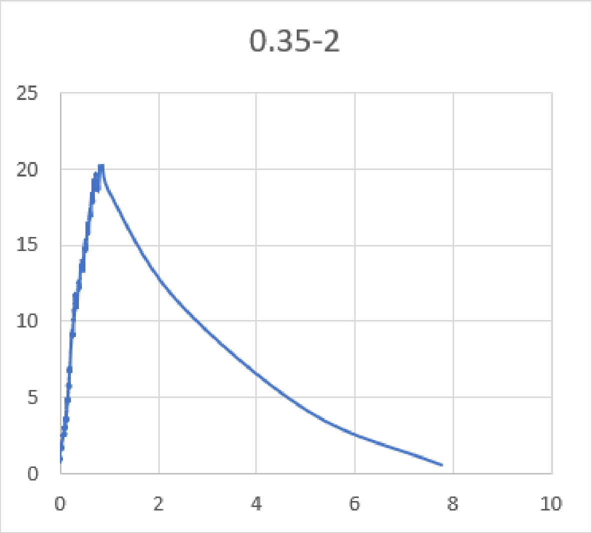
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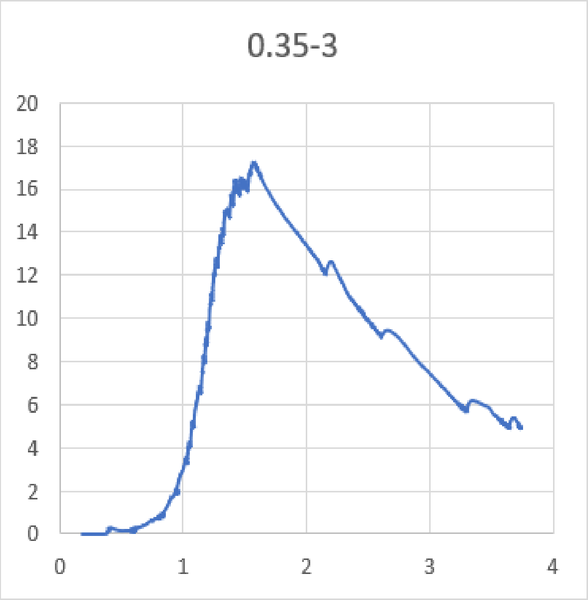
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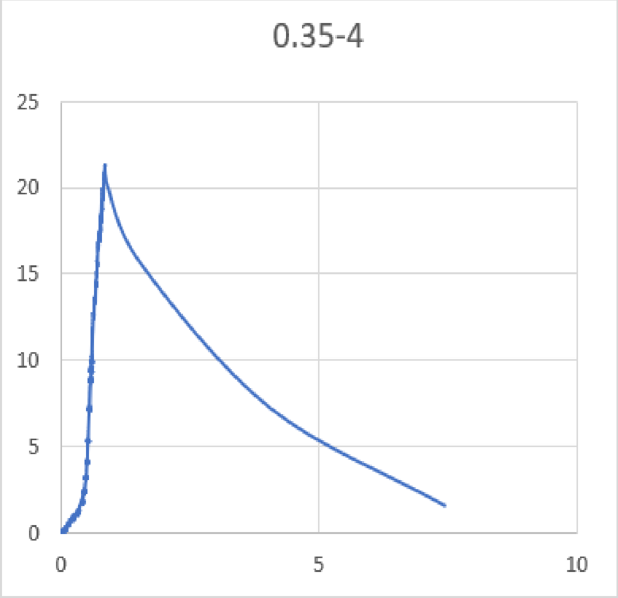
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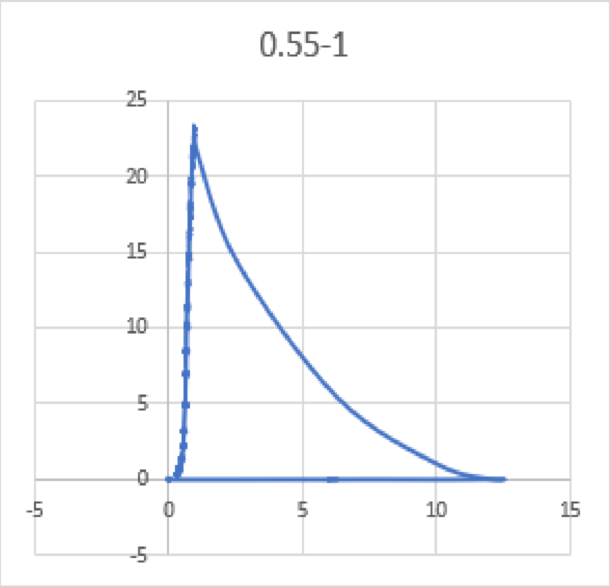
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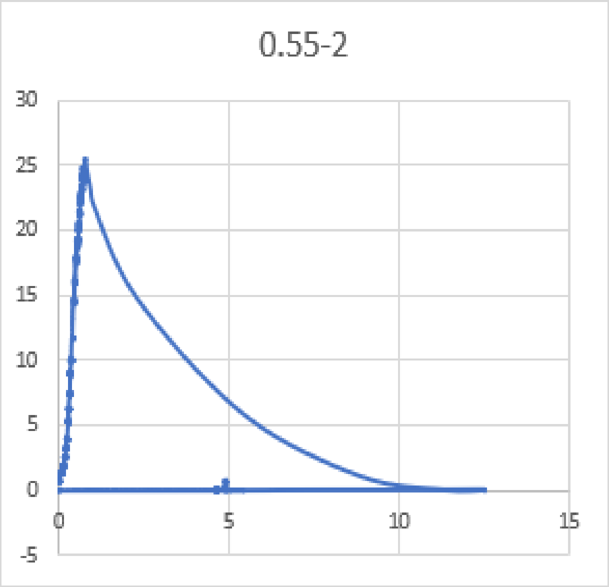
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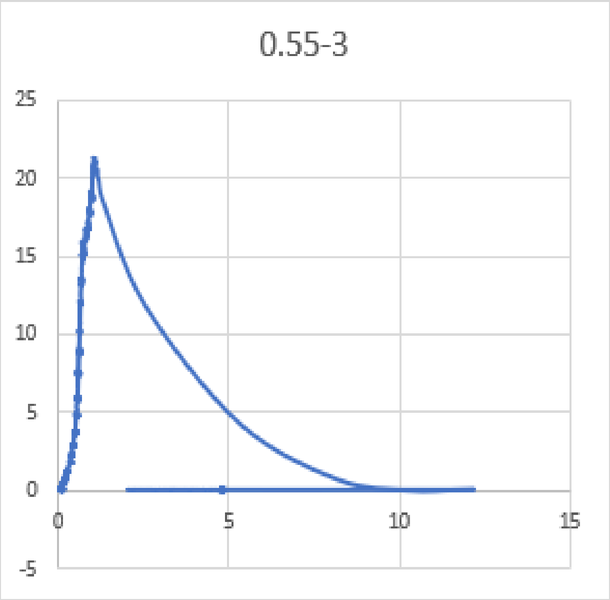
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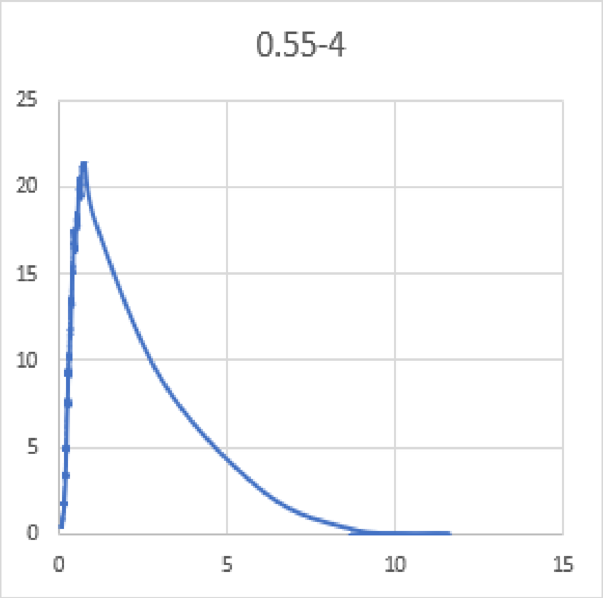
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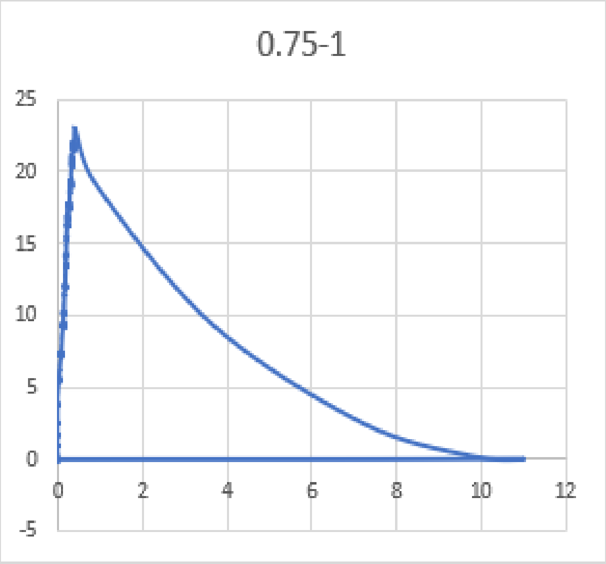
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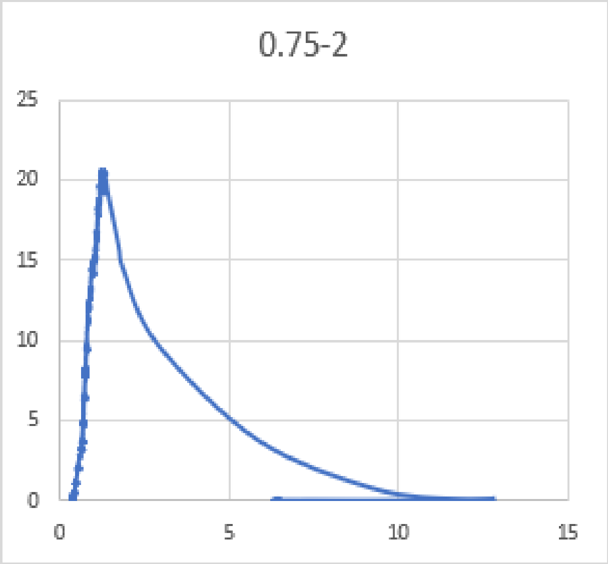
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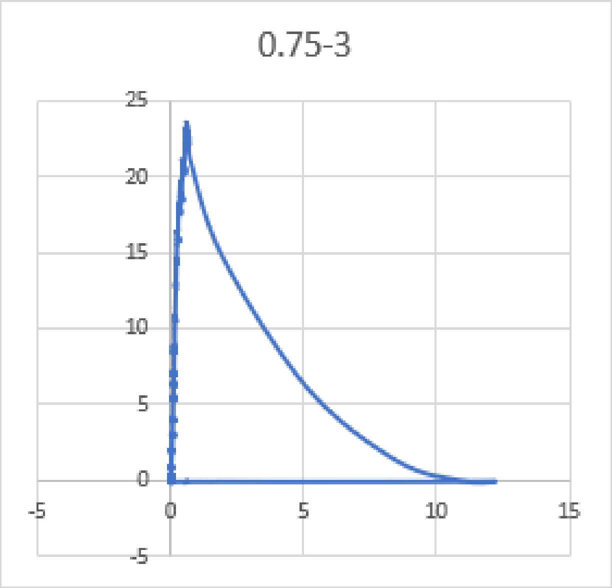
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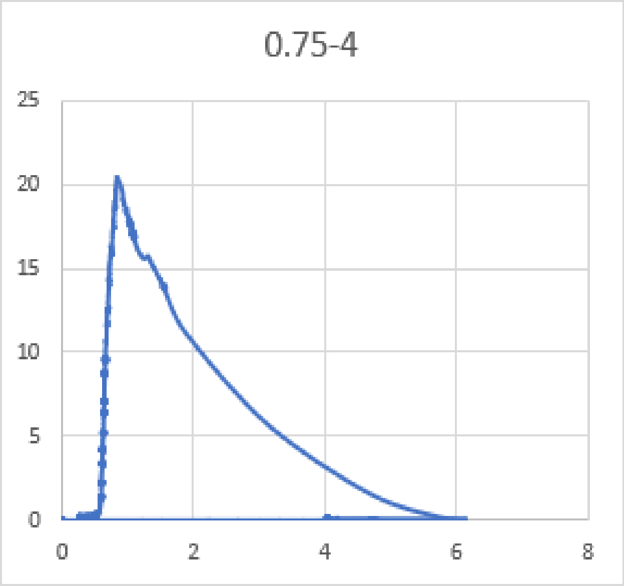
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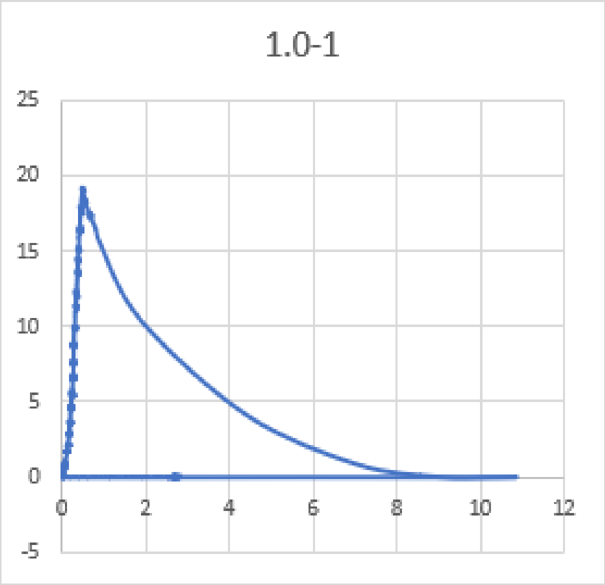
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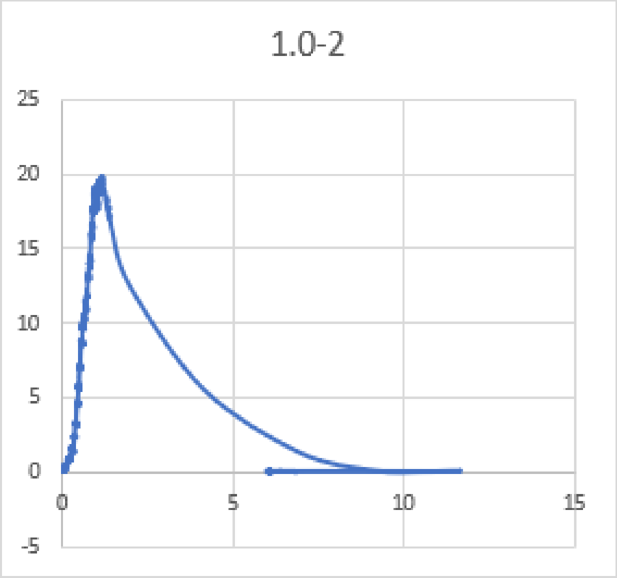
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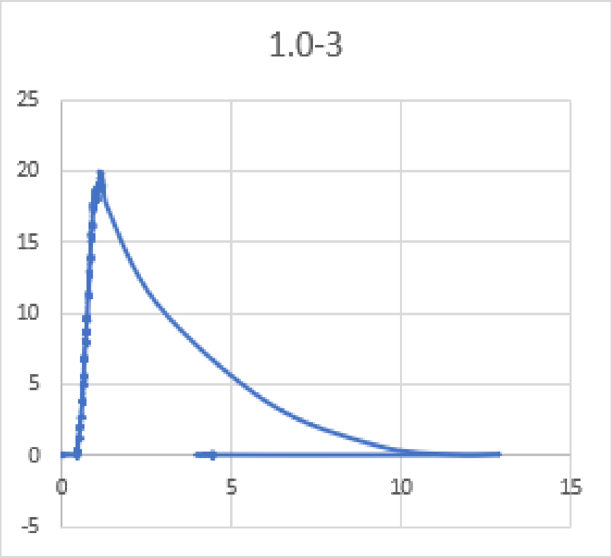
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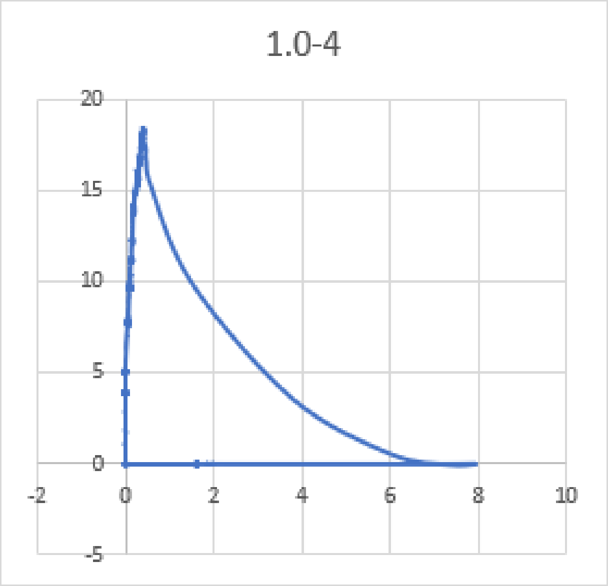
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Appendix 2 - Non-destructive Measurements

Appendix 2 comprises the unprocessed recorded information such as weight, outer diameter (OD), length, and sonic measurements from all experimental sets on the day of crushing. It also includes certain derived quantities such as volume, modulus of elasticity (M), and P-wave velocity.

Non-destructive 3 days

Plug	Mass, g	OD,mm	L,mm	Vol,m3	Density,kg/m3	Sonic,μs	Vp m/s	M (Gpa)	Average M
Ref -1-1	99.612	32.88	65.49	5.5607E-05	1791	23.6	2775	13.8	
Ref-1-2	101.962	32.88	64.78	5.5004E-05	1854	21.1	3070	17.5	
Ref -2-1	99.42	32.88	66.04	5.6074E-05	1773	24	2752	13.4	15.3
Ref-2-2	101.705	32.88	64.69	5.4928E-05	1852	21.7	2981	16.5	
0,35-1-1	99.755	32.88	66.15	5.6167E-05	1776	22.6	2927	15.2	
0,35-1-2	100.684	32.88	63.79	5.4163E-05	1859	21	3038	17.2	
0,35-2-1	100.248	32.88	66.06	5.6091E-05	1787	22.3	2962	15.7	16.2
0,35-2-2	99.575	32.88	64.12	5.4444E-05	1829	21.2	3025	16.7	
0,55-1-1	95.915	32.88	66.15	5.6167E-05	1708	23.8	2779	13.2	
0,55-1-2	100.753	32.88	64.59	5.4843E-05	1837	21.1	3061	17.2	
0,55-2-1	95.971	32.88	66.53	5.649E-05	1699	23.8	2795	13.3	15.0
0,55-2-2	99.757	32.88	64.52	5.4783E-05	1821	21.6	2987	16.2	
0,75-1-1	96.114	32.88	66.71	5.6643E-05	1697	23.4	2851	13.8	
0,75-1-2	102.73	32.88	63.64	5.4036E-05	1901	19.6	3247	20.0	
0,75-2-1	97.104	32.88	66.37	5.6354E-05	1723	23.3	2848	14.0	16.5
0,75-2-2	103.298	32.88	64.82	5.5038E-05	1877	20.9	3101	18.1	
1,0-1-1	95.961	32.88	66.31	5.6303E-05	1704	23.8	2786	13.2	
01.0-1-2	100.027	32.88	64.47	5.4741E-05	1827	21.5	2999	16.4	
1,0-2-1	95.391	32.88	66.32	5.6312E-05	1694	23.8	2787	13.2	14.8
1.0-2-2	98.891	32.88	63.95	5.4299E-05	1821	21.4	2988	16.3	

Non-destructive 28 days

Plug #	Mass, g	OD, mm	L, mm	Volume, m3	Sonic, μs	Density, kg/m3	Velocity, m/s	M (Gpa)	Average M
Ref 1-1	108.48	33.01	65.13	5.5739E-05	19.5	1946	3340	21.7	
Ref 1-2	108.89	33.18	67.39	5.8269E-05	20	1869	3370	21.2	
Ref 2-1	112.59	33.04	65.67	5.6304E-05	20.4	2000	3219	20.7	
Ref 2-2	113.43	33.03	67.53	5.7863E-05	20.9	1960	3231	20.5	
Ref 3-1	112.06	33.06	67.43	5.7883E-05	21.3	1936	3166	19.4	
Ref 3-2	106.86	33.01	67.23	5.7537E-05	20	1857	3362	21.0	20.8
0.35-1	111.88	33.1	67.58	5.8152E-05	20.7	1924	3265	20.5	
0.35-2	111.46	33.06	67.76	5.8166E-05	21.2	1916	3196	19.6	
0.35-3	111.61	33.03	67.42	5.7769E-05	21.4	1932	3150	19.2	
0.35-4	112.22	33.01	67.47	5.7742E-05	21	1943	3213	20.1	19.8
0.55-1	112.94	33.02	67.41	5.7726E-05	20.4	1956	3304	21.4	
0.55-2	112.13	33.04	67.46	5.7838E-05	20.8	1939	3243	20.4	
0.55-3	112.39	33.03	67.91	5.8189E-05	21	1931	3234	20.2	
0.55-4	112.51	33.07	67.15	5.7677E-05	20.2	1951	3324	21.6	
0.55-5	112.16	33.04	67.11	5.7538E-05	20.1	1949	3339	21.7	21.0
0.75-1	111.98	33.01	67.57	5.7828E-05	20.8	1936	3249	20.4	
0.75-2	112.34	33.01	67.34	5.7631E-05	20.7	1949	3253	20.6	
0.75-3	112	33	67.28	5.7544E-05	20.2	1946	3331	21.6	
0.75-4	112.29	33.09	67.2	5.779E-05	20.3	1943	3310	21.3	21.0
1.0-1	111.82	33.07	67.27	5.778E-05	21.2	1935	3173	19.5	
1.0-2	112.12	33.07	67.43	5.7918E-05	21.2	1936	3181	19.6	
1.0-3	112.98	33.02	67.57	5.7863E-05	21.3	1953	3172	19.6	
1.0-4	109.43	33.01	67.44	5.7716E-05	21.1	1896	3196	19.4	19.5

Appendix 3 – UCS measurements

UCS result (3 Days)

UCS (Max Load, N), 3 days					
	Ref	Ref+0.35 g SiO2	Ref+0.55g SiO2	Ref+0.75 g SiO2	Ref+1.0 g SiO2
	9.987	13.32	15.4	13.04	13.35
	10.85	14.01	15.08	16.26	14.31
	10.69	15.14	14.93	11.59	13.81
	12.28	14.7	15.83	15.49	11.94
Average, Max Load	11.0	14.3	15.3	14.1	13.4
% Change	-	30.50	39.80	28.70	21.92

UCS (MPa), 3 days					
	Ref	Ref+0.35 g SiO2	Ref+0.55g SiO2	Ref+0.75 g SiO2	Ref+1.0 g SiO2
	11.8	15.7	18.1	15.4	15.7
	12.8	16.5	17.8	19.1	16.9
	12.6	17.8	17.6	13.6	16.3
	14.5	17.3	18.6	18.2	14.1
Average, UCS	12.9	16.8	18.0	16.6	15.7
% Increase	-	30.23	39.53	28.68	21.7

UCS result (28 days)

UCS (Max Load, N), 28 days					
	Ref	Ref+0.35 g SiO2	Ref+0.55g SiO2	Ref+0.75 g SiO2	Ref+1.0 g SiO2
	16.98	19.7	23.29	23	19.21
	16.93	20.18	25.43	20.64	19.81
	20.35	17.23	21.28	23.53	19.87
	17.85	21.31	21.32	20.49	18.37
	20.53				
	16.53				
Average, Max Load	18.2	19.6	22.8	21.9	19.3
% Change	-	7.75	25.12	20.45	6.16

UCS (MPa), 28 days					
	Ref	Ref+0.35 g SiO2	Ref+0.55g SiO2	Ref+0.75 g SiO2	Ref+1.0 g SiO2
	19.9	23.0	27.2	26.9	22.5
	19.8	23.6	29.7	24.1	23.2
	20.9	20.1	24.9	27.5	23.2
	19.3	24.9	24.9	24.0	21.5
	23.8				
	24.0				
Average, UCS	21.3	22.9	26.6	25.6	22.6
% Increase	-	7.51	24.88	20.19	6.1

Appendix 4 - leakage and absorption test

All the measurements and results obtained during the leakage and absorption test following heating cycles of 3, 6, and 9 days.

Heat cycle1 (3 days)

		Ref	Ref+0.35	Ref+0.55	Ref+0.75	Ref+1.0
Weight of plug without water		232.11	234.22	235.14	237.86	229.76
weight of plug with water		256.39	257.2	258.45	259.15	254.28
weight of cup w/o water		16.28	16.38	16.3	16.58	16.35
Wt of fluid added on the top		24.28	22.98	23.31	21.29	24.52
After 24 hours						
Wt of plug with water		256.27	257.05	258.33	259.02	254.02
Wt of cup with water		16.28	16.38	16.3	16.58	16.35
Wt of plug after removal of water		241.59	241.81	240.23	243.38	237.78
Wt of fluid on the top		14.680	15.240	18.100	15.640	16.240
Results						
Leakage		0.00	0.00	0.00	0.00	0.00
Absorption		9.48	7.59	5.09	5.52	8.02
Evapuration		0.12	0.15	0.12	0.13	0.26

Heat cycle2 (6 days)

		Ref	Ref+0.35	Ref+0.55	Ref+0.75	Ref+1.0
Weight of plug without water		232.22	233.5	231.25	236.44	229.83
weight of plug with water		254.24	256.53	255.13	258.71	254.99
weight of cup w/o water		16.28	16.38	16.3	16.58	16.35
Wt of fluid added on the top		22.02	23.03	23.88	22.27	25.16
After 24 hours						
Wt of plug with water		253.9	256.2	254.79	258.34	254.63
Wt of cup with water		16.28	16.38	16.3	16.58	16.35
Wt of plug after removel of water		241.03	241.08	237.28	242.72	238.48
Wt of fluid on the top		12.870	15.120	17.510	15.620	16.150
Results						
Leakage		0.00	0.00	0.00	0.00	0.00
Absorption		8.81	7.58	6.03	6.28	8.65
Evapuration		0.34	0.33	0.34	0.37	0.36

Heat cycle3 (9 days)

		Ref	Ref+0.35	Ref+0.55	Ref+0.75	Ref+1.0
Weight of plug without water		231.54	232.45	231.47	234.96	228.34
weight of plug with water		255.52	255.48	255.42	256.71	254.24
weight of cup w/o water		16.28	16.38	16.3	16.58	16.35
Wt of fluid added on the top		23.98	23.03	23.95	21.75	25.9
After 24 hours						
Wt of plug with water		255.44	255.42	255.35	256.66	254.19
Wt of cup with water		16.28	16.38	16.3	16.58	16.35
Wt of plug after removal of water		240.44	239.88	237.27	240.88	237.03
Wt of fluid on the top		15.000	15.540	18.080	15.780	17.160
Results						
Leakage		0.00	0.00	0.00	0.00	0.00
Absorption		8.9	7.43	5.8	5.92	8.69
Evapuration		0.08	0.06	0.07	0.05	0.05

Heat cycle4 (28 days)

		Ref	Ref+0.35	Ref+0.55	Ref+0.75	Ref+1.0
Weight of plug without water		230.3	230.68	230.23	236.64	232.44
weight of plug with water		253.4	253.46	256.85	259.02	256.23
weight of cup w/o water		16.28	16.38	16.3	16.58	16.35
Wt of fluid added on the top		23.1	22.78	26.62	22.38	23.79
After 24 hours						
Wt of plug with water		253.16	253.28	256.49	258.71	255.98
Wt of cup with water		16.28	16.38	16.3	16.58	16.35
Wt of plug after removel of water		245.08	243.49	241.9	246.9	244.34
Wt of fluid on the top		8.080	9.790	14.590	11.810	11.640
Results						
Leakage		0.00	0.00	0.00	0.00	0.00
Absorption		14.78	12.81	11.67	10.26	11.9
Evapuration		0.24	0.18	0.36	0.31	0.25

Appendix 5 - Rheology test

All the measurements and results obtained during the Rheology test

RPM	Ref	Ref +0.35	Ref +0.55	Ref +0.75	Ref +1.0
300	107	110	101	92	87
200	87	87	78	72	69
100	61	60	54	52	49
60	49	48	44	42	40
30	38	37	33	32	31.5
6	22	21	22	20	19.5
3	16	15.5	17	12	13.5

Parameters	Ref	Ref + 0.35	Ref + 0.55	Ref + 0.75	Ref + 1.0
tc(lbf/100sqft)	14.776336	13.69	14.421766	12.27381156	12.9146797
mc (lbf-s/100sqft)	0.09803	0.10426	0.08503	0.08451	0.07458