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Advantages and Current Limitation of One-Part Geopolymers Developed for O&G Industry: Apple-to-Apple Comparison

By

Ole Berg Sylte

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Abstract

The development of geopolymers for use in the oil and gas industry has gained significant recognition in recent years due to the pressing need for sustainable and environmentally friendly alternatives in the sector. The oil and gas industry has a significant impact on the environment, and the cementing in oil and gas operations contribute to a large part of the total emissions. Geopolymers, on the other hand, offer a viable solution that not only reduces the environmental impact but also offers improved performance and cost-effectiveness.

This work addresses evaluation of a one-part granite-based geopolymer developed for O&G industry, with focus on well construction and well abandonment. To evaluate potential of the technology, a comparison is done with neat API class G cement. The evaluation includes essential tests defined by API RP 10B-2 such as free water and fluid loss, thickening time, viscosity, sonic strength, uniaxial compressive strength, and static gel strength.

In this study of geopolymers, I made notable findings regarding its characteristics and challenges. One key observation is the difficulty in mixing. Consistency tests revealed that after mixing, the geopolymer will be thicker in the beginning, then gets thinner with shearing. This finding presents challenges in achieving desired workability.

Additionally, the study examined the fluid retention properties of geopolymers compared to conventional cement (OPC). Geopolymers showed relatively good fluid retention, although not meeting the standard requirements. This indicates a need for further research to improve fluid retention capabilities.

Another significant finding is the absence of free water in geopolymer samples. This suggests that water used in the mixture becomes chemically bound during geopolymerization, contributing to its strength and durability.

Overall, these findings offer valuable insights into the behavior and properties of geopolymers in the oil and gas industry. While challenges in mixing consistency and fluid retention exist, the absence of free water highlights the potential of geopolymers as sustainable alternatives. Further research and optimization efforts can unlock enhanced performance and broader applications.

Acronyms

A – Area

API RP – American Petroleum Institute Recommended Practices

Bc – Bearden Consistency Units

BHCT – Bottom Hole Circulating Temperature

BHST – Bottom Hole Static Temperature

ECD – Equivalent Circulating Density

F – Force

HPHT – High Pressure High Temperature

In – Inches

mm – Millimeters

MPa – Mega Pascals

NCS – Norwegian Continental Shelf

O&G – Oil and Gas

OPC – Ordinary Portland Cement

Pa – Pascals

P&A – Plugging and abandonment

RPM – Revolutions per Minute

UCA – Ultrasonic Cement Analyzer

UCS – Uniaxial Compressive Strength

σ – Pressure

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1. Introduction

In O&G industry, cement is used both for zonal isolation and permanent plugging and abandonment (P&A). According to the NORDSOK D-10 standard, the purpose of zonal isolation is to provide a continuous, permanent, and impermeable hydraulic seal in the casing annulus or between casing strings, to prevent flow of formation fluids, resist pressures and give structural support to the casing or liner. Generally, the column of cement should be 100 meters above the casing shoe. For permanent plugging of wells, the purpose of the plug is to prevent any flow of formation fluids between formation zones to reach the seabed.

Production of cement clinker is estimated to produce a staggering 0.95-ton CO_2 for 1 ton of cement (Turner, et al., 2013). The most common cement used today is called Ordinary Portland cement, from now on referred to as OPC. In addition to having environmental concerns regarding greenhouse gases in production, OPC also has shown some weaknesses historically with the primary failure mechanisms being cracks and brittleness due to temperature and pressure changes, volume changes causing micro annuli and poor cementing practices (Alvi, et al., 2020).

With the pressing need for innovation in both reducing the emissions and improving the performance of the cementing material, this is where Geopolymers come in as an interesting option. The concept of inorganic polymers, which was introduced by Joseph Davidovits in 1975, explores the relationship between inorganic chemistry and ongoing geopolymerization reactions. This field of study aims to investigate the behavior of various compositions and concentrations of products through research and optimized mix designs. The goal is to develop an alternative product to OPC by harnessing the potential of inorganic polymers. As a result of this research and development, the idea of geopolymer cement emerged as a promising solution (Davidovits, 1991). There are different types of geopolymers based on the used ingredients. Of these one may refer to metakaolin-, fly ash-, rice husk ash-, slag-based, or combination of these. Most of the time, slag is used as source of calcium or magnesium to obtain early strength. There are two different main scenarios of how to produce geopolymer generated from blast furnace slag. The most favorable case is if the slag is available as a by-product from other industries. In this case the energy needed for the production is reduced by 59%. In the other case, where one must produce the slag, the energy needed is reduced by 43% (Turner, et al., 2013).

Geopolymers have shown promising properties for civil engineering such as low chemical shrinkage, meaning that the geopolymers maintain their dimensions, which is one crucial requirement for use in oil and gas industry for long term integrity of wells. They have also shown low permeability meaning they resist the passage of fluids and gases. This property is beneficial for applications that require containment or protection against water ingress, chemical penetration, or gas leakage. low Young’s modulus which means that the material indicating that it is more flexible and can better withstand external forces without cracking or breaking. Geopolymers have also shown sufficient strength development, stability, tolerance to high temperatures, tolerance to contamination with mud and long-term durability (Khalifeh, et al., 2018). Overall Geopolymer shows promising results to improve well cementing operations and a capable option for improved cost effectiveness. However, these properties have been obtained from different types of geopolymers at different curing conditions. A thorough work on one type of geopolymers is limited to granite-based geopolymers developed by Khalifeh (Khalifeh, 2016), (Chamssine, et al., 2021), (Eid, et al., 2021).

1.1. Objective

This project aims to provide a comprehensive overview of the current benefits and limitations for using a one-part granite-based geopolymer developed for primary cementing and well abandonment operations, and comparing the results with the most used cement class on the Norwegian Continental Shelf (NCS), API Class G cement. The testing conducted in this study will be performed under varying pressure and moderate temperature conditions, simulating those encountered in the intermediate casing section. Importantly, the testing will be conducted under the same conditions for the geopolymer and the neat API Class G cement to enable a direct comparison between the two materials. The outcome(s) of this project will help the researchers to further develop the geopolymers towards field use.

To obtain the objectives, the employed test procedures are in accordance with the American Petroleum Institute (API) Standard 10B-2, thereby ensuring that the results obtained are consistent with other historical tests performed on various comparable materials. By adopting a standardized approach, the study aims to generate reliable and comparable data that can contribute to the wider knowledge base of cementing materials used in the oil and gas industry. The findings of this research may potentially lead to the adoption of new and improved cementing materials that can meet the specific requirements of the oil and gas sector.

2. Methodology

2.1. Slurry design and blending procedure

This research has been performed by comparing a specific one-part granite-based geopolymer, there is added 12M potassium hydroxide solution (KOH) as accelerator. The OPC is made from 792 grams of pure Class G cement, delivered by Dyckerhoff and mixed with 342 grams of water, to produce a standard cement base. The mix designs of the slurries have been tabulated in (Table 1) below.

Table 1: Mix design of the slurries used in this study

	Class G cement (792 g)	Granite-based geopolymer (845.3 g)
Water (g)	348	254.2
12M KOH (g)	0	64.55
Density of slurry (sg)	1.90	1.87

When mixing the slurries of both geopolymer and Dyckerhoff Class G cement the American Petroleum Institute Recommended Practices (API RP 10B-2) procedure for mixing slurries was followed. The blender used was an OFITE Waring Commercial Blender see (Figure 1). After Weighting up the additives to the slurry, the slurry should be mixed at a constant of 4000 Revolutions per minute (RPM) for 15 seconds while adding the dry material. After all the dry material is added, the slurry is mixed at 12000 RPM for another 35 seconds to ensure that it is mixed properly. If the time surpasses the 15 seconds for wetting the slurry and adding all the dry material, the time should be noted. This was not encountered while mixing the geopolymer slurry, but it was close to the limit which would give it a lower mixability score than that of the OPC. The OPC slurry mixed way easier and could be sufficiently wetted within 10 seconds at 4000 RPM.

Figure 1: Blender, OFITE Waring Commercial Blender

2.2. Ultrasonic Cement Analyzer method

The UCA tests have been performed with a *Chandler UCA*, see (Figure 2) below. The testing followed API RP 10B-2. The objective of the performance from these tests is to see how fast sound travel through the material, in this study the material will be the geopolymer and OPC and by that calculate how the material builds strength over time in static conditions.

The way the machine works is that it sends a sonic signal in the top end of the cell through the material in the cell. In the other end there is a receiver that registers the time the signal uses to pass through the material. As the material gets harder the sonic signal will travel faster. Hence, we can calculate the relation between the sonic transfer time and the sonic strength. The results we get will have to be manipulated with an algorithm that can give a more precise estimate of the strength depending on the medium the sonic signal is sent through. Therefore, we will have to compare the results received here with the results from the uniaxial compressive strength tests that will be further explained in this thesis.

Normally the machine software is adjusted in relation to the density of the cement, as regular cement is what the UCA machine normally is used for and created for. This is because the density (among some other factors) of the medium also impacts the transfer time of the sonic signal. The tests were performed while simulating the bottom hole static temperature (BHST) which in this thesis is at 60°C and at 2000 Psi (13.8 MPa). This is to see how fast and how much strength the material builds under these conditions. The benefit of the UCA test compared to other tests is that it measures sonic strength development, and we can monitor and get a good insight as to how the material builds strength over time.

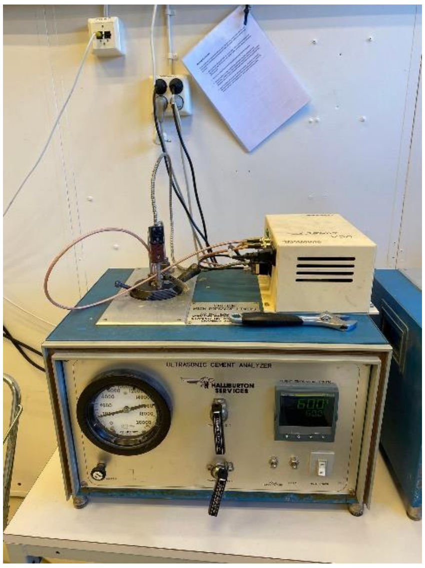


Figure 2: Chandler UCA machine

2.3. Uniaxial Compressive Strength method

The cementing material in oil and gas operations are meant to work as a barrier from surrounding fluids in the well and work as a mechanical support to the casing (Lima, 2022)~~.~~ To be able to be able to withstand the pressures encountered in a well, knowledge about the materials strength development is one of the key factors to successful cementing operations.
The Uniaxial Compressive Strength (UCS) testing has been performed following API RP 10B-2 where cylindrical molds are filled with geopolymer and OPC According to the API standard, the molds should be longer than the diameter, and shorter than double the diameter. In this testing, the molds were between 70-71 mm long and a diameter of between 50-51 mm. It is important to take care of potential air bubbles in the slurry by filling it gradually and knocking on the mold to remove the bubbles. It is important to remove as many air bobbles as possible because they can impact the results of the test. After the molds are filled, they are cured in a bath for 24 hours, three days and seven days at BHST and atmospheric pressure. Three samples for each time interval have been made for both geopolymer and OPC to get good and comparable data with reduced room for error. The results obtained from this test will help us to create a good relation between the transfer time and the compressive strength in the UCA and give direct data as to how much strength the material develops over the specified time periods. The UCS machine is shown in (Figure 3) below.

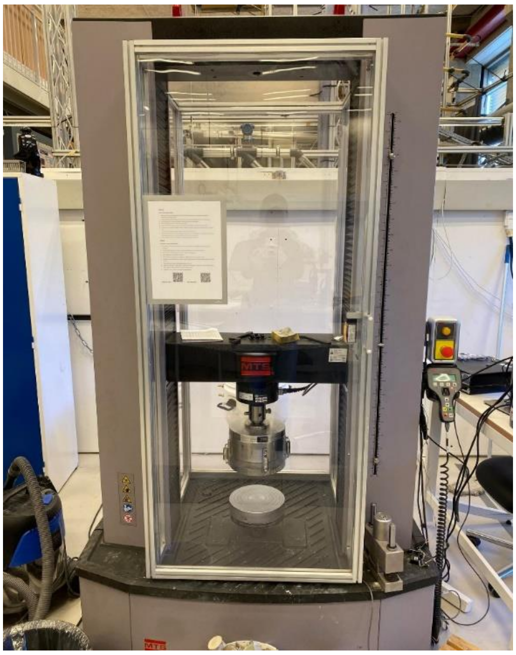


Figure 3: UCS machine, MTS Criterion Model 45

2.4. Atmospheric Consistency Test method

This testing has followed API 10B-2 standards and has been tested at 40℃ for both geopolymer and OPC, which is the bottom hole circulating temperature (BHCT). The slurries are mixed according to the method explained in section 2.1 and poured into the cells used in these experiments as shown in (Figure 4). The cell is rotated at a rate of 150 RPM, while a thread holds the paddle inside the cell in place. The Bearden Consistency Unit (Bc) is measured by registering the tensive force in the thread. Cement slurry often starts below 30 Bc and the test is often considered done when it reaches above 100 Bc. The cement is also considered unpumpable above 50 Bc. The experiment is supervised to minimize the risk of damaging the equipment if the slurry should suddenly get solid. The test is therefore stopped when it reaches 60 Bc. According to the data given by the UCA at 60℃, we can have a rough estimate of how long it will take to harden, but here it is constantly circulating and will therefore give a different result, which will give an insight into the effect circulation has on the thickening time. Thickening time is how the slurry develops its strength over time.

Figure 4: Atmospheric Consistometer, Ofite Model 60

2.5. High Pressure High Temperature Consistency test method

The high pressure, high temperature (HPHT) consistency tests have been performed according to the API RP 10B-2 with an Ofite HPHT consistometer, see (Figure 5). The slurries were first mixed in the warring blender and poured into a cell that can handle high pressure and high temperature. After mixing, the test should be on within 5 minutes of mixing the slurry to get the best result without a long static period before it starts circulating. The test has been performed on both slurries by starting at room temperature and reaching BHCT in 15 minutes, which is the simulated pumping time, and the same for pressure ending at 2000 Psi and remaining constant until the end of the test. The reason for performing both atmospheric and HPHT consistency test is to gather knowledge about the impact of pressure in relation to thickening time.

Figure 5: OFITE HPHT consistometer

2.6. Rheology method

The testing of rheological properties of the geopolymer and OPC has been performed following the API RP 10B-2 standard and used an OFITE model 900 Viscometer, see (Figure 6). Preconditioned slurry is poured into a small cup and placed in the machine and press the "cem" button. This is an automatic model, and the "cem" button makes it run through the API RP 10B-2 procedure for testing rheology, made for cements. The fact that the procedure is automatic helps with eliminating potential human errors. The test involves evaluating the shear stress at specific shear rates, 3, 6, 30, 60, 100, 200, and 300 (RPM) with up and down readings, where it shears the slurry for 10 seconds, then registers the value. Shear rate of 3 RPM is used to measure the gel strength after 10 seconds, and a 10-minute static period. The machine provides values in oilfield units that must be converted to standard SI units. In addition to the viscometer, there has been used a heating cup that kept the slurry at the specified temperature. The testing has been performed with BHCT as the test simulates different circulation velocities the slurry may encounter while being pumped.

Figure 6: Viscometer, OFITE Model 900

2.7. Fluid Loss method

The Fluid loss tests have been performed according to the API RP 10-B2 standard, where the preconditioned slurry is placed in a pressurized cup with 1000 Psi (6.9 MPa) on the top, putting pressure on the fluid. The fluid that the material loses during the test is collected in a graduated cylinder and the final amount is referred to as the fluid loss. The equipment used is shown in (Figure 7) below.

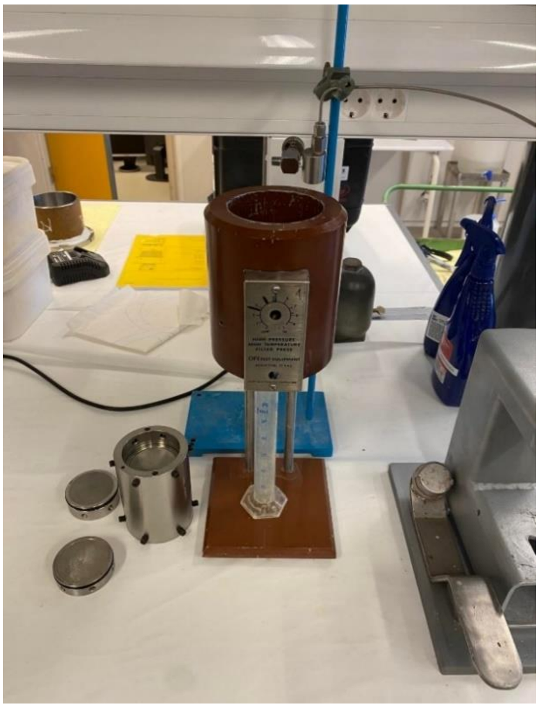


Figure 7: Fluid Loss Equipment

2.8. Static Gel Strength, mechanical method

The static Gel Strength mechanical testing has been performed following the API RP 10-B2, where unconditioned slurry is poured into the testing cell and placed into the Ofite Twin Cell UCA machine, see (Figure 8). Then the test is started where the slurry is conditioned for 15 minutes and then measures the gel strength development with 10-minute intervals.

Static gel strength is measured to get an overview of how the cement evolves its gel strength. When a cement is put into a static condition, it will start building gel strength. Knowledge of the development of gel strength can be essential in cases where you must prevent gas from migrating through the cement while it hardens. As it will lose hydrostatic pressure in the hardening process, it must be able to withstand the gas migration by developing gel strength and not lose so much pressure that one encounters underbalance of pressure in the well.

Figure 8: SGSm - Model 120-51 Twin Cell UCA

2.9. Free Water method

Free water is a standard test performed on cement in the oil and gas industry to get knowledge about if the fluid in the slurry will migrate in the curing process. When a cement is put in place and starts to set, it is important that it gets a homogenous and even strength throughout its length. The testing is done by first conditioning the slurry to get consistent results. After conditioning, the slurry is poured into a graduated cylinder at the standard volume of 250 ml. It is important that it is isolated from the surrounding air by either some tape or in this case a plastic film that prevents the air from evaporating the fluid that migrates to the top during the test. If there is free water on top of the sample after the two hours, we report this number as the free fluid number. According to (ZHOU, 2011) the free water from a cement slurry will have effect on the compressive and tensile strength development. Free fluid can also be an indication of settlements and sedimentation. (Figure 9) below illustrates the method used in this test.

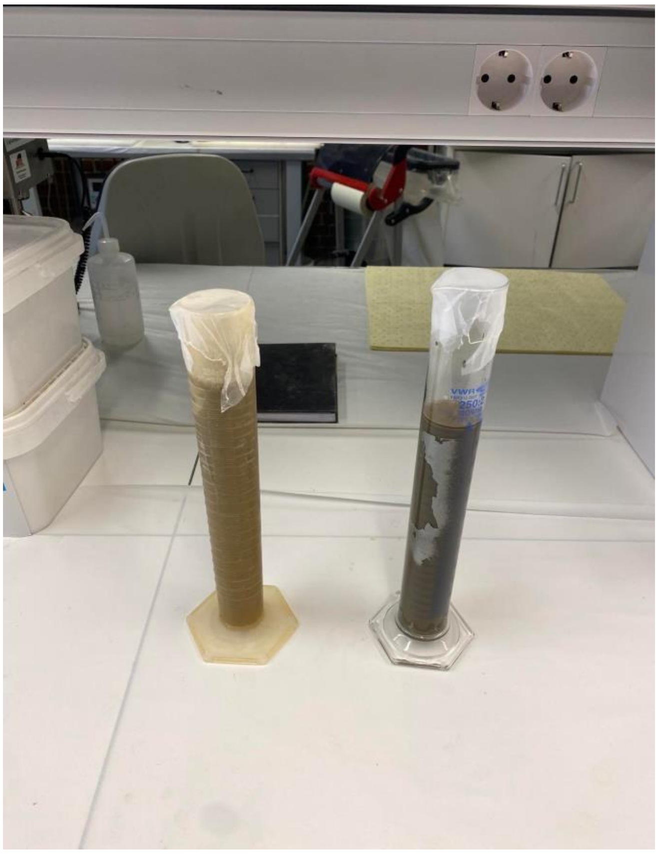


Figure 9: Free Water - Graduated Cylinders

3. Results and Discussion

3.1. Rheology

Understanding the rheological properties of cement slurries is essential for optimizing the pumpability, flowability, and stability of the slurry during the critical period after mixing. The critical period is crucial because it represents the window of opportunity for effectively pumping the cement slurry into the desired location within the wellbore. It is during this period that the slurry's rheological properties, such as viscosity and yield stress, play a significant role in maintaining the slurry's pumpability and stability. This knowledge allows for efficient cement placement, ensuring successful oil well cementing operations (Tao, 2020).

The slurries for these tests are conditioned for 20 minutes, starting at room temperature, then gradually heated at one degree Celsius per minute. This is done to achieve the most consistent results possible. The results from the rheology testing on the geopolymer is listed in (Table 2) and the results from the OPC is listed in (Table 3) below. In the tests, the up readings mean that they have been measure from the lowest RPM and up to the highest.
There we see that the geopolymer has much higher values than that of the OPC. This indicates that the viscosity of the geopolymer is higher. Viscosity is calculated based on the ratio between shear stress and shear rate. To get the apparent viscosity one should divide the shear stress by the shear rate as shown in formula (3-1) below.

$$\mu = \frac{SS}{SR} \qquad 3\text{-}1$$

The viscosity of the geopolymer and the OPC is illustrated in (Figure 10) below. The viscosity of the OPC begins way higher than the viscosity of the geopolymer. The OPC is also more shear thinning as it gets thinner than the geopolymer at around 200 RPM. It is worth noting that one never encounters pumping rates equivalent to shear rates of above 150 RPM in a well, so this is not a big concern. Both slurries behave as non-Newtonian fluids, meaning they are affected by shear rates. The geopolymer has a much lower yield point than the OPC, which can be beneficial during pumping due to lower pressure required to pump.

We can also see that from the unconditioned rheology tests listed in (Table 4) and (Table 5) below, where the test is performed by doing a ramp down-reading, that the geopolymer is much affected by the conditioning and that there is a big difference in the conditioned and unconditioned geopolymer. This is not the case for the OPC, as it shows basically the same rheology's whether it is conditioned or not, the OPC gets a little thicker with conditioning. The API RP 10B-2 standard suggests that one should condition the slurry before doing rheology testing for ensuring consistent results. I have included the unconditioned tests because it provides information about the rheological properties. The possibility to compare them also illustrates the importance and impact of having consistent conditioning standards to get consistent results.

Table 2: Shear stress profile, conditioned geopolymer

SS [RPM]	*3*	*6*	*30*	*60*	*100*	*200*	*300*
SS up [Pa]	*4*	*6*	*18*	*30*	*45*	*83*	*121*
SS down [Pa]	*4*	*5*	*16*	*29*	*45*	*85*	*121*

Table 3: Shear stress profile, conditioned OPC

SS [RPM]	*3*	*6*	*30*	*60*	*100*	*200*	*300*
SS up [Pa]	*11*	*19*	*45*	*57*	*62*	*72*	*78*
SS down [Pa]	*10*	*17*	*43*	*55*	*60*	*69*	*78*

Table 4: Shear stress profile, unconditioned geopolymer

SS [RPM]	*3*	*6*	*30*	*60*	*100*	*200*	*300*
SS down [Pa]	*51*	*80*	*147*	*222*	*266*	*334*	*355*

Table 5: Shear stress profile, unconditioned OPC

SS [RPM]	*3*	*6*	*30*	*60*	*100*	*200*	*300*
SS down [Pa]	*12*	*20*	*27*	*32*	*38*	*49*	*60*

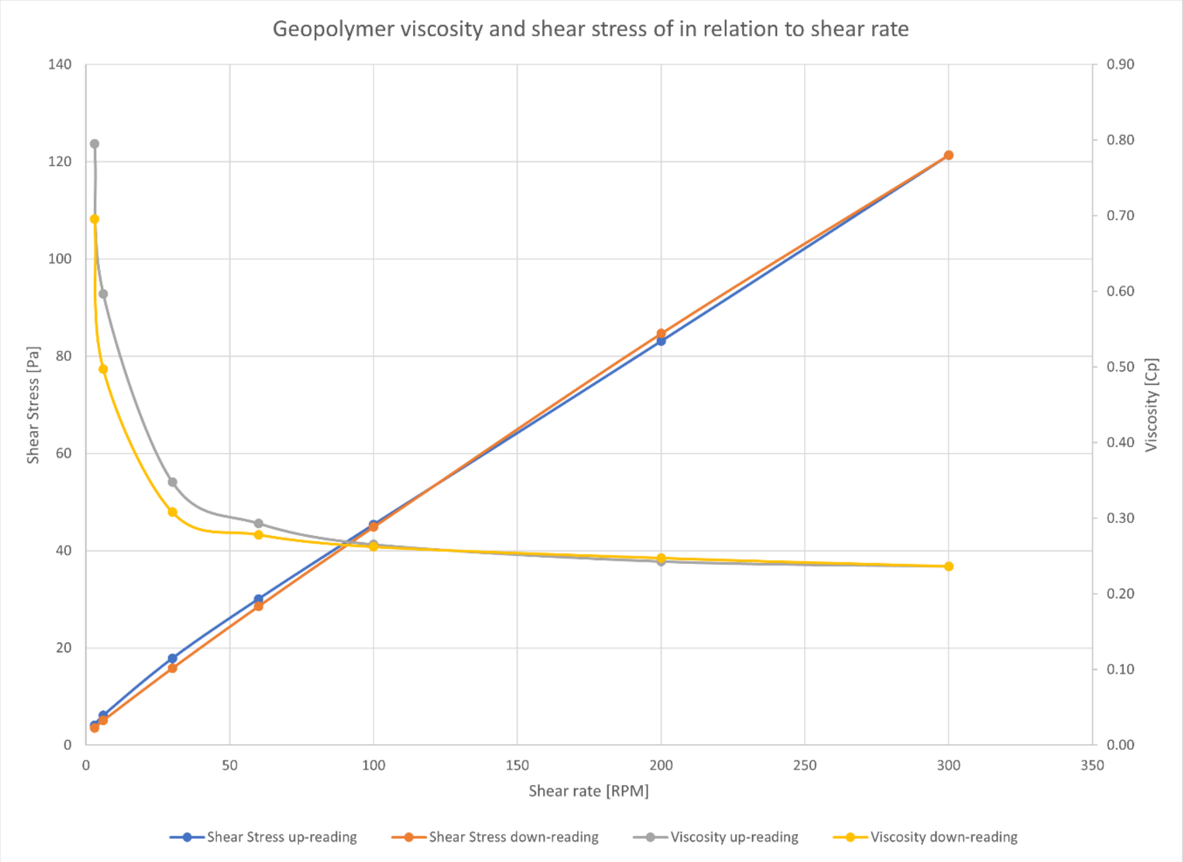


Figure 10: Geopolymer Viscosity and shear stress

The shear stress readings of the geopolymer gives a non-Newtonian curve because there is a small yield stress.

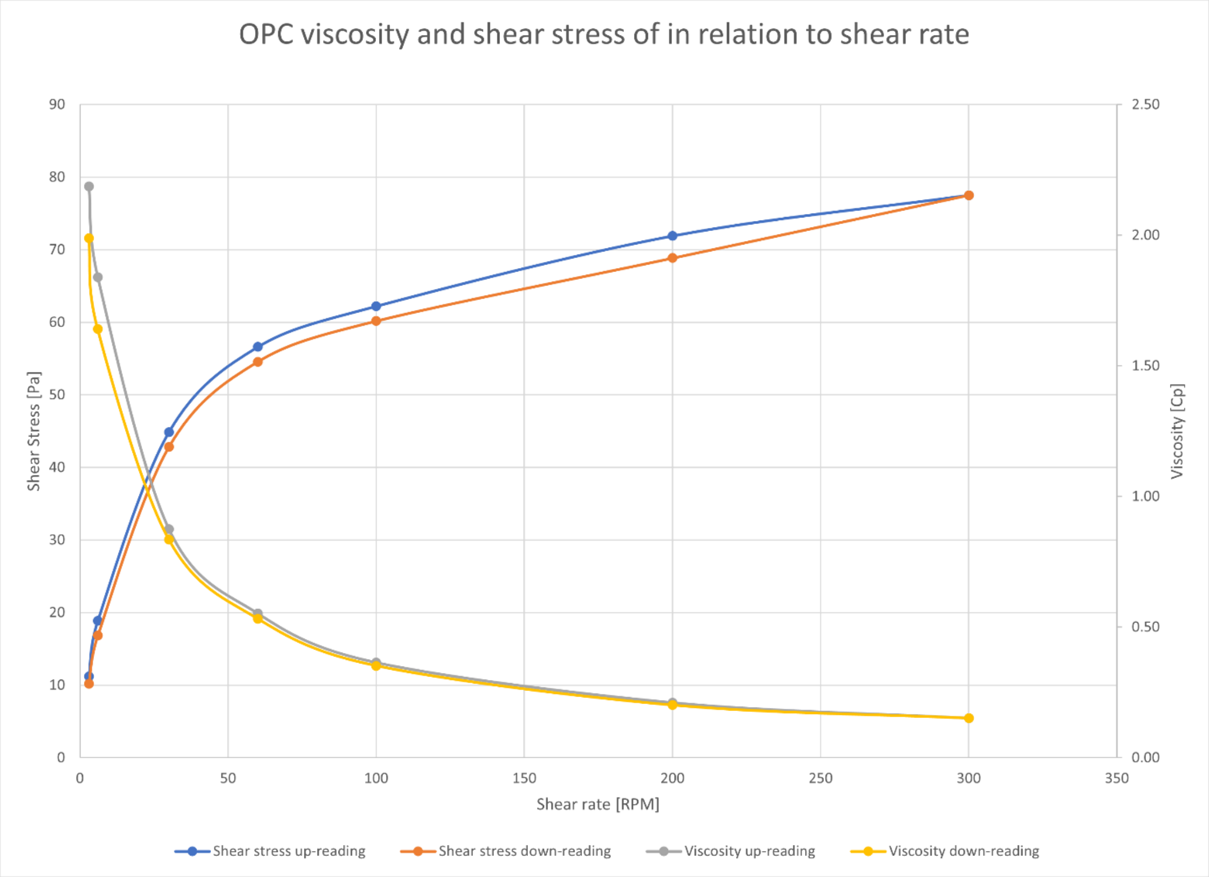


Figure 11: OPC Viscosity and shear stress

The rheology tests also include a Static gel strength reading after a static period of 10 seconds and 10 minutes. This is to get an estimate of how fast the material builds gel strength. The gel strengths for the different slurries are listed in (Table 6) below.

Table 6: Gel strength, rheology test at 40°C

Gel strength [Pa]	10 Seconds	10 minutes
Geopolymer	13	88
OPC	23	34

3.2. Thickening time, atmospheric and HPHT

The Atmospheric Consistency test has shown that like we see from the rheology's that the geopolymer is much more viscous early on and shows a Bc of as much as 23 from the start. Then the circulation forces bring it down to below 10 Bc for some time before it starts building up to 60 Bc. It reaches 60 Bc with atmospheric pressure and 40℃ in 1.6 hours, which is about 98 minutes. The fact that the Bc starts at 23 and goes down may be a challenge for the industry that has to be tackled because it will cause higher pumping pressure in the beginning of the pumping and can possibly create underbalance when it gets thinner down in the well. From an operational point of view, slurries under 40 Bc is considered pumpable, and above 40 Bc is considered risky to pump (Hamie, et al., 2022). The consistency of the OPC starts below 10 Bc and is stable until it starts to build slowly up to reach 60 Bc after 3.82 hours, which is about 229 minutes. In the trajectory of the OPC we see the opposite of the geopolymer, where it in this case gets thicker in the beginning then stabilizes at 15 Bc for 90 minutes then starts building strength more smoothly until it reaches 60 Bc. The optimal trajectory for thickening time would be if the Bc was at a constant and predictable value until the desired pumping time and the slurry starts building strength fast after that.

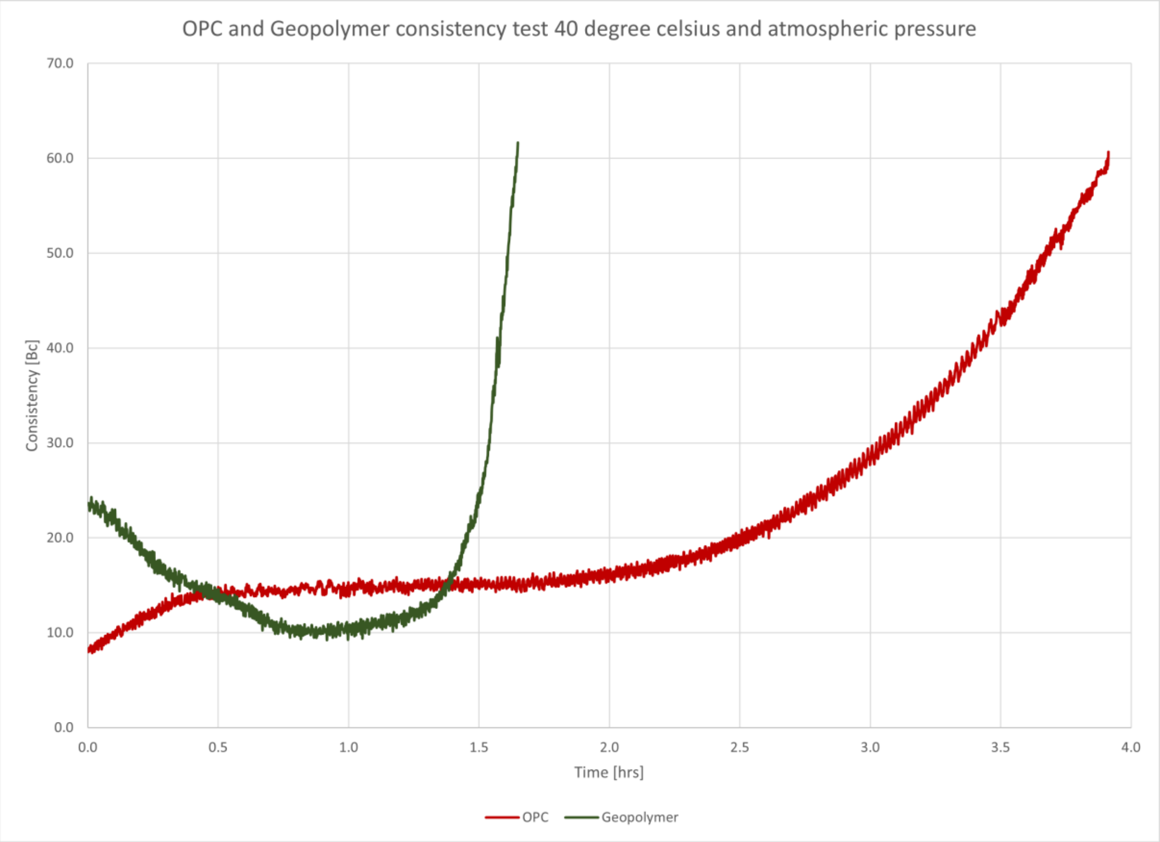


Figure 12: Geopolymer and OPC atmospheric consistency test

The high temperature high pressure consistency test, from now on called HPHT consistency tests gave the following results as shown in Figure 13 below. There we can see that the geopolymer slurry is strongly affected by the increase in pressure, as the thickening time is reduced by 67 % and now reaches 60 Bc in 32 minutes. For the OPC we see an almost identical curve in the thickening time which indicates that the pressure has little effect on the strength development of the slurry. The thickening time for the OPC is reduces by 14 % when the added pressure is included, as it goes from 229 minutes in the atmospheric test, to 198 minutes in the HPHT test.

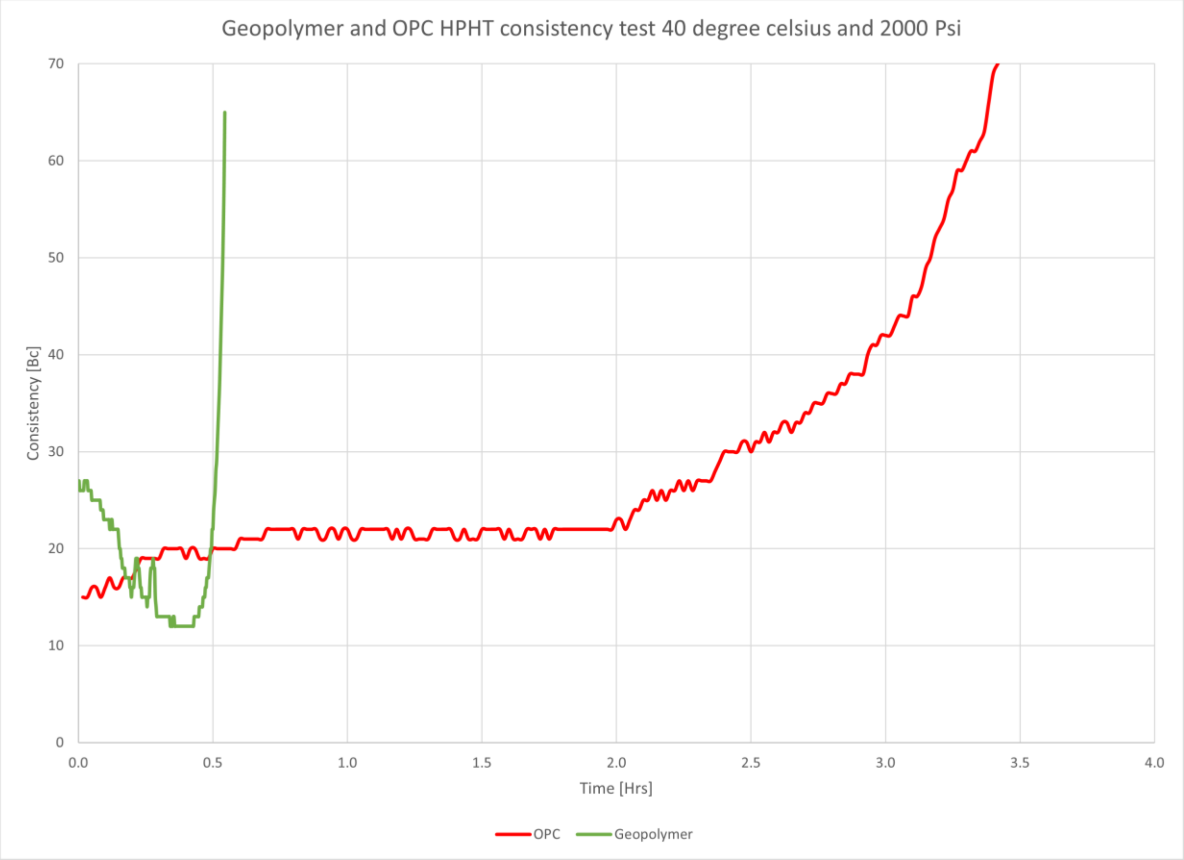


Figure 13: HPHT Geopolymer and OPC consistency test

3.3. Fluid Loss

Fluid loss control are crucial in oil and gas drilling operations to prevent the dehydration of cement slurries into the formation. Without proper fluid loss control, water leaks out of the slurry, leading to slurry dehydration at the formation wall. This results in the formation of a dry cement filter cake, which can compromise zonal isolation and create pathways for gas migration. Additionally, the filter cake occupies space along the borehole wall, reducing the annular gap and impeding fluid flow. Hence, effective fluid loss control is vital for maintaining zonal isolation, preventing gas migration, and optimizing fluid flow during drilling operations (DeBruijn, et al., 2021).

The Geopolymer showed a relatively short blow-through time of 27 seconds as shown in (Table 7) below. Upon cessation of the test, the cylinder contained 31 ml of fluid with no spills. In comparison, the OPC showed a significantly faster blow-through time of 9 seconds, resulting in 20 ml of fluid in the cylinder. Notably, some of the fluid spilled due to the high pace of discharge.

The test findings suggest that the Geopolymer is relatively more resistant to fluid loss under pressure than OPC. Nevertheless, like OPC, it requires additives or modifications to improve fluid retention. A good and successful fluid loss test will normally not blow through during the entire 30 minutes with less than 50 mL of the fluid blown through (Bannister, 1985). The industry has developed multiple additives that can be added to the slurry to enhance fluid retention. However, further research is necessary to establish if these additives have the same effect on geopolymers as they do on cement. Additives that make cement more resistant to fluid loss function by creating barriers by forming molecular shapes, by chemical bonds that prevent fluid from passing through.

Table 7: Fluid Loss results

Slurry	Time [Sec]	Fluid [ml]
Geopolymer	27	31
OPC	9	20

3.4. UCA

The graph of the UCA shows that the transit time is reduced continuously throughout the time the test was on. This makes for an interesting result that can be further researched as to see when it will reach a plateau. We can see from (Figure 14), that the Sonic Strength is in direct relation with the transfer time as it is a calculation based on this data. As mentioned in the methodology, the results received from the UCA machine are based on an algorithm suited for cement with normal densities. Therefore, we must calculate a new algorithm that can be used for the geopolymer to make the result accurate.

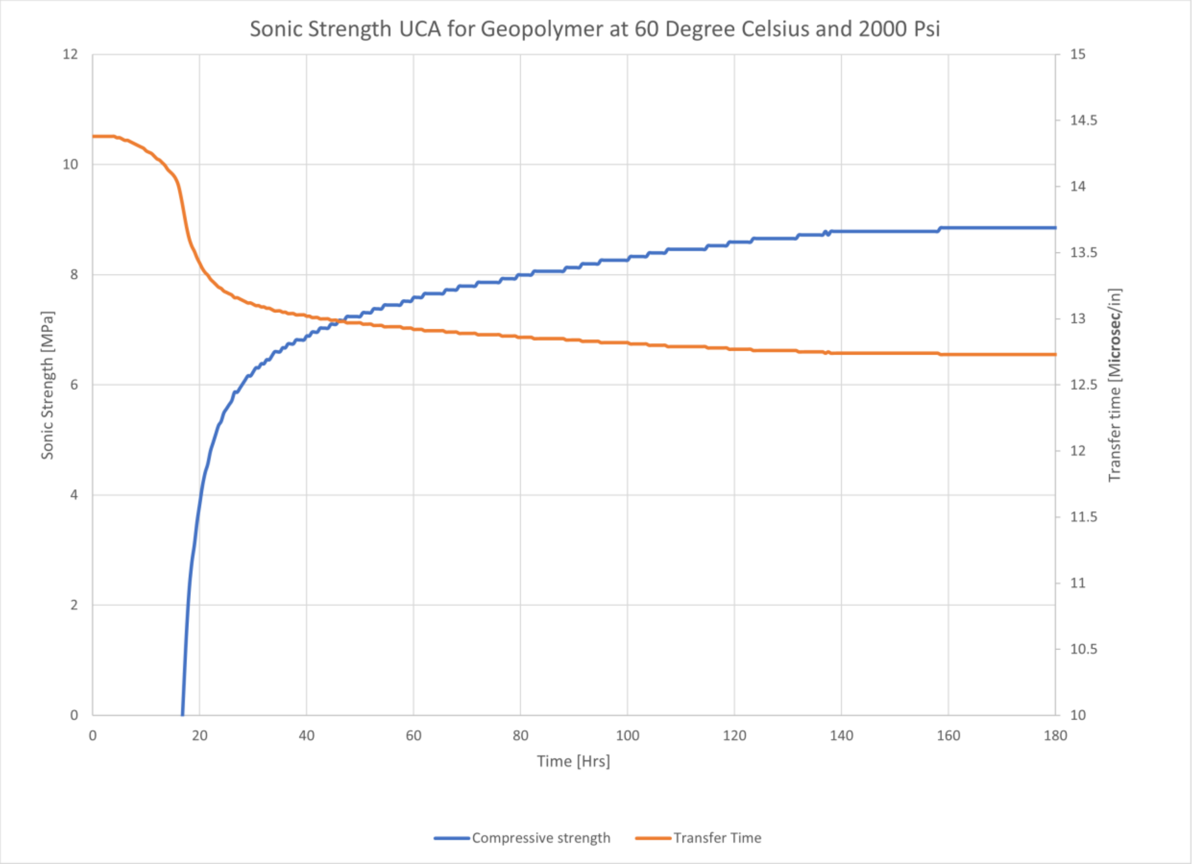


Figure 14: UCA Geopolymer 60℃ and 13.7 MPa

The method of producing the algorithm to calculate the sonic strength is illustrated in (Figure 15). There we used the results received from the UCA and take the transfer time measured at the same time periods that the compressive strength was measured in the UCS testing, 24 hours, 3 days, and 7 days (Khalifeh, et al., 2018). After reviewing the results from the compressive and compare them with the results in the sonic strength, we see that the new algorithm and the results fits quite well.

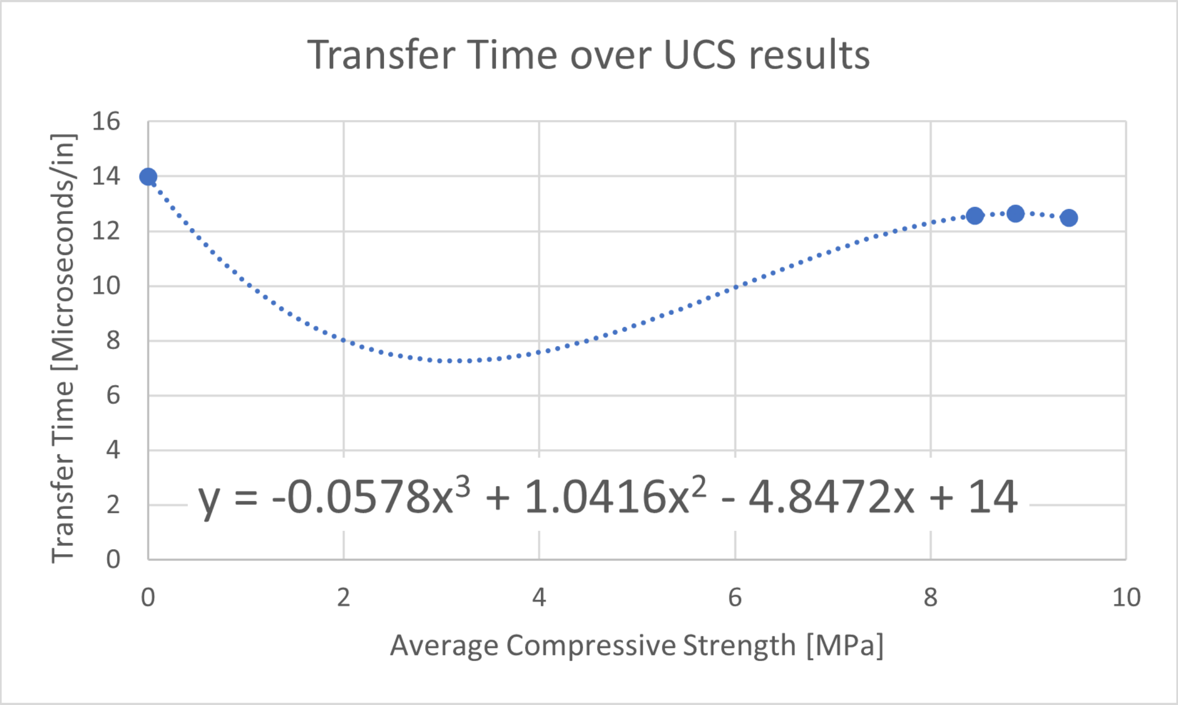


Figure 15: Generated algorithm for Sonic Strength Development

When comparing the strength development we see that the OPC develops much higher strength than the Geopolymer which is in favor of the OPC, see (Figure 14 above and Figure 16) below, as there are requirements for the cementitious material in a well to be able to withstand massive pressures. Further research is needed to improve the compressive strength of the geopolymer, as additives and tweaks in compositions can have a big impact on strength development for any material.

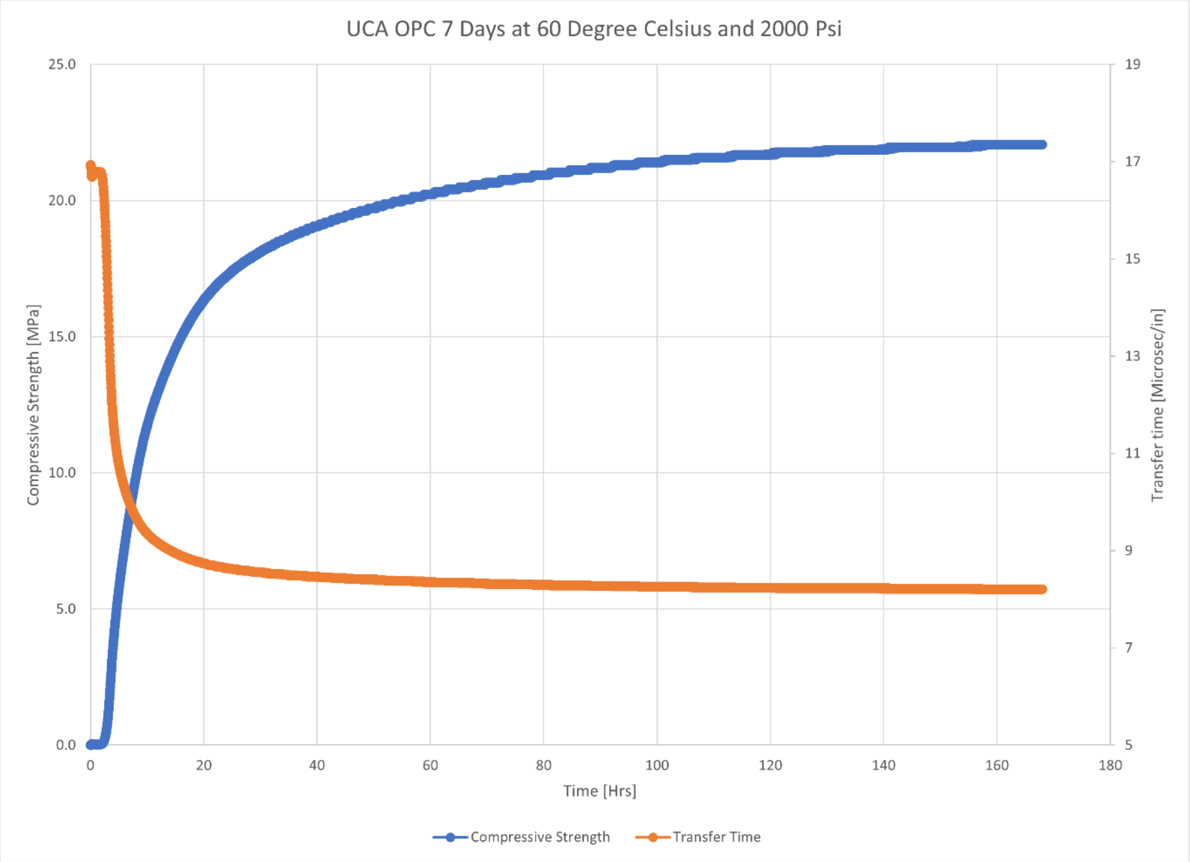


Figure 16: UCA OPC 60℃ and 13.7 MPa.

3.5. UCS

The uniaxial compressive strength is an accurate way of measuring the actual capacity of how much force that can be applied to the material before it breaks. In (Figure 17) and (Figure 18) below, the peak pressure applied to the samples before breaking is illustrated. For the geopolymer, the 24-hour curing gave an average pressure of 8.87 MPa to break the three samples. On day seven, the average was increased by 6.2 % and the new average peak pressure was 9.42 MPa. In the Geopolymer we can see a slight increase in the compressive strength as it cures over the seven days. We see the same with the OPC that it increases its strength over time, and it has a much higher peak pressure of 30.5 MPa in average.

When the peak loads are collected from the UCS machine, to calculate the compressive strength, one must calculate the amount of force it can take per area. The diameters of the cylindrical samples are on a range between 50 and 51 mm. This is to find out how much pressure the material can take, and it makes it easier to translate the findings into other areas of research such as construction and civil engineering. The formula for calculating the pressure is as shown in formula 3-2 below.

$$\sigma = \frac{F}{A} \qquad 3\text{-}2$$

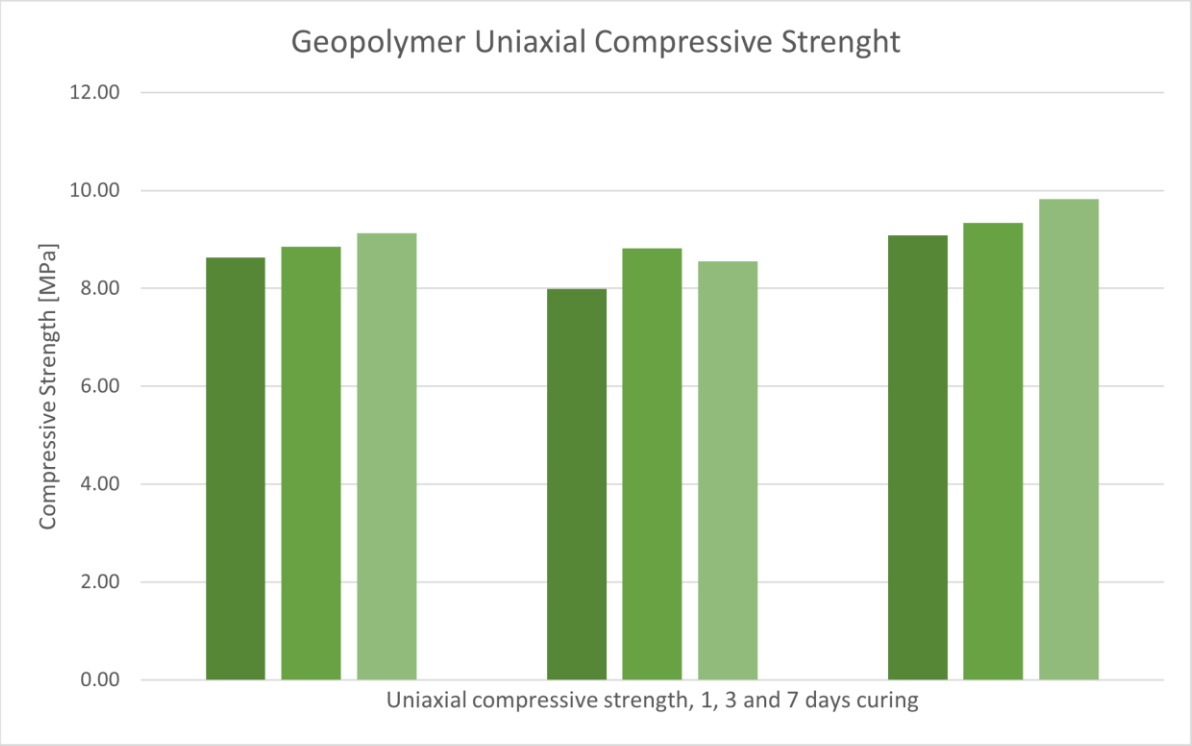


Figure 17: Geopolymer UCS Results

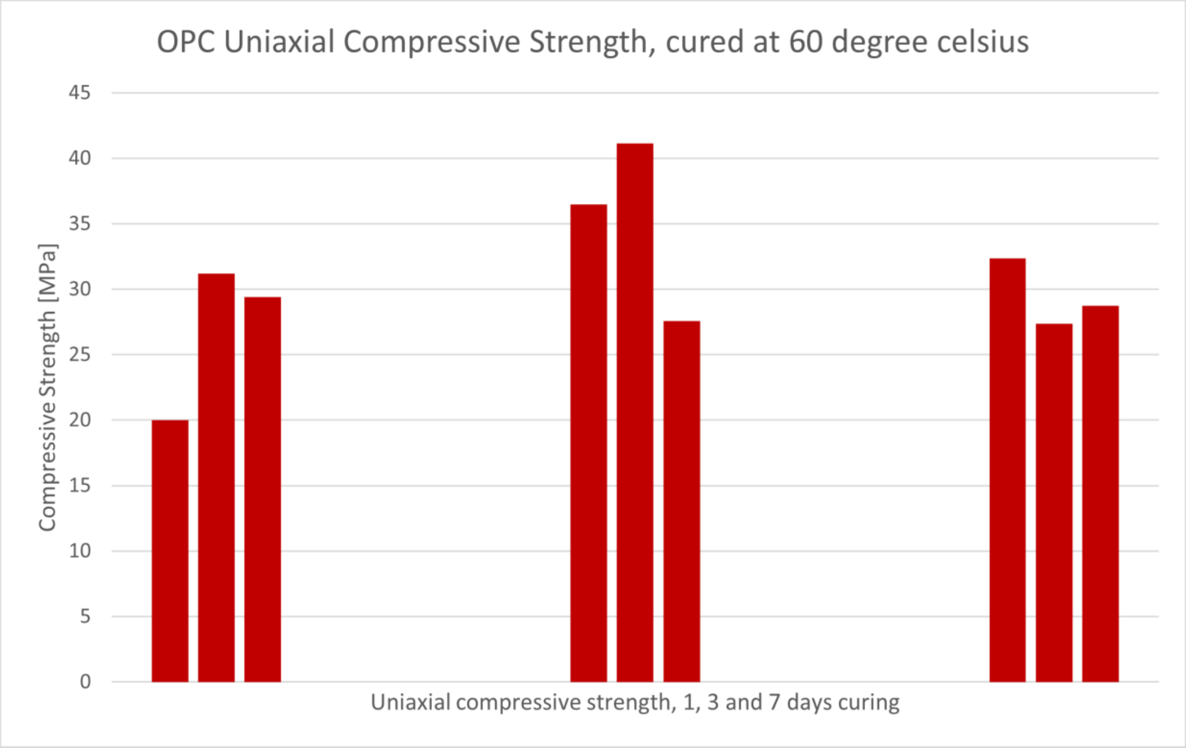
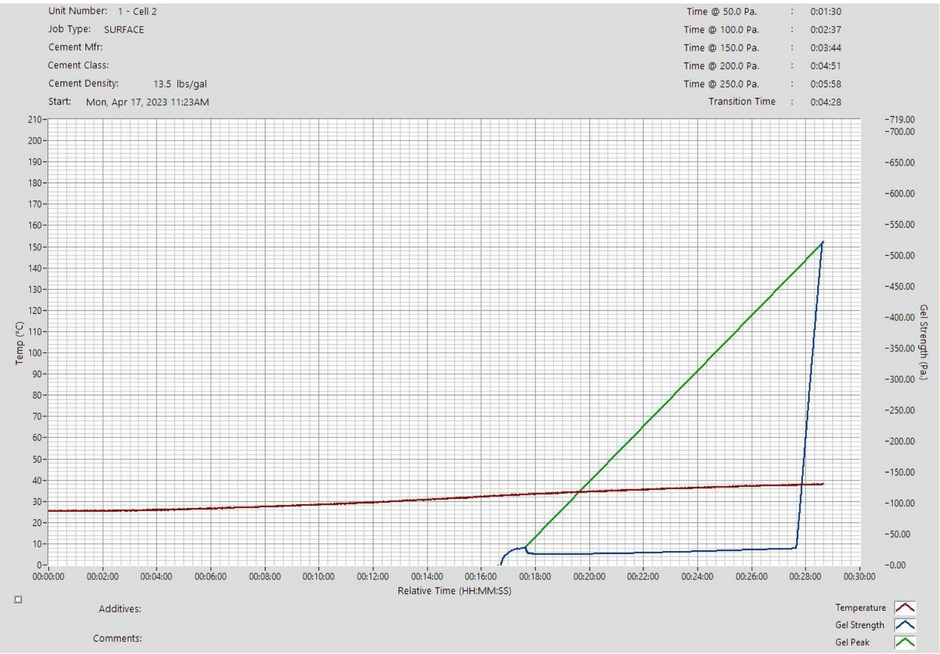


Figure 18: OPC UCS Results

3.6. SGS

The measurement of static gel strength (SGS) plays a crucial role in the understanding and control of gas migration in cemented wellbores. Gas migration occurs when gases infiltrate the cemented annulus due to a reduction in hydrostatic pressure during early gelation. SGS, which represents the shear stress at interfaces, is widely accepted as a concept to describe the strength development of hydrating cement. However, it is important to note that SGS alone does not fully capture the mechanical properties and gas-tightness of a cement slurry. As the slurry gels, its mechanical properties are governed by the solid fraction, bond strength between solid particles, and the compressibility of the cement matrix. To accurately predict gas-migration potential and understand the process, these properties need to be considered (Li, et al., 2016). (Figure 19) illustrates the gel strength behavior of the geopolymer sample throughout the testing process. After the initial conditioning phase, the gel strength of the geopolymer is measured to be 8 Pa. Subsequently, during the first 10-minute static period, the gel strength increases significantly and reaches the desired threshold of 250 Pa. As a result, the testing program automatically terminates since the desired limit has been achieved.

This observation provides valuable insight into the gel strength development of the geopolymer and highlights its ability to rapidly gain strength within a short duration. The significant increase in gel strength indicates the formation of a stable and robust gel structure, which is essential for the geopolymer's performance and application in various engineering contexts.



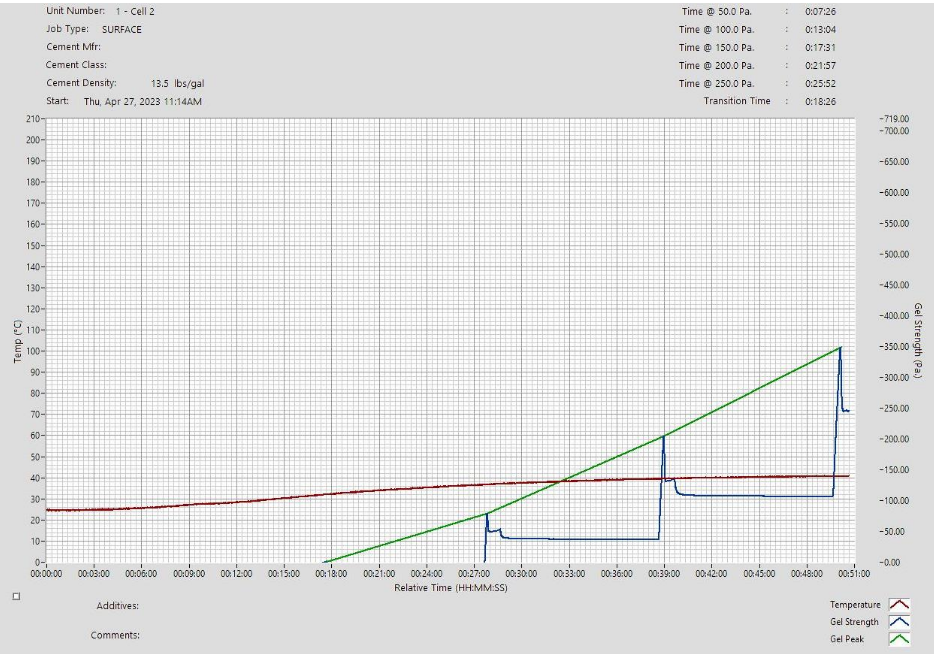
Unit Number: 1 - Cell 2
Job Type: SURFACE
Cement Mfr:
Cement Class:
Cement Density: 13.5 lbs/gal
Start: Mon, Apr 17, 2023 11:23AM

Time @ 50.0 Pa. : 0:01:30
Time @ 100.0 Pa. : 0:02:37
Time @ 150.0 Pa. : 0:03:44
Time @ 200.0 Pa. : 0:04:51
Time @ 250.0 Pa. : 0:05:58
Transition Time : 0:04:28

Additives:
Comments:

Figure 19: Geopolymer SGS result

The OPC static gel strength test shows a more normalized result, see (Figure 20) below, where the gel strength builds slowly up until it reaches the desired gel strength of 250 Pa. With the OPC we can see two more measurements, which gives us more feedback and deeper understanding of the gel strength development. To improve this test for testing on the geopolymer, one could have more frequent measurements of the gel strength as an alternative. To only have the trajectory that it surpassed the desired strength within the second measurement lets us know that it has built the strength but says little about the development.



Unit Number: 1 - Cell 2
Job Type: SURFACE
Cement Mfr:
Cement Class:
Cement Density: 13.5 lbs/gal
Start: Thu, Apr 27, 2023 11:14AM

Time @ 50.0 Pa. : 0:07:26
Time @ 100.0 Pa. : 0:13:04
Time @ 150.0 Pa. : 0:17:31
Time @ 200.0 Pa. : 0:21:57
Time @ 250.0 Pa. : 0:25:52
Transition Time : 0:18:26

Additives:
Comments:

Figure 20: OPC SGS Result

3.7. Free Water Results

According to the results of the free water test conducted on both geopolymer and OPC, see (Table 8) below. It was found that neither material had any free water present after two hours. This indicates that both materials possess desirable characteristics of homogeneity and low permeability, which makes it less prone to crack or form voids during the setting process. The absence of free water also suggests that sedimentation, which means the settling of heavier particles in the lower end over time, is unlikely to occur. These findings highlight the excellent quality of both geopolymer and OPC and underscore their potential to provide optimal performance and structural stability in well construction for zonal isolation and permanent plugging.

Table 8: Free water results

Slurry	Prosentage of free water
OPC	0 % free water
Geopolymer	0 % free water

4. Conclusion

In conclusion, the testing of the geopolymer material has provided valuable insights into its characteristics and potential applications in the industry. However, certain challenges and limitations have been identified that may impact its practical use.

One of the major findings from the mixing and the rheology tests is that the geopolymer exhibits a high viscosity and is challenging to mix, especially in its unconditioned state. This high viscosity poses practical difficulties for industrial applications, as it can hinder the ease of handling and processing of the geopolymer material and require a very large pumping pressure to be pumped down the well. To overcome this challenge, the incorporation of superplasticizers could be explored as a potential solution to improve the workability and ease of mixing.

Furthermore, the rheology tests also indicate that the geopolymer undergoes a gradual breakdown of viscosity under shear stress, reaching a viscosity of around 10 Bc. This observation further emphasizes the importance of addressing the mixing challenges, as it highlights the need to mitigate the high initial viscosity for improved processing and application in the industry.

In terms of strength development, the geopolymer demonstrates a lower strength compared to ordinary Portland cement. This finding suggests that additional optimization may be required to enhance the geopolymer's strength performance and ensure its suitability for specific structural applications where higher strength is desired.

On a positive note, the geopolymer exhibits better fluid retention properties and faster gel strength development. These characteristics can be advantageous in certain applications where rapid strength gain and fluid retention are crucial and can also have a positive influence on rig-time.

In summary, while the geopolymer material presents some challenges related to its mixing and strength development when compared to traditional cementitious materials, it also possesses desirable attributes such as improved fluid retention and faster gel strength development. Addressing the mixing difficulties using something like superplasticizers and further optimizing the geopolymer formulation could enhance its practicality and expand its potential applications for the industry. Further research and development efforts are needed to fully explore the geopolymer's capabilities and overcome its current limitations.

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