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THE SIGNIFICANCE OF SILICA AND OTHER ADDITIVES IN GEOTHERMAL WELL CEMENTING

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ABSTRACT

Geothermal drilling is a capital intensive venture that needs extensive resources to explore and develop to production phase. The well drilling, for instance, involves geoscientific exploration, drilling and casing using cement slurry. The reliability of the power plant will depend on the lifespan of the production wells in the geothermal field. There are many factors that make a well be non-productive, such as poor well casing among others.

In high temperature geothermal fields, which are rich with harmful geothermal fluids, there is a need to design and formulate cement slurry that can withstand these environments. Portland cement is stabilised by adding a silica component to achieve good compressive strength development and reduction of permeability in the cement. Pozzolonic Portland cement can be a viable option too. In Olkaria, Kenya, 20% silica flour by weight of cement is used to prevent strength degradation by the CO₂ rich environment that causes gas channelling having an adverse impact on cement bond integrity, hence accelerating strength retrogression. Most wells are highly permeable and therefore one of the greatest challenges in cementing is due to circulation losses. Mica flakes are currently used to prevent or minimize losses. New loss of circulation materials such as Cementing Lost Circulation Fibers (CLCF) could be a viable option. The new fluid loss control (FLC) agent ADVA Cast 530 gives improved rheological properties. Other possible alternatives to the challenges of lost circulation are to reduce the density of the slurry by using foam cement or to introduce new additives such as perlite, microspheres and other low density pozzolanic materials.

To fully analyse the strength retrogression of well cements in Kenya, that are exposed to high temperatures over their lifetime, tests of cement slurries at the laboratory should ideally be simulated at close to actual well temperatures (bottom hole circulating temperature (BHCT) and bottom hole static temperature (BHST)) over a few months, since this would give a better indication of the strength retrogression. Current research in the geothermal sector seem to lack testing at high enough temperatures over a sufficiently long period.

1. INTRODUCTION

Geothermal well cementing is one of the most critical operations of anchoring casings in the well. This is done using cement and cement additives mixed with water in the designed formulation. The objective of any casing cementing program is to ensure that the total length of the annulus (either casing to casing annulus, or casing to open hole annulus) is completely filled with sound cement that can withstand long term exposure to geothermal fluids and temperatures. Geothermal wells require a well designed slurry to give sufficient strength and to provide a seal between the formations during its productive life.

Designing a cement slurry for a geothermal well is a complex task which considers a careful choice of cement, retarders, fluid loss additives, dispersants, silica flour, and extenders. The right ratio of additives to blend in the cement should be designed correctly before being used to case the well, considering properties such as good rheological/flow to be able to pump it. It must not set before it has been pumped to the desired location and it should have enough compressive strength with low permeability when it sets. In the design phase, an increase of temperature will decrease the plastic viscosity and yield viscosity. A good laboratory slurry test should be done to evaluate the ratios that are good to counter the strength retrogression.

The silica flour additive acts as an anti-retrogression agent at high temperatures. When carbon dioxide (CO₂) is present such as in Olkaria, 15-20% of silica flour by weight of cement (BWOC) is used to make the cement resistant to CO₂. In Iceland, the temperatures can be very high but CO₂ has not been an issue, and therefore, 40% silica flour (BWOC) can be used. This paper seeks to analyse the importance of using silica flour and other additives when carrying out geothermal well cementing operations in wells located in high temperature geothermal fields.

1.1 Well cementing

Well cementing is the process of mixing a cement slurry composed of dry cement, water, and additives and pumping it down through a steel casing to the annular space between the wall of the well and the outside of the casing as shown in Figure 1. It consists of primary cementing and remedial cementing. Primary cementing is the process of placing a cement sheath in the annulus between the casing and the formation, while remedial cementing occurs after primary cementing where the cement is injected into strategic well locations for various purposes, including well repair and abandonment.

1.2 The importance of cementing

The dry cement is converted to slurry cement by mixing it with water and cement additives through a well

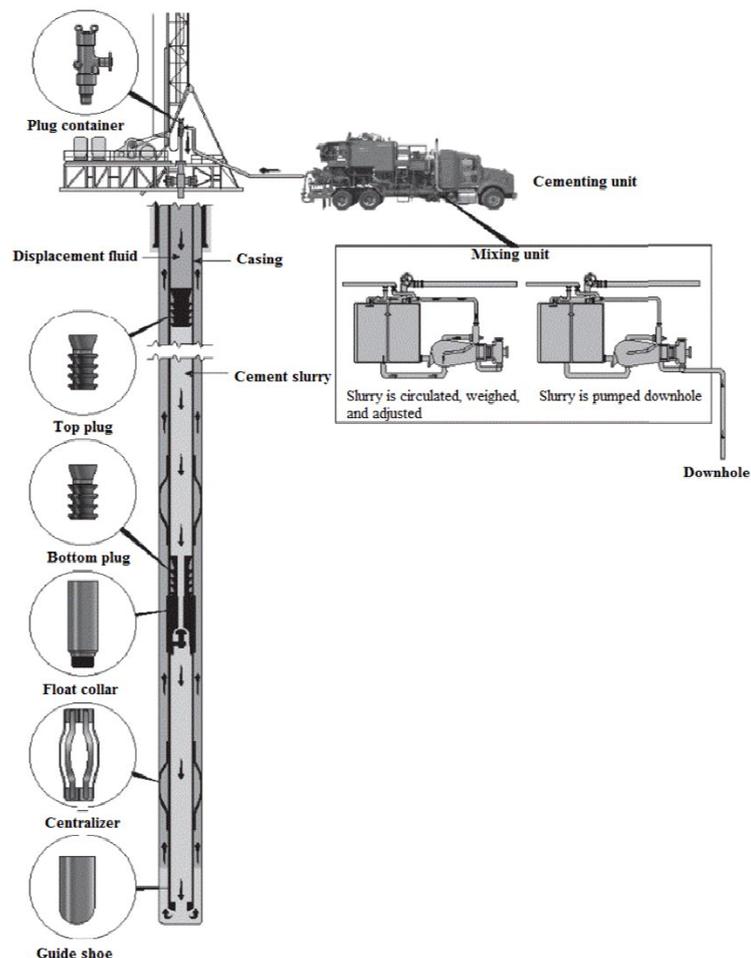


FIGURE 1: Typical cementing process (API 2009)

formulated design in the laboratory and it is pumped through the annulus from the surface of the geothermal well to facilitate the sound integrity of the well and improve its life span and performance. The well acts as a high-pressure containment vessel at elevated temperatures which should resist failure by deformation, fatigue, fracturing, and corrosion during its operating life (Agapiou and Charpiot, 2013).

The most important functions of a cement sheath between the casing and the formation are:

- a) To prevent the movement of liquid from one formation to another or from the formation to the surface through the annulus.
- b) Provision of mechanical support of the casing string with associated wellhead equipment in the well.
- c) To support the well bore walls (in conjunction with the casing) to prevent the collapse of the formation.
- d) To prevent blowouts by forming a seal in the annulus.
- e) Protection of the casing from corrosion.

Cementing is also used to condition the well:

- a) To seal loss of circulation zones.
- b) To stabilize weak zones (washouts, collapses).
- c) To plug a well for abandonment or for repair.
- d) To kick off side tracking in an open hole or past junk.
- e) To plug a well temporarily before being re-cased.

1.3 Geothermal well slurry design

In general, there are five steps in designing a successful cement placement:

- a) Analysing the well conditions: reviewing objectives for the well before designing placement techniques and cement slurry to meet the needs of the life of the well. Fluid properties, fluid mechanics and chemistry all influence the design used for well.
- b) Determining slurry composition and performing laboratory tests on the fluids designed in the first step to make sure they meet the requirements.
- c) Determining the slurry volume to be pumped, using the necessary equipment to blend, mix and pump the slurry into the annulus, establishing backup and contingency procedures.
- d) Monitoring the cement placement in real time: comparisons should be made with the first step and make adjustments where necessary.
- e) Post-job evaluation of the result of the cementing operation is a continuous process and should be compared with the design in the first step and adjusted accordingly where necessary.

2. CEMENT PROPERTIES AND ADDITIVES

2.1 Cement Classifications

Cement is manufactured by fusing calcium carbonate (limestone) and aluminium silicate (clay) with small iron and with a possible addition of gypsum (calcium sulfate dehydrate). Its major component is tricalcium silicate which reacts with water to form calcium silicate hydrate (CSH). There are several types of cement being manufactured for geothermal well use. Typical cement used for geothermal wells are class A and G. The American Petroleum Institute (API) Spec 10A classifies cement into classes listed below:

- 1) Class A - Intended for use when special properties are not required and available in ordinary (O) grade.
- 2) Class B - Intended for use when conditions require moderate or high sulfate-resistance. It is available in both moderate sulfate-resistant (MSR) and high sulfate-resistant (HSR) grades.
- 3) Class C - Intended for use when conditions require high early strength. It is available in ordinary (O), MSR and HSR grades.
- 4) Class D - Intended for use under conditions of moderately high temperatures and pressures. It is available in MSR and HSR grades.
- 5) Class E - Intended for use under conditions of high temperatures and pressures. It is available in MSR and HSR grades.
- 6) Class F - Intended for use under conditions of extremely high temperatures and pressures. It is available in MSR and HSR grades.
- 7) Class G - Intended for use as basic well cement. It is available in MSR and HSR grades. No additives other than calcium sulfate and/or water shall be inter-ground or blended with the clinker during the manufacture of class G well cement.
- 8) Class H - Intended for use as basic well cement. It is available in MSR grade. No additives other than calcium sulfate and/or water shall be inter-ground or blended with the clinker during manufacture of class H well cement.

Cement without any additives that modify setting time or rheological properties is called Neat Cement. This cement should not be used at temperatures $> 110^{\circ}\text{C}$ (230°F) because it loses strength and increases permeability above that temperature. The process is time and temperature dependent. In a test of API Class G (the usual high-temperature oil well cement), it was found that neat cement compressive strength decreased by 77% from 5,050 to 1,150 psi, and permeability increased from 0.012 to 8.3 millidarcy in 60 days at 160°C (320°F) in geothermal brine. Regression is somewhat dependent on geothermal fluid chemistry (Gallus, et al., 1979).

2.2 Cement additive materials

Cement additives have been developed to allow cement to be used in different well conditions. The additives development has been an ongoing task over a decade to improve performance properties wherever they are used. The additives commonly used are listed below:

- a) Silica flour: This is fine-ground quartz that is mixed with cement to counter high temperatures that have an adverse effect on the compressive strength of the well. It is an additive that is mixed with cement to 35-40% (BWOC) but percentage can be also be scaled down to 20% (BWOC) in areas with the presence of CO_2 to improve its properties that counter strength retrogression and lower the permeability of cement in high temperature wells as curing progresses. A set cement that consists of a cement silica ratio less than or equal to 1.0 tends to have higher compressive strengths and lower water permeability.
- b) Fluid loss additives (filtration control): The fluid loss additives reduce the rate at which water from cement is forced into permeable formations in cases of positive differential pressure. These additives are polymers such as cellulose and polyvinyl alcohol.
- c) Extenders (water adsorbing or light weight additives): Extenders are a broad class of materials that reduce the density or the cost of a slurry. Some examples are bentonite and sodium silicate, pozzolan or fly ash.
- d) Loss circulation additives (macro plugging materials): These additives are used to plug permeable, unconsolidated or weak zones that have a tendency to draw in fluid. Larger particles can be placed in cement slurry with broad particle size distributions. Ideally, they should be inexpensive and non-toxic, not accelerate or retard rapidly and have sufficient strength to bridge a fracture. The most used additives are ground walnut hull and mica flakes.
- e) Accelerators (reaction rate enhancers): Accelerators shorten the setting or thickening time of cement slurries. Generally, they are used in low temperature formations to increase the rate of strength

development but they do not increase the compressive strength of cement. Calcium chloride is normally used at 2-3% by weight of cement.

- f) Retarders (nucleation poisoners): Retarders are used to increase the setting or thickening time of cement slurries or retard the cement setting, and are generally used in cases of high temperatures. They do not decrease the compressive strength of the cement but slow down the rate of strength development. Examples of retarders are natural lignosulfonates and sugars.
- g) Dispersant (reduce slurry consistency): They are used to reduce the viscosity of the cement slurry and are useful in designing high density slurries and improve fluid loss control. An example is sodium chloride.
- h) Weighing agents (high density particulate): They allow the formulation of high density cement slurries that are normally required when the bottom hole pressure in the well is high. These weighing agents have heavy particulate materials such as iron oxide, barite or titanium oxide.
- i) Antifoam agents (surfactants that alter surface tensions): Many additives cause foaming problems during slurry mixing, causing the centrifugal pump to air lock and affect the pumping pressure. The slurry can be mixed with anti-foamers such as silicones to avoid foaming.

2.3 Cement properties

There are several cement properties that are tested and determined through experiments while designing slurry at the cement laboratory before the actual blending is done. These properties are important to counter strength retrogression of cement, help facilitate the placement of the cement and are also a source of information that can be used to review how the process was carried out with a view to improve if need be in the future. These properties are:

- a) Compressive strength: The pressure it takes to crush the set cement is measured in this test. This test indicates how the cement sheath will withstand the differential pressures in the well. The set cement cubes are removed from a pressurized curing chamber and placed in a hydraulic press, where increasing uniaxial load is exerted. The compressive strength is then calculated by dividing the load at which failure occurred by the cross-sectional area of the specimen. In destructive testing, the cement slurry is poured into two-inch cubical moulds. The cement cubes are then cured for 8, 12, 16, 24, 48 and 72 hours at bottom-hole temperatures and pressures. The compressive strength of cement slurries is determined at 90°C and 5000 psi for 18-24 hrs according to the API standard. In destructive testing, the cement cubes are then crushed to determine their compressive strength in psi. In a non-destructive test, sonic speed is measured through the cement as it sets and the value converted into compressive strength using an empirical relationship initially established from the mechanical compressive strength and transit time data for various slurry systems (Nelson and Guillot, 2006). Good compressive strength in a well means lower porosity and increased durability which depends on the water to cement ratio, additives, bottom hole static temperature and time from setting. The strength retrogression caused by high temperature over time can be mitigated by adding 40% silica flour (BWOC) or 15-20% of silica flour (BWOC) in areas where there is a presence of CO₂ gas.
- b) Rheology: The cement slurries are non-Newtonian fluids with yield stress, which require a shear stress in excess of a certain threshold value that must be applied in order to put the slurry into motion. When the shear stress in the slurry is above the yield stress, the slurry behaves as a viscous fluid. The basic reason for determining rheological properties is to predict the plastic viscosity and yield point values. Information on rheology properties is key to assess the possibilities for mixing and pumping cement slurries and predict the effect of wellbore temperature on slurry placement. Rheology of fluids also has a major effect on solids setting, free fluid properties and on friction pressures. Thus, it is mostly controlled by mud displacement in the annulus, friction pressure drop in the annulus and the hydraulic horse power required to place the cement. It can be varied by adding a dispersant which will automatically alter the physical properties, modifying the flow velocity, pumping rate and pressure losses. The slurry viscosity is measured using a Fan viscometer. The slurry sample should be conditioned for 20 minutes in an atmospheric consistometer before

measurements are taken at ambient conditions and at Bottom Hole Circulating Temperature (BHCT) when possible. Measurements should be limited to a maximum speed of 300 rpm. Readings should also be reported at 200, 100, 60, 30, 6 and 3 rpm (Joel, 2009).

- c) **Thickening time:** This is the length of time in which the cement slurry will remain in pumpable fluid state at wellbore temperature and pressure. The slurry should be designed so that it will not develop excess viscosity and become unpumpable during the time it takes to pump the slurry into the wellbore. This is normally dictated by the kind of cement and retarder used. If not properly designed, the fluid will become too viscous and the cement cannot be placed as designed. In high temperature wells, more concentrations of retarders would be needed to bring up the thickening time range that is required, while in lower temperatures less retarder should be used to decrease the thickening time of the cement. Accelerators can also be used in very small portions to save time and cost but extra care should be taken as the cement then sets more rapidly. If over pressured formations containing gas are being cemented, excessive thickening time can allow gas to migrate and flow through the cement matrix while it sets. Failure to prevent gas migration can cause problems, such as high annular pressure at the surface, poor zonal isolation and loss of production. The thickening time is determined using a high pressure high temperature (HPHT) consistometer (rated at a pressure up to 30,000 psi (206.8 MPa) and temperatures up to 204°C (400°F) and measured in terms of the consistency unit Bc (Bearden consistency). The thickening time of designed cement slurries is determined at 90°C for a differential pressure of 5000 psi. The cement slurry is mixed according to API procedures and poured into the slurry cup assembly. The slurry cup is placed in the test vessel and the pressure is increased via an air-driven hydraulic pump. A temperature controller governs the internal heater which maintains the necessary temperature profile, while a magnetic drive mechanism rotates the slurry cup assembly at 150 rpm. A potentiometer controls the output voltage, which is directly proportional to the amount of torque the cement exerts upon an API-approved paddle. A dual channel strip chart recorder registers the cement consistency and temperature as a function of time. The temperature and maximum consistency during 15 minutes to 30 minutes after the initiation of the test and the time for the cement slurry to reach the consistency of 100 Bc are then recorded (Broni-Bediako et al., 2015).
- d) **Density:** This is weight per unit volume of the cement slurry and given in units of kg/m^3 or g/cm^3 . It is normally adjusted to balance the formation pressure, control the loss of cement slurry into weak zones and for effective mud removal. The slurry density is normally kept higher than that of mud to facilitate the displacement of mud from the annulus. At the cement laboratory, the density of slurry should be measured after removing entrained air to eliminate errors in the slurry design. The density of cement slurry from the initial mixing stage on the surface is very critical to the ultimate performance of the slurry downhole and any deviation from that may significantly affect the anticipated performance, such as thickening time and inadequate strength of the cement bond in the well. Examples of lighter density slurries are foamed cement slurries or low-density additives such as perlite. The foamed cement with lower densities can be achieved by using compressed nitrogen gas to design densities of 400 kg/m^3 to 700 kg/m^3 but that requires careful control of the annulus surface pressures to avoid gas channels and voids. Light weight, foamed cement provides satisfactory support to the pipe but has less strength than the regular Portland cement. If higher densities are required, heavy weight materials like iron ore or barite are added to the cement slurry. Dispersants which allow less water to cement ratio while still maintaining pumpability can also be used to make heavy weight slurries.
- e) **Slurry stability:** This is the suspending capability and uniformity of the slurry at the simulated wellbore temperature and is assessed through two tests, free water and solid settling, as cement normally has a narrow water requirement range over which it is stable. The slurry must have sufficient viscosity to prevent solids settling and free water development. When the slurry is thin, solids settle and water will rise to the top of the cement column before it sets. This free water and solid settling separation have harmful effects, such as bridging in the annulus, lack of zonal isolations and water pockets causing casing collapse if rapid temperature increase is encountered later in the production life of a well.
- f) **Fluid loss:** This is designed to measure slurry dehydration during and immediately after cement placement under simulated wellbore temperature and differential pressure of 69 bars (1000 psi). The

differential pressure prevents fluid flow from the formation to the wellbore and when differential pressure exits into the formation, water in the slurry leaks to the formation, leading to loss of circulation. Poor fluid loss control will lead to a change of water-cement ratio, an increase in slurry viscosity and it will affect the pumpability, hence having a negative impact on the success of primary cementing. The test duration is 30 minutes and results are quoted as ml/30 min. API fluid-loss rate of 50-100 ml/30 min. (for 0.6 l of slurry) is considered satisfactory in most primary cementing (Gaurina-Medimurec et al., 1994).

- g) Free water: The free-water test is designed to measure the separation tendency of the free fluid that will collect on top of the cement slurry column between the time it is placed and the time when it gels and sets in the laboratory, using a 250-mL graduated cylinder as a simulated wellbore as the operational procedure permits preparation of the slurry at elevated temperatures and pressures. The two hour test period is initiated when the conditioned slurry is poured into the graduated tube. The suspended solids will separate from the slurry and settle toward the bottom of the cement column and it is evident with slurries containing weighting agents. This will lead to micro channelling, solids settling and formation of water pockets that can cause the collapse of the casing once it is heated up. The maximum permissible percentage of free water is 0.5%. The specification and operational test procedures are contained in API Spec 10, Section 6, and Appendix M. As interest increases in cementing deviated wellbores, many operators are evaluating free-water development by orienting the graduated cylinder at the angle of deviation of the well which has resulted in an increase in free water being recorded.

3. EFFECTS OF HIGH TEMPERATURE ON CEMENT PROPERTIES

In high temperature fields, the physical and chemical behaviour of well cement changes significantly, therefore the placement time dictates the length of time in which the cement will be required to be in liquid condition. The slurry should be designed to set quickly after placement to save time and money. Accurate BHCT will give a precise thickening time estimation of how long cement slurry stays liquid before it is set or cured. Portland cement is majorly a calcium silicate material, the main components being tricalcium silicate (C_3S) and dicalcium silicate (C_2S). By mixing these components with water, both hydrate to form a gelatinous calcium silicate hydrate called C-S-H gel, which is responsible for the strength and dimensional stability of the set cement at ordinary temperatures. In addition to C-S-H gel, a substantial amount of calcium hydroxide $Ca(OH)_2$ is liberated.

C-S-H gel is the product of the hydration that happens even at elevated temperature and pressure and is an excellent binding material at well temperatures of less than $110^\circ C$ ($230^\circ F$). At higher temperatures, C-S-H gel is subject to metamorphosis, which typically results in a reduction of compressive strength and increased permeability of the set cement. This condition is called strength retrogression. C-S-H gel often converts to alpha dicalcium silicate hydrate ($\alpha-C_2SH$) which is highly crystalline and much denser than C-S-H gel. As a result, a shrinkage occurs which is harmful to the integrity of the set cement.

The compressive strength and water permeability behaviour of Portland cement systems cured at $230^\circ C$ ($446^\circ F$) is explained in Figure 2, which

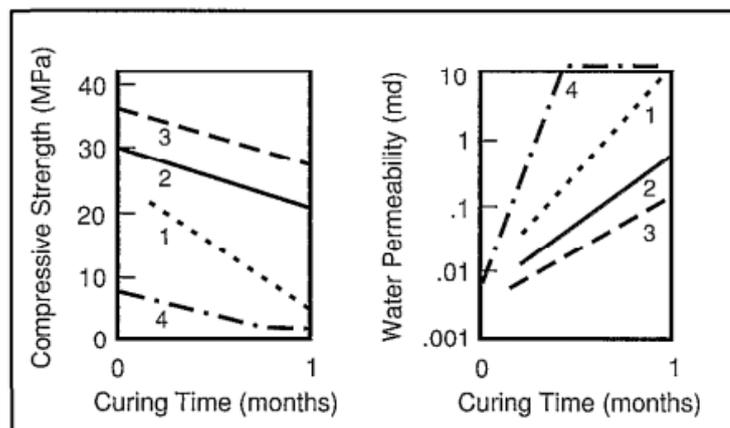


FIGURE 2: Compressive strength and permeability behaviour of neat Portland cement system at $230^\circ C$ (Nelson and Eilers, 1985)

describes a significant loss of compressive strength that occurred within one month. However, the levels to which the strength falls are sufficient to support the casing in the well (Suman and Ellis, 1977), only a severe permeability increase causes fluid migration to other zones. To prevent well cementing interzonal communication, the water permeability of well cement should be less than 0.1 md but within one month, the water permeabilities of the normal density Class G systems (1, 2) were 10 to 100 times higher than the recommended limit. The permeability of the high density Class H system (3) was barely acceptable. The deterioration of the lower density extended cement (4) was much more severe.

The strength retrogression problem can be prevented by reducing the bulk lime-to-silica ratio (C/S ratio) in the cement (Carter and Smith, 1958). To achieve this, the Portland cement is partially mixed with ground quartz, usually as fine silica sand or silica flour, at determined ratios while designing the slurry at a cement laboratory.

4. CHEMISTRY OF CEMENT WITH GEOTHERMAL FLUIDS

4.1 Carbonate acid equilibrium

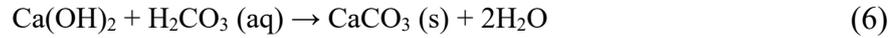
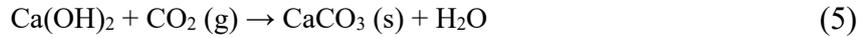
In Olkaria, most reservoirs have a neutral pH, and thus when boiling occurs, the water tends to have a pH above neutral or turns to the alkali side of the pH scale. However, a worst case scenario could be where steam is condensing to form acidic conditions and such zones might cause problems. There is no clarity on how much CO₂ is harmful but acidic conditions are not good for the integrity of the cement. Carbon species, including aqueous CO₂, bicarbonate ion (HCO₃⁻) and carbonate ion (CO₃²⁻), which react with cement even at atmospheric conditions exist in geothermal fluids, leading to loss of strength and integrity of the cement. The dissolution of CO₂ and dissociation of H₂CO₃ are greatly dependent on the pH, salinity and CO₂ partial pressure of the fluid. Therefore, to prevent well damage from carbon species, it is necessary to develop new cement and a good laboratory test of cement. The reaction of ordinary cement with CO₂ is normally accelerated in a humid or wet environment where CO₂ gas will be in equilibrium with the water phase through equilibria explained in Equations 1-4 below (Randhol and Cerasi, 2009):



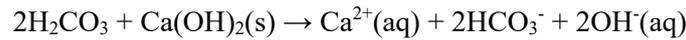
Carbonate acid will form when gas phase CO₂ begins to dissolve into the water or fluid phase, hence the higher CO₂ gas partial pressure, more CO₂ will dissolve and consequently cause a low pH that is very corrosive to materials such as cement and steel. As carbonate acid interacts with cement, its compressive strength is fairly compromised and permeability will be above the limit. To avoid a strength reduction and to achieve zero or low permeability as well, the cement system must be designed with low bulk lime to silica (C/S) ratio, less than or equal to 1.0 (Nelson and Gouedard, 2006). However, this does not apply in an environment with high levels of CO₂ (Hedenquist and Stewart, 1985). Calcium silicate hydrate mineral and calcium silicate hydroxides are the cement phases which are most susceptible to carbonation; their deterioration is accelerated when bentonite is present in the cement (Eilers, Nelson and Moran, 1983). By reducing the silica flour concentration from 35% to 20% by weight of cement (BWOC), the cement becomes more resistant to CO₂ (Milestone et al., 1986).

4.2 Cement behaviour in low pH environment

Cement containing slaked lime or $\text{Ca}(\text{OH})_2$ will react with the CO_2 in the atmosphere or in solutions as shown in Equations 5 and 6 below, respectively (Randhol and Cerasi, 2009):



Thus, carbonation refers to the interaction process of $\text{Ca}(\text{OH})_2$ and CO_2 which leads to a lower porosity due to the precipitation of limestone or calcium carbonate (CaCO_3) that take up a larger volume than the $\text{Ca}(\text{OH})_2$. This process may also induce the corrosion of steel reinforcing bars, due to the reduction of alkalinity, which may cause severe damage to a structure. The molar volume increases from 33.6 to 36.9 cm^3 when cement is subject to a chemical attack from formation fluids and substances injected from the surface into reservoirs (Shen and Pye, 1989). Saline geothermal fluids can damage cement integrity especially those containing carbon dioxide (CO_2) and sulfates (SO_4^{2-}). As a result of thermodynamic equilibrium, the pore fluid in cement, which is strongly alkaline at $\text{pH} \sim 13$, will chemically interact with the slightly acidic formation brine. In addition (SO_4^{2-}) in the formation brine reacts with cement to form hydrous calcium aluminate silicates ($\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12} \cdot 26\text{H}_2\text{O}$) and gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) which have a greater bulk volume than the cement pores and hydration products as shown below in Equation 7 (Bello and Radonjic, 2014), which induces stress that causes cement fracturing due to crystal growth.



It is expected that when cement is exposed to acidic formation brines, outward diffusion of Na^+ , K^+ and OH^- from the cement matrix can occur as a result of the concentration gradient between the surrounding formation brine and the cement pore water. The diffusion of Na^+ , K^+ and OH^- out of the cement matrix lowers the pH of the cement, causing $\text{Ca}(\text{OH})_2$ to dissolve. Then CO_2 combines with water to form carbonic acid which in turn dissolves calcium ions (Ca^{2+}) out of cement matrix to form calcium carbonate (CaCO_3). The Equation 8 below describes the dissolution of Ca^{2+} from the $\text{Ca}(\text{OH})_2$ (Bello and Radonjic, 2014):



As the $\text{Ca}(\text{OH})_2$ in the cement matrix is dissolved and leached, the pH of the cement drops causing the CaCO_3 to start dissolving. This leaves the calcium silicate hydrate with no defence, causing the decalcification of calcium silicate hydrate into Ca^{2+} , OH^- and amorphous silica gel in Equation 9 and 10 below (Bello and Radonjic, 2014):



The leaching process increases the porosity and modifies the microstructure arrangement of the cement matrix leading to increase in permeability.

4.3 Gas migration in the well annulus

When a pressure difference exists at the formation face it serves as an entry of formation fluids into the annulus. The fluids naturally migrate to lower pressure zones such as a broken casing joint due to connection problems or has collapsed to due to water pockets that occurred after a poor cement job. It can also possibly escape out of the well to atmospheric pressure during discharging when a master valve is opened in a geothermal well as shown in Figure 3. Gas migration is a complex problem involving

fluid density control, mud removal, cement slurry properties cement hydration, and cement/casing/formation bonding. Gas migration can be prevented by reducing the permeability of the cement system during the critical liquid-to-solid transition time. The cement slurry should not take a long time to set immediately after placement as that will give room to the gas to migrate, which creates pores that weaken the cement bond and compromises the compressive strength of well.

There are several contributing factors to gas flow during and after cementing:

- a) A channel of mud within the slurry that normally occurs when there is poor mud displacement or contaminated cement slurry.
- b) A micro annulus between formation cement or cement casing.
- c) If gas movement into slurry occurs, there are two options: at best cement will be porous and at worst there will be a channel allowing a gas migration upwards to the surface which might lead to a blowout.
- d) The hydrostatic pressure falls below the pore pressure during displacement or before the cement is fully set because low-density cement systems with high water to cement ratios can exhibit fairly high permeability (0.5 to 5.0 md).

In order to minimize the possibility of gas migration and successful cementing in gas bearing formations the following cement practices and slurry additives are recommended:

1. Effective mud removal is a requirement for a good cement job.
2. Low fluid loss is one of the key elements in cementing gas-bearing zones. If filtrate leaves the slurry for the formation, the resulting volume loss will cause a pressure drop in the slurry, which will allow gas flow.
3. A good cement bond between formation/cement and formation/casing must be obtained and not broken. Pressure testing casing after cement setting, or displacing the casing to a lighter fluid after cement setting, may create a micro annulus which results in a weak bond, providing a path for a gas breakthrough. Injection/fracture pressures or thermal stresses can also weaken the cement bonding to the casing during the well life, which increases the chances of gas migration.
4. Additives that reduce or eliminate slurry shrinkage during setting are used, such as bentonite or sodium silicate.
5. A design of zero free water in the slurry is critical, otherwise the slurry will be homogenous as lighter, unbound water will migrate upwards.
6. Shortening the time until the end of the transitional state is very beneficial as longer setting time allows more opportunity for gas to flow.



FIGURE 3: Vertical well discharge testing process with gases being released to atmosphere in Olkaria IV field, Kenya

5. APPLICATION BEFORE AND AFTER USING SILICA FLOUR IN OLKARIA, KENYA

5.1 Methodology

KenGen test cement samples at the cement testing laboratory in Olkaria, where Portland cement class A is sourced from the manufacturer in bulk in Athi River, near Nairobi. As mentioned earlier, Portland class A cement is only stable up to a temperature of 110°C and when the temperature exceeds that, the cement has to be modified by blending with chemical additives as it loses strength and increases permeability above that temperature. The typical additives that were used before silica flour was introduced to Olkaria are bentonite (gel), mica flakes, retarder, fluid loss, perlite and bridging agents. Deciding which of these additives are to be included in each of the composition samples is based on the well conditions and simulated at the laboratory. The temperature of the well and actual bottomhole pressure (BHP) are the most critical factors to be considered before carrying out any test at the laboratory since it strongly affects the setting time of the cement slurry and over time it will make the cement bond lose strength if not properly formulated. In Olkaria, the tests that are performed are a thickening time test, free water test, fluid loss test, slurry density test, rheology test and a UCA compressive strength test, where many samples are evaluated in the laboratory and the samples with the superior properties are chosen. Desired results include high compressive strength, adequate setting time (not too long or short for the cement operation process), zero free water or less than 0.5%, required slurry density and good rheological or flow properties. In Kenya, the blended cement is used to cement geothermal wellbores of 13-3/8 inch and 9-5/8 inch casings, mainly to protect the well from adverse effects of geothermal fluids, seal off formations, support the casings and increase the productive life of a well in a high temperature (150°C to 350°C) environment. In 2015, silica flour was introduced and used to blend cement together with other additives.

5.2 Tests interpretations

The experiments were performed on ordinary Portland cement at a bottom hole static temperature (BHST) of 150°C and a pressure of approximately 3000 Psi. The cement composition is shown in Table 1 where the ratios of silica flour were varied from 10% to 20% (BWOC). This ratio is considered suitable for Olkaria field due to the presence of CO₂ in the geothermal fluid. The slurry composition ratios after mixing and when it is ready for pumping is illustrated in Table 2. Figures 4, 5, and 6 are based on the percentage in total volume for samples A, B, and C where the proportions of components are graphically expressed with the cement taking a major portion followed by water and silica, the rest are minor elements in the mixture.

TABLE 1: Compositions of the cement samples with specific gravity of 1.80

	Concentrations (in % BWOC)	Sample A (10% BWOC) for silica flour	Sample B (20% BWOC) for silica flour	Sample C only typical ratios (no silica flour)
Cement (g)		792	792	792
Silica flour (g)		79.2	158.4	0
Bentonite or gel (g)	2.0	15.84	15.84	15.84
Mica flakes (g)	3.0	23.76	23.76	23.76
Retarder (g)	0.3	2.376	2.376	2.376
Fluid loss agent (g)	0.3	2.376	2.376	2.376
Dispersant (g)	0.3	2.376	2.376	2.376
Water (g)	46.0	364.32	364.32	364.32

TABLE 2: Percentage of slurry components after mixing and when it is ready to be pumped into the well

Slurry components in litres after mixing and ready for pumping	Sample A (%)	Sample B (%)	Sample C with no silica flour (%)
Cement (l)	61.88	58.28	65.96
Water (l)	28.47	26.81	30.34
Silica flour (l)	6.19	11.66	0
Mica flakes (l)	1.86	1.75	1.98
Bentonite or gel (l)	1.24	1.17	1.32
Fluid loss agent (l)	0.12	0.12	0.13
Dispersant (l)	0.12	0.12	0.13
Retarder (l)	0.12	0.12	0.13
Total (%)	100	100	100
Compressive Strength (MPa)	12.24	20.31	11.03

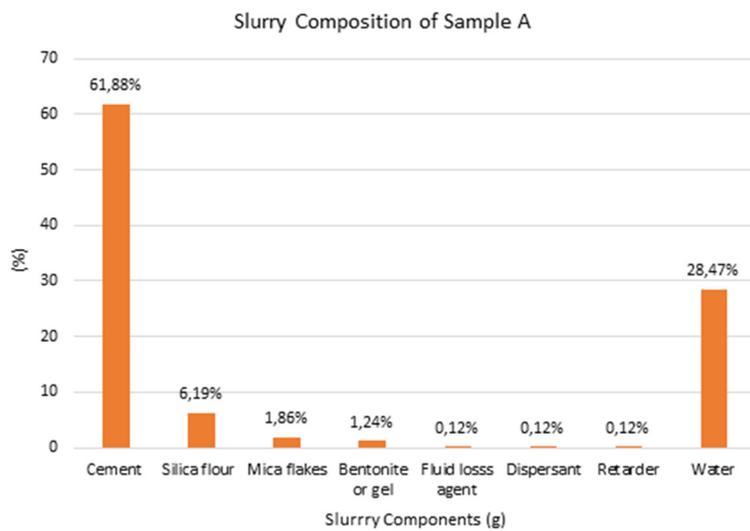


FIGURE 4: Percentage variations of slurry components of Sample A

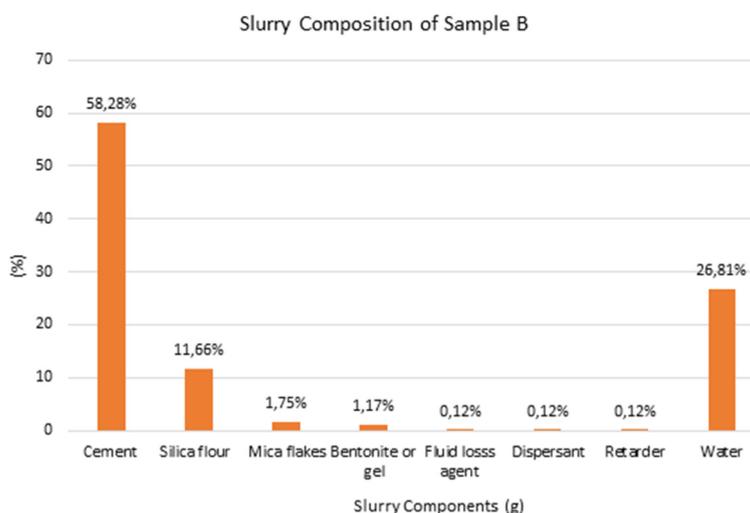


FIGURE 5: Percentage variations of slurry components of Sample B

5.3 Thickening time

The thickening time is the amount of time necessary for the cement slurry to reach a consistency of 100 Bc or poises at different well temperatures, depths and pressure conditions which are simulated at the cement laboratory using a pressurized consistometer. It also represents the amount of time the slurry will remain pumpable. The test of sample B and the results tabulated in Table 3 show a breakdown of time schedule incurred at the site while pumping slurry into the well and there was an additional contingency time of 1.30 hrs that would be used to repair the pump in case of any unforeseen failure while in operation. This time is very critical and cannot be excluded in the design part since slurry can easily set and block the cementing pump unit if not well formulated.

Table 4 and Figure 7 show the thickening time for the lead slurry while Table 5 and Figure 8 show the thickening time for the tail slurry. The consistency mark of 100 Bc was recorded after 145 minutes and 134 minutes respectively for the two results while factoring in time to mix the lead and tail, drop the top plug and displace the slurry. These results were adequate and safer to

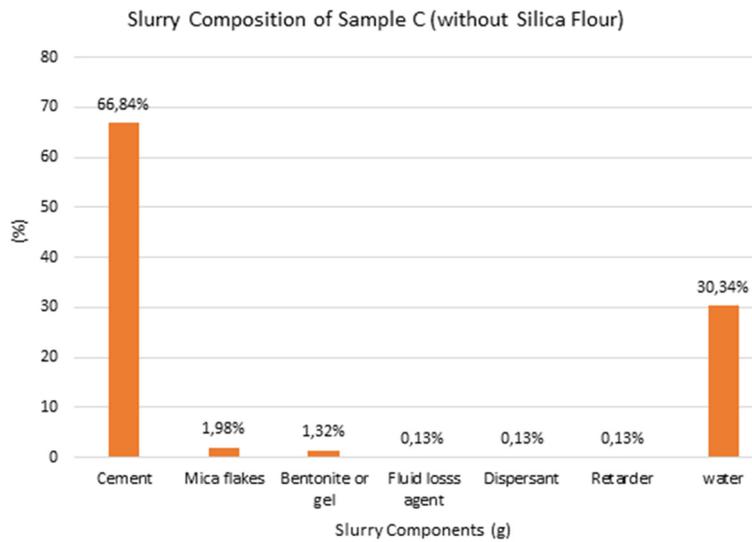


FIGURE 6: Percentage variations of slurry components of Sample C with typical additives (no silica flour)

TABLE 3: Thickening time schedule

Activity	Volume (m ³)	Pumping rate (m ³ /min)	Time (min)	Cumulative time taken for lead (min)	Cumulative time taken for tail slurry (min)
Mix and pump lead slurry	19.7	0.8-1	15.76	15.67	
Mix and pump tail slurry	10.65	0.8-1	8.52	24.19	8.52
Drop top plug	-	-	10	34.19	18.52
Displacement	22.6	1	22.6	56.79	41.12
				Time for lead = 56.79	Time for Tail = 41.12
	Safety factor (1.30 hours)			146.79	131.12

the operations. It should be noted that shorter times increase risk while longer times are subject to increasing measurement error and uncertainty, hence should be avoided at all cost. The thickening time was also within the API accepted range of 90 minutes minimum time.

5.4 Fluid loss test

The fluid loss test was conducted for 30 minutes using a volume of 100 ml before it blew up and the collected filtrate volume was recorded as 6.3 ml/30 minutes. Based on the collected filtrate volume, the fluid loss into formation of the well can be calculated using Equation 11:

$$\begin{aligned}
 \text{Calculated API Fluid Loss} &= 2 \times Q \times \frac{5.477}{\sqrt{t}} \tag{11} \\
 &= 2 \times 6.3 \times \frac{5.477}{\sqrt{30}} \\
 &= 13 \text{ ml}
 \end{aligned}$$

TABLE 4: Thickening time for lead slurry

Consistency (BC)	40	50	60	70	100
Time (mins)	115	120	123	126	145

TABLE 5: Thickening time for tail slurry

Consistency (BC)	40	50	60	70	100
Time (mins)	83	109	115	120	134

where Q , is the volume (ml) of filtrate collected at the time t (min) of the blowout. The results show that the calculated fluid loss is 13.0 ml of slurry which is lost into the low medium permeability formation over a period of 30 minutes out of 100 ml that were simulated at the laboratory and it is within the API accepted limit of 50-100 ml/ 600 ml of slurry.

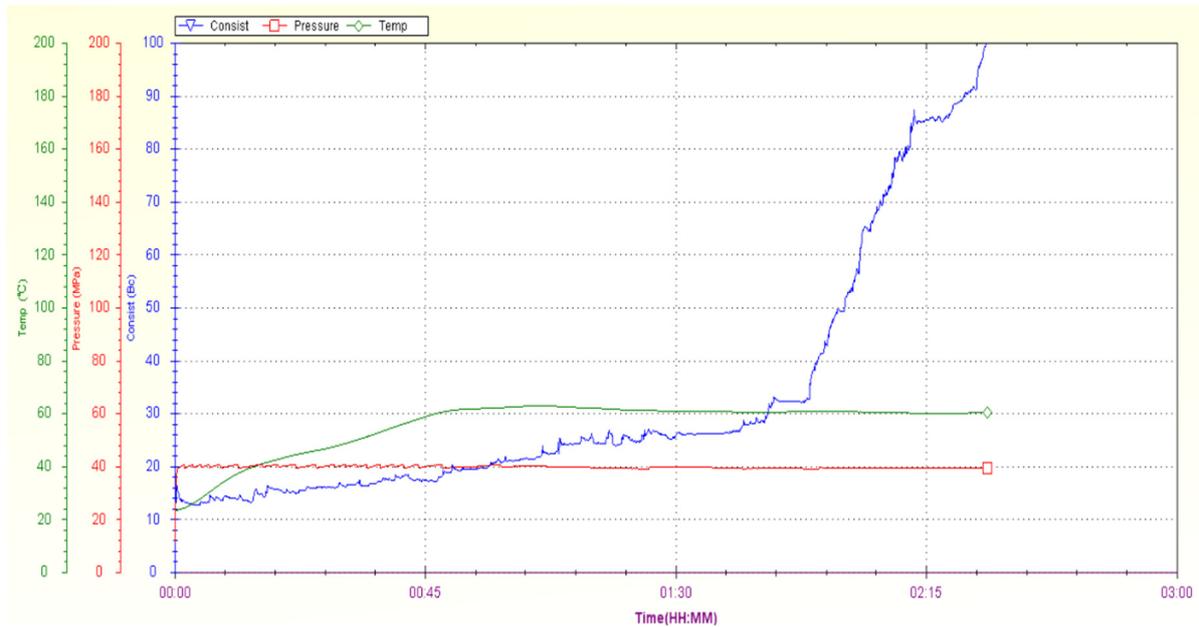


FIGURE 7: Thickening time test for lead slurry

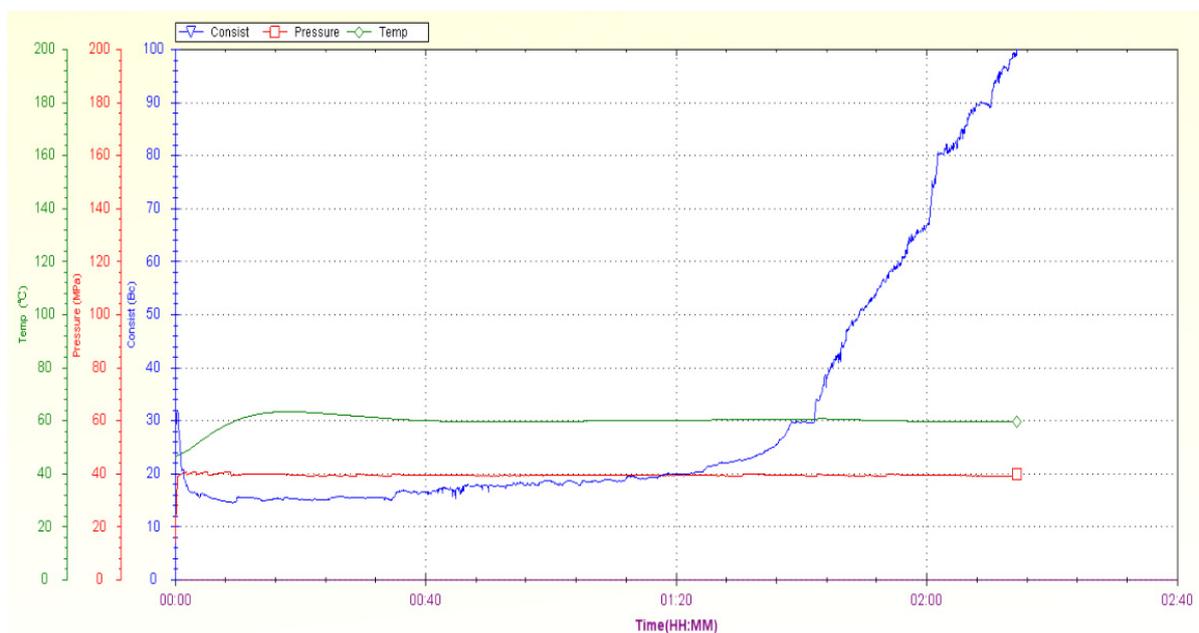


FIGURE 8: Thickening time test for tail slurry

5.5 Rheology tests

The rheological data is given in Table 6 where the measurement was done using a Model ZNN-D6 viscometer that is equipped with a factory installed R1 rotor sleeve, B1 Bob, F1 torsion spring, and a

stainless steel sample cup for testing according to API specification RP 13B and the slurry mixture shown in Table 1. Sample B was used.

TABLE 6: Rheology results from Model ZNN-D6 six-speed rotational viscometer

Speed (rpm)	600	300	200	100	6	3
Instrument readings	73	57	41	30	13	11

Using the Model 35 viscometer, the shear rate and the shear stress can be calculated from the instrument's raw data using Equations 12 and 13 (Nelson and Guillot, 2006)

$$\dot{\gamma} = 1.705 \times \Omega \quad (12)$$

and

$$\tau = 0.5109 \times \theta \quad (13)$$

where $\dot{\gamma}$ = nominal shear rate in 1/s
 Ω = viscometer speed in rpm
 θ = viscometer reading in instrument degrees
 τ = shear stress in Pascals

The calculated shear stress and shear strain values are given in Table 7 and shown in Figure 9.

TABLE 7: Shear rate and shear stress values

Shear rate (1/s)	1023	511.5	341	170.5	10.23	5.115
Shear stress, Pa	37.2957	29.1213	20.9469	15.327	6.6417	5.6199

It is assumed that the slurry sample B follows the Bingham plastic model, so the plastic viscosity (μ_p) and yield point (τ_0) for any selected slurry density can be approximated by Equations 14, 15, and 16 (API, 1997)

$$\mu_p = 1.5 \times F(\theta_{300} - \theta_{100}) \quad (14)$$

where μ_p = plastic viscosity of the slurry in centipoise (cp)
 F = torsion spring factor for the instrument, (taken as $F=1$ for the instrument used)
 θ_{300} = instrument reading at 300 rpm
 θ_{100} = instrument reading at 100 rpm

or

$$\mu_p = 0.0015 \times F(\theta_{300} - \theta_{100}) \quad (15)$$

where μ_p = plastic viscosity in pascal-seconds (Pa-s)

and

$$\tau_0 = 0.4788 \times [(F \times \theta_{300}) - (1000 \times \mu_p)] \quad (16)$$

where τ_0 = yield point shear stress of the slurry in Pascals
 μ_p = plastic viscosity in Pas

It should be noted that only the shear rate between 100 and 300 rpm is used. The instrument is not considered accurate outside this range.

According to the Bingham model the shear stress and shear strain relationship is linear as shown in equation 17 where

$$\tau = \tau_0 + \mu_p \times \dot{\gamma} \tag{17}$$

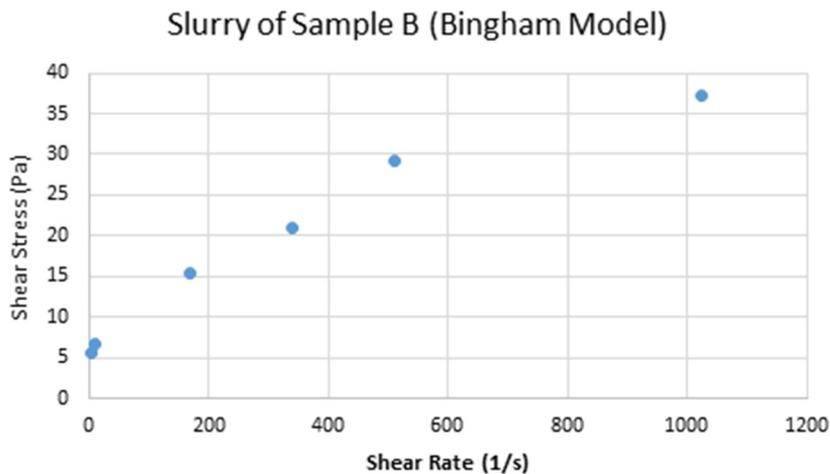


FIGURE 9: The shear stress plotted vs. shear rate for the tested sample. The orange box shows the yield point and the slope of the line is the plastic viscosity

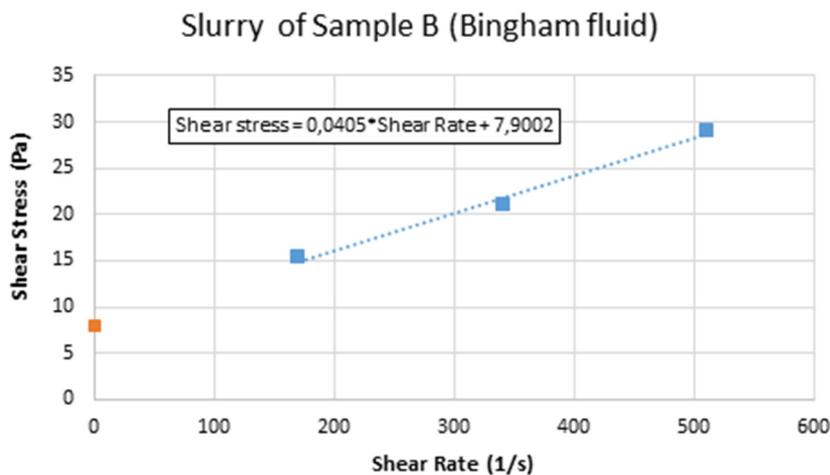


FIGURE 10: The shear stress plotted vs. shear rate for the tested sample. The orange box shows the yield point and the slope of the line is the plastic viscosity

Utilizing the Bingham model in Figure 10, the yield point of the mixture of sample B is 7.9 Pa and the plastic viscosity is 0.0405 Pas. The yield point of 7.9 Pa is within the API recommendation maximum range of 10 Pa for Bingham plastic. A slurry whose yield point is higher than 10 Pa will not flow under pressure during pumping, signifying that the solids have already started settling.

5.6 Compressive strength tests

The compressive strength of samples A and B was tested and their values recorded as illustrated below in Figures 11 and 12, respectively. After 24 hours of curing, the compressive strength of sample A was 1833 psi (12.64 MPa) while that of sample B was 2946 psi (20.31 MPa). The experiment was stopped after 25 hours but the compressive strength was still increasing at this point. The compressive strength of sample A after 25 hours was 1842 psi (12.70 MPa) and that of sample B was 3017 psi (20.80 MPa). When silica flour was introduced there

was a significant improvement in compressive strength as compared to the typical test that was done without it. Figure 13 below captures a situation where silica flour was not used in 2014 before it was introduced in 2015 in Olkaria, Kenya, where the compressive strength after 24 hours of curing was recorded as 1600 psi (11.03 MPa).

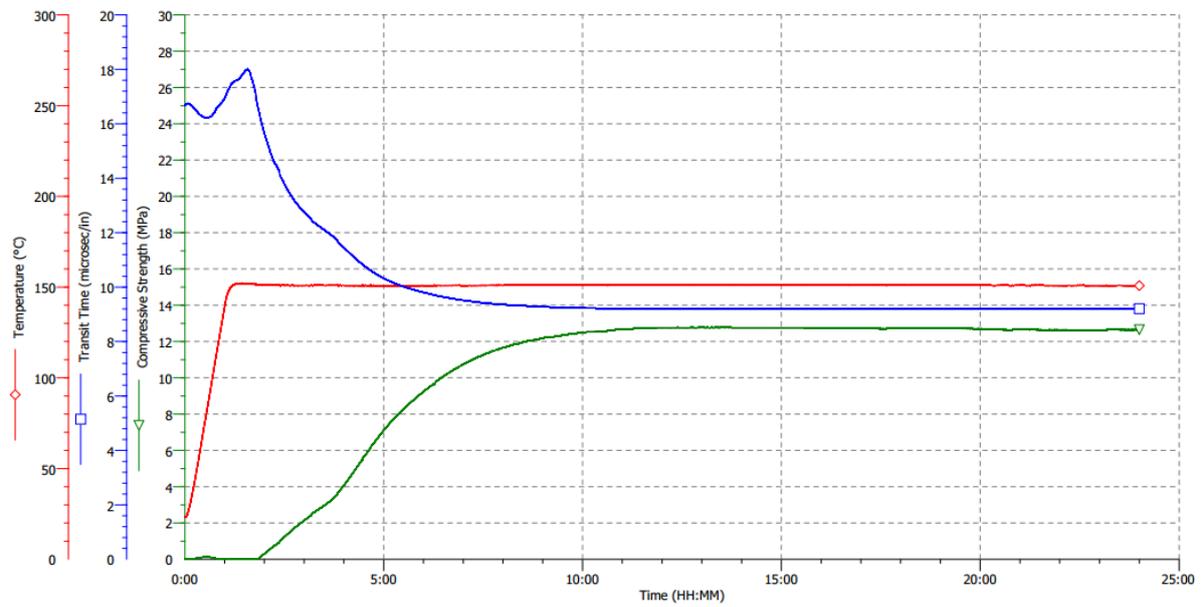


FIGURE 11: The compressive strength development of blended Portland Class A cement cured at BHST of 150°C and approximately 3000 psi (Sample A)

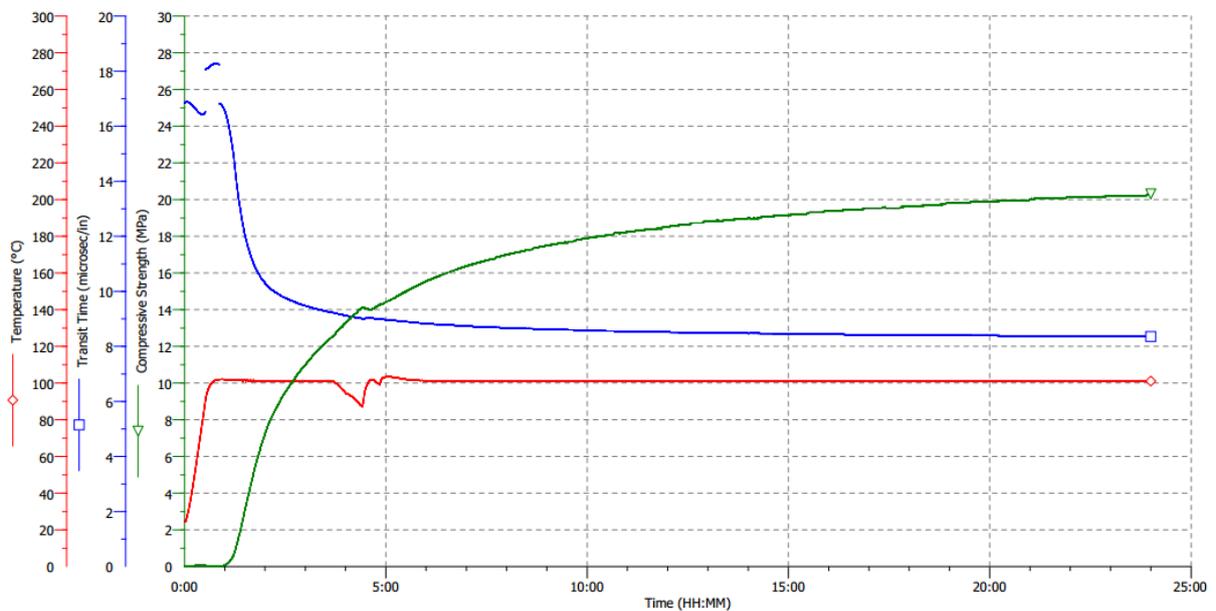


FIGURE 12: The compressive strength development of blended Portland Class A cement cured at BHST of 150°C and approximately 3000 psi (Sample B)

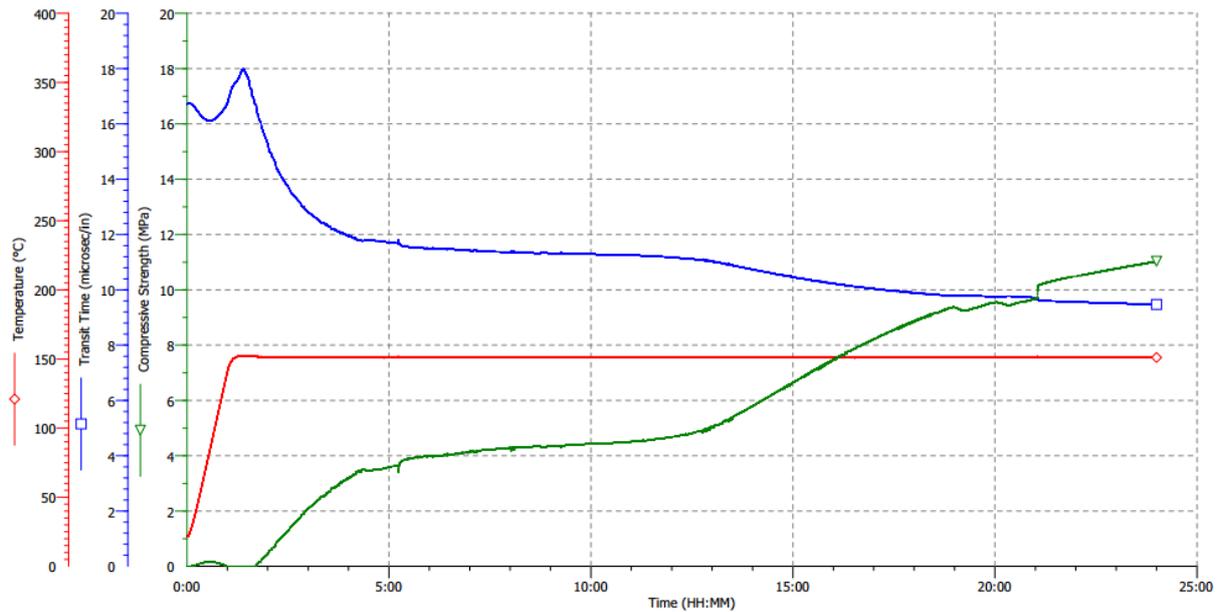


FIGURE 13: The compressive strength development of blended Portland Class A cement, Sample C (with no silica flour) cured at BHST of 150°C and approximately 3000 psi

6. CASE STUDY OF TESTS DONE AROUND THE WORLD

6.1 Compressive strength

In the research done by Wallevik et al., 2004, various cement slurries were exposed to different temperatures over a length of time after setting. The graph in Figure 14 shows the deductions of the compressive strength simulation of ordinary Portland cement slurry with 40% silica flour (BWOC) in a temperature of 20°C to 80°C with different w/c that was performed by Wallevik et al. (2004). Their results were subjected to a monitoring of 1 to 3 days of curing. For 1 day their samples were subjected to temperatures of 21°C and 40°C while the 3 day samples were similarly subjected to temperatures of 20°C, 40°C and 80°C. The results show that the 1 day sample curing at 40°C attained a higher compressive strength of 12.8 MPa than the sample curing at 21°C with only 7.9MPa. Similarly, the samples that were cured for 3 days at temperatures of 80°C, 40°C, and 20°C recorded a compressive strength of 23.5 MPa, 18.5 MPa, and 14.7 MPa respectively. This clearly indicates that temperature is a factor that affects the curing and the strength development of cement slurry in the well. The compressive strength test indicated that all the laboratory simulations conform to the API standards range of 673 Psi (4.64 MPa) to 785 Psi (5.41 MPa) after eight hours of setting but this also varies with different chemical additives used.

The effects of strength retrogression are very costly when not prevented through a well designed slurry that will counter acidic geothermal fluids and high temperature conditions. This can be done by reducing the bulk lime to silica ratio (C/S) in the cement by blending a designed ratio of silica flour or silica fumes by weight of cement. In the research done by Nelson and Eilers, 1985, various silica flours and silica sands were exposed to curing at elevated temperatures over a period of 24 months. They noted that there was significant improvement in the performance of Portland Class G cement stabilised with silica sand and silica flour at elevated temperature ranges of 230°C to 320°C as shown in Figure 15. The compressive strength and permeability of class G cement slurries stabilised with silica flour and silica sand at elevated temperature was recorded after setting for a duration of 24 months. They confirmed that Class G cement stabilised with silica flour at 320°C and 230°C had the highest compressive strength

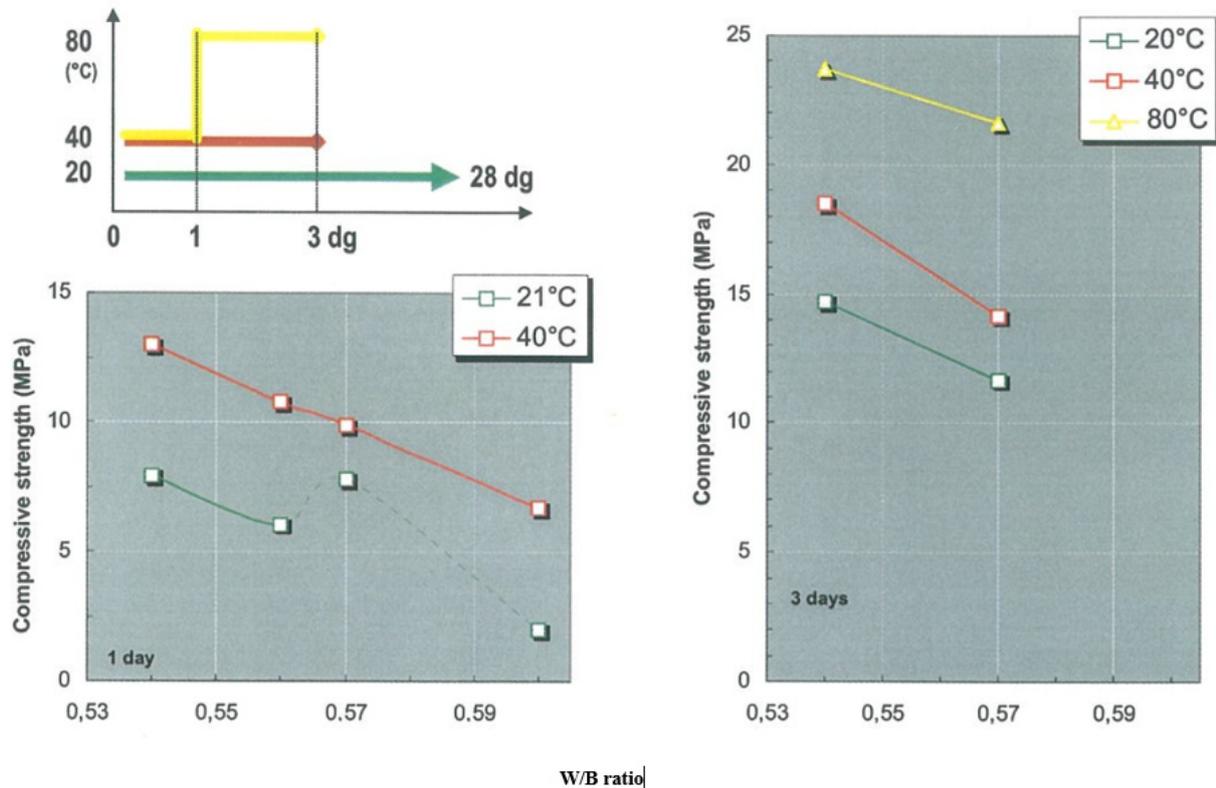


FIGURE 14: Compressive strength development at 20, 40, and 80°C (Wallevik et al. 2004)

of 50-51 MPa compared to silica sand stabilised at 230°C which had the least compressive strength of 42 MPa. Also, there were fairly good permeability results for Class G cement system that was stabilised with silica flour at a temperature of 320°C and 230°C with a permeability of 0.1 md (API accepted standard is 0.1 md) but the permeability in the silica sand stabilised cement is 0.2 md, which is above the acceptable limit of the API standard.

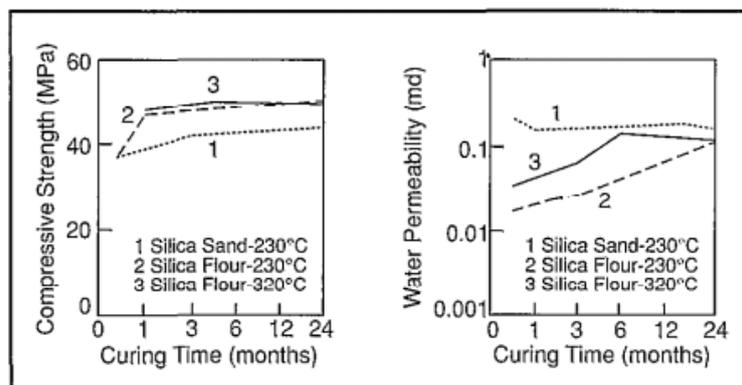


FIGURE 15: Compressive strength and permeability behaviour of 1920 kg/m³ Class G systems stabilised with 35% silica (Nelson and Eilers, 1985)

6.2 Permeability

The cement stabilising chemical additive silica components are typically categorised into three parts according to their size of particles as silica sand (175-200 µm particle size), silica flour (±15 µm particle size) and silica fumes (0.1 µm particle size). The silica flour does not increase the yield value or plastic viscosity by the same amount as the silica fume does, but acts as filling material in the cement as it reacts with water. However, silica fumes are very vital in controlling the permeability properties in cement. An increase in permeability is also an indication of strength retrogression in cement but cement permeabilities of less than 0.1 millidarcy (md) are deemed adequate. Values higher than this, particularly due to either a change in temperature or a change in the examined time frame, can indicate strength retrogression. Test studies on permeability based on type of silica content were performed by using approximately 0.1 µm particle sizes and 15 µm particle sizes under a curing temperature of 230°C

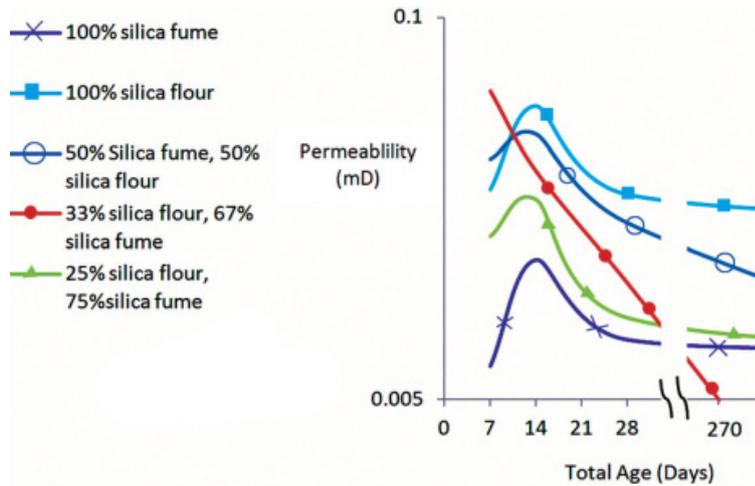


FIGURE 16: Effect of permeability behaviour of silica stabilized Portland cement system, containing various amounts of silica flour and silica fumes (Grabowski and Gillot, 1989)

at 400 psi (Grabowski and Gillott, 1989). Figure 16 illustrates that the permeability recorded was all below the API standard maximum of 0.1 md. The highest permeability recorded was the cement blend of 100% silica flour with 0.05 md. The other cement blend ratios recorded permeability figures of less than 0.05 md. According to the study, the cement blend with 33% silica flour and 67% silica fumes had zero permeability after 270 days of setting, thus this sample makes the best property of cement slurry that are necessary to counter strength retrogression.

6.3 Rheological testing

The traditional cement blend fluid loss control additive that has been in use in Iceland over a long time is PSP 322 but a test that was performed by (Wallevik et al., 2004) shown in Figure 17 revealed that PSP 322 has little effect on reducing the yield value, compared to newer additives (π Polymers). These π Polymers are up to 10 times more effective at reducing the yield value. ADVA Cast 530 is one of these polymers that is currently being used in Iceland. The new Icelandic blends had all the same additives as the traditional one apart from ADVA Cast 530 (0.06%) which was used as a fluid loss control agent for improved rheology and the amount of bentonite is 1.5% (instead of the traditional 2%). In Kenya CFL-122 (carboxyl methyl cellulose based) with a temperature range of 150°C is used.

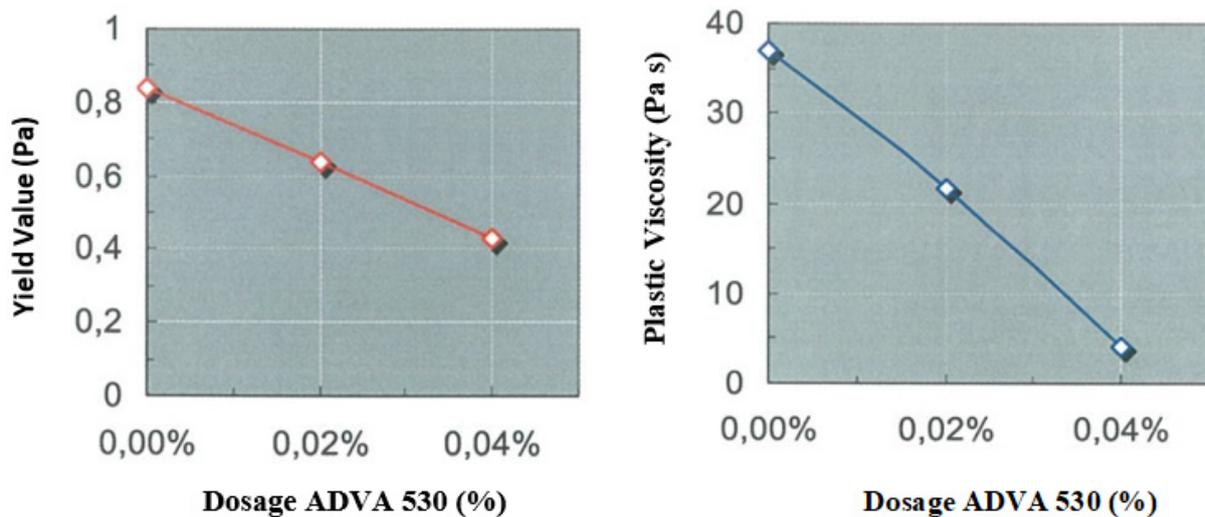


FIGURE 17: The rheological effects of ADVA Cast 530 on the Norwegian G-class cement with w/c=0.56 (Wallevik et al., 2004)

7. POST CEMENTING EVALUATIONS

After carrying out any cement job there is a need to evaluate the quality of the job so that if there are any problems they can be addressed and rectified quickly and efficiently. There are several methods and tools that can be used for evaluating a cement job. Using a single method will not give all of the necessary answers to form a conclusion about the success or failure of a cement job but a combination of the various tools and methods will contribute to a well informed decision that can be used to feed into a continuous improvement plan. Following are few methods used among many others.

- a) Pressure test or leak off test - This is a critical test done in Olkaria, and is performed after every surface or intermediate cement job to verify the mechanical integrity of the casing. When the cement samples set, the casing shoe is drilled out for 3 m into the new formation and the casing internal pressure is increased until the pressure at the casing shoe exceed the pressure that will be applied at the next phase of drilling. If the casing shoe does not hold the pressure then it shows a poor cement job and an immediate remedial job should be done to correct it. The casing cement bond is tested first by closing the blow out preventers and hydraulically pressurizing the cemented casing to 300 psi and observing any pressure drop for ten minutes. If the bond is holding, the drilling out of cement then proceeds to three metres below the casing shoe into the new formation (Ng'ang'a, 2014)
- b) Temperature surveys - These are logs that are performed to locate the top of the cement within 24 hours of the cement curing phase before the temperature anomaly fades. This involves running a thermometer inside the casing in cases where there is no cement returns to the surface of the well and it could have been lost to fractured permeable zones. The results will be key to taking the next course of action to achieve a successful cement job. The thermometer will respond to an exothermic reaction which generates heat due to a cement hydration reaction and the sharp increase in temperature from the ambient conditions will therefore indicate the top of the cement.
- c) Variable density log (VDL) - This provides a full wavelength of the received signal at the sensor. It is transmitted via the casing, formation and mud thus indicating the quality of the cement bond between the casing and cement, and the cement and the formation. The arrival time of the signal is a function of distances travelled and the density of the medium. The signals, which pass directly through the casing, are recorded and displayed as parallel, straight lines to the left of the VDL plot. In circumstances of a good bond between the casing and cement, cement and formation is presented by wavy lines to the right of the VDL plot as shown in Figure 18 The wavy lines relate to those signals which have passed into and through the formation before passing back through the cement sheath and casing to the receiver sensor. If the bonding is poor the signals will not penetrate to formation and parallel lines will be recorded all across the VDL plot (Steingrímsson, 2011).
- d) Cement bond log (CBL) – The CBL tool uses typical sonic log principals of refraction to make its measurements where a generated wave travels from the acoustic transmitter, through the mud, and refracts along the casing-mud interface back to the receivers to evaluate the quality of the cement bond between the casing and cement and the cement and formation. It also indicates the top of the cement. It is a downhole probe that is run to the well in a centralised position. The travel time and amplitude of the continuous sound pulses generated by the transmitter are measured by the receiver, placed at a distance (usually 3 ft) from the transmitter as a function of depth. The amplitude will be at maximum where there is no cement or poorly cemented sections, and at minimum where the casing is well cemented (Steingrímsson, 2011).

8. NEW ADDITIVES AND CEMENT TYPES FOR HIGH TEMPERATURE WELLS

8.1 Thermal cement

Pozzolan-Portland Cements (PPC) is a product of inter grinding clinker (OPC) together with gypsum and pozzolanic materials in certain ratios and blending them thoroughly in certain proportions. The strength of PPC is dependent on the amount of pozzolanic material, any percentage of 15-35% is safe but beyond that strength is compromised. These pozzolanic materials are categorised as natural

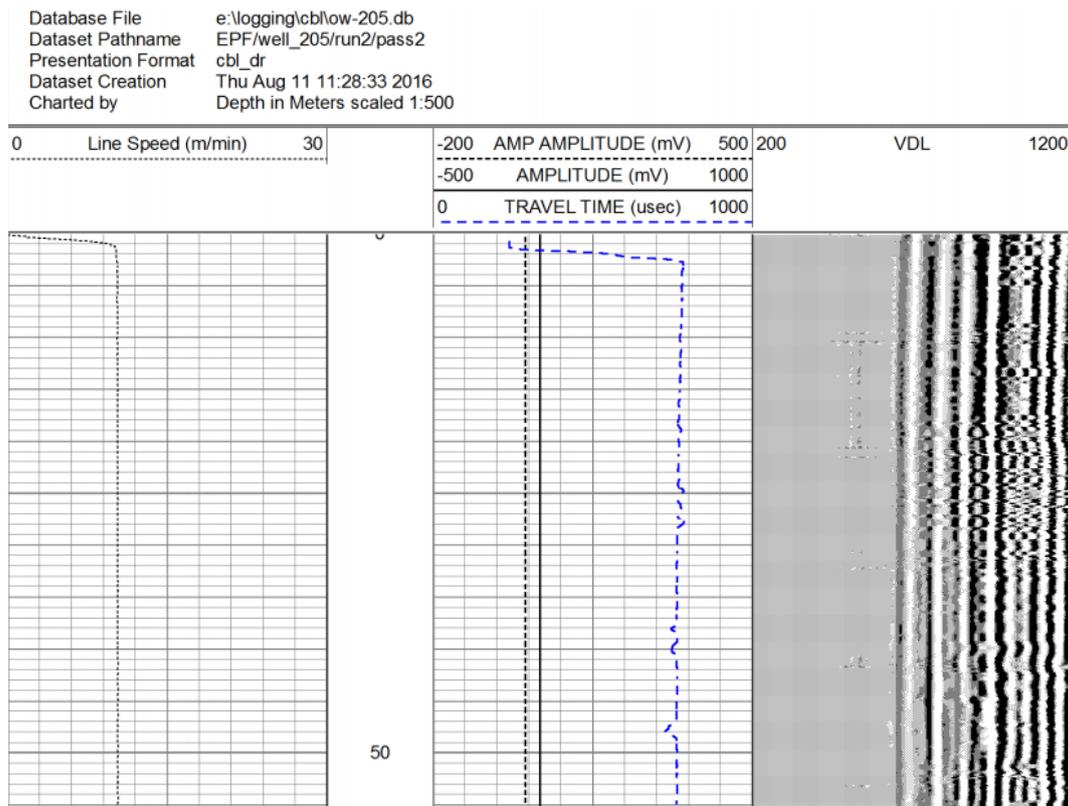


FIGURE 18: Examples of CBL and VDL (Olkaria, Kenya, 2016)

materials which includes clay, shale, volcanic tuffs, and diatomaceous earth, while the artificial materials are fly ash, silica fume, rice husk and ground granulated blast-furnace slag. The Icelandic tests on cement have included fly ash and silica fumes used as pozzolanic material additives and suggested that these materials increase both the yield and the plastic viscosity (Wallevik et al., 2004). Therefore, if pozzolanic materials were to be added to the cement blend it would probably require some sort of a dispersant as well to counter the negative effects on rheology properties. The positive effect of an addition of pozzolanic materials to API Portland cements is to reduce permeability and protect the cement from a chemical attack by geothermal fluids or formation waters with the low pH found in CO₂ injections zones. Furthermore it can reduce the effect of a sulfate attack which is relatively dependent on the slurry design.

8.2 Newly improved additives

Cementing Lost Circulation Fibers (CLCF) - In fractured zones there can be losses of the slurry during cementing jobs and a CLCF material can help form a bridging network in the loss zone or loss of circulation depth and return the circulation. It is designed to be placed only at the loss zone and can be added directly to the cement mix tank or on the blended cement without affecting the desired cement properties. It will work well together with other cement components and there will be no extra cement to be prepared for anticipated losses. This will minimise cement waste and eliminate its disposal cost. CLCF works better than mica flakes which have been used as a circulation material for a long time (Salim and Amani, 2013).

Microsphere – These are hollow sphere chemical additives which are free flowing powders that consist of synthetic polymers which are biodegradable in nature with a particle size less than 200 μm. They are used when slurry densities from 8.5 to 11 lbm/gal are required. Microspheres can be acquired as an end product of power generating companies, fly ash has a small composition of spheres but more can be

found when fly ash is disposed of in waste ponds. The low-density hollow spheres normally float on the top which make it easy to separate them by a flotation process. These hollow spheres are composed of silica-rich aluminosilicate glasses typical of fly ash, and are normally packed with a combination of combustion gases such as CO₂, NO_x, and SO_x. They offer high strength to weight ratio when filled with nitrogen thus providing a more consistent composition that reveals a better resistance to mechanical shear and hydraulic pressure. The negative effect is their tendency to crush during mixing and pumping when exposed to hydrostatic pressure resulting in an increase in slurry viscosity, less volume, and premature slurry dehydration. When microspheres are blended with light weight slurry, it provides a strength development that can also help minimize fluid loss, solids setting and free water segregation (Mitchell et al., 2011).

ADVA Cast 530 – This a fluid loss control agent or chemical additive that also improves other properties such as reducing the yield value and plastic viscosity. It comes in a liquid form that can easily be added to the slurry during mixing. The amount of ADVA Cast 530 used in a slurry can vary with the type of application, but will normally range from 200 to 650 ml/100 kg of cement, which is the range recommended for use from the manufacturer. It is highly compatible with other chemical additives and with high levels of workability, thus producing super fluid self-consolidating concrete (SCC) without segregation, high early strength development and superior concrete surface finish. It is currently used in Iceland to blend cement and the quantity used is 0.06% (BWOC) based on (Wallevik et al., 2004).

9. DISCUSSION AND RECOMMENDATIONS

- All the current cement blends and testing procedures at Olkaria, Kenya are considered satisfactory and conform well to API set standards. However, it would be interesting to test the current blends with microspheres and new fluid loss additives, such as ADVA Cast 530 to see how it compares with the current blends.
- The compressive strength of the ordinary Portland cement starts decreasing above 110°C but this can be mitigated by the addition of silica. It is generally recommended that 35-40% silica flour (BWOC) is added to the cement slurry to combat strength retrogression, but in corrosive well environments, such as where there is a presence of CO₂, the addition should be reduced to 15-20% to resist the attack of CO₂ rich fluids. Pozzolonic Portland cement might be a viable option in high temperature and CO₂ rich environments as it can give good compressive strength, reduce the slurry density and it is very resistant to any chemical attack by geothermal fluids. However, the inclusion of pozzolanic material might also require other additives as well to counter any negative effects on rheology properties.
- To fully analyse the strength retrogression of well cements in Kenya, that are exposed to high temperatures over their lifetime, the tests of cement slurries at the laboratory should ideally be simulated at close to actual well temperatures (BHCT and BHST) over a few months, as this would give a better indication of the strength retrogression caused by high temperature environments. Current research in the geothermal sector seems to lack testing at high enough temperatures over a sufficient period.
- Most wells in Olkaria are highly permeable and therefore circulation losses are one of the greatest challenges in cementing them. Mica flakes are currently used to prevent or minimize losses. New LOC materials such as Cementing Lost Circulation Fibers (CLCF) could be viable options. Other possible alternatives lost circulation challenges are to reduce the density of the slurry by using foam cement or to introduce new additives such as perlite, microspheres and other low density pozzolanic materials. Other things such as improved rheology can also help to reduce frictional pressure generated during cementing as well improve fluid loss, workability of the slurry, setting characteristics of the cement, and slurry consistency while pumping.

- Geothermal fluids and high thermal conditions are very detrimental to the cement/steel bond in a well, thus a sound slurry should be designed to counter their adverse effects and give the well a longer productive life. The shoe joint section signifying the end of the casing string should be cased with good quality cement and well formulated slurry as this is the entry point of geothermal fluids into the main well.
- Good casing centralisation ensures that there is eccentricity of cement in the annulus to provide good zonal isolation, the creation of a hydraulic seal and it provides casing structural support, while the contrary of that is the occurrence of mud pockets that cause channelling problems, poor strength and exert a high mechanical load on the pipe. Good well conditioning should be done prior to running casings into the well to remove mud cakes and debris. Circulation should be performed for at least 2 hours while reciprocating the casing to clean the wellbore before the actual well cementing process starts.

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NOMENCLATURE

BWOC	- By weight of cement
BHCT	- Bottom hole circulating temperature
HPHT	- High pressure high temperature
FLC	- Fluid loss control
HT	- High temperature
BHST	- Bottomhole static temperature
BHP	- Bottomhole pressure
C/S	- Bulk lime to silica ratio
CSH	- Calcium silicate hydrate
w/b	- Water/(cement +silica ratio
w/c	- Water to cement ratio
API	- American Petroleum Institute
BFS	- Blast furnace slag
OPC	- Ordinary Portland cement

Bc	- Bearden consistency
am	- Amorphous shape
md	- millidarcy
ml	- milligram
MPa	- Mega pascal
Psi	- Per square inch
τ	- Shear stress (Pa)
UCA	- Ultrasonic cement analyzer
HAC	- High alumina cement
CLFC	- Cementing lost circulation fibers
LOC	- Loss of circulations
ASW	- Average cement slurry weight in kilograms per litre (kg/l)
ISO	- International Organization for Standardization
ASTM	- American Society for Testing and Materials

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