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A REVIEW OF CASING CEMENTING PRACTICE FOR GEOTHERMAL WELLS IN MENENGAI FIELD, KENYA

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ABSTRACT

The nature of highly fractured and weak rock formations can make cementing of geothermal wells challenging. A primary cementing job is usually designed to completely fill the annulus up to the surface. This is usually not achieved in the Menengai geothermal area due to loss of cement slurry into the formation. As a result, it becomes necessary to carry out cement backfill jobs until the annulus is completely filled.

During backfilling, there is a risk of trapping water in the casing-to-casing annulus. Such water could enter the annulus from the surface through the side valves, or it could be free water segregating from the cement slurry placed in the annulus. Investigations in Iceland using downhole video cameras have revealed cases of casing collapse attributable to pressure from the expansion of trapped water as the well heats up during production. It is therefore imperative to try to minimise the risk of trapped water in the casing-to-casing annulus as much as possible during cementing. An assessment of the possibility of having trapped water between the anchor and production casing annuli of the existing wells in Menengai, Kenya, is made. Ways to minimise this risk without compromising the integrity of the cement sheath are explored, through a review of backfill volumes and design of an appropriate slurry for backfill jobs using currently available materials.

1. INTRODUCTION

A geothermal well is essentially a high-pressure pipeline that conducts geothermal fluid from the reservoir to the surface. The integrity of the well comes from the casings that are cemented in place during the well construction. The casing and cement sheath should maintain the integrity of the well until the end of its productive life.

Casings run and cemented in geothermal wells will be subjected to high thermal stresses during the working life of the well. Therefore it is important that there is uniform cementation over the full length of the casing, such that the stress is distributed over the length of the casing as uniformly as possible and that stress concentrations are avoided (Hole, 2008a). Therefore, casing cementing jobs must be planned and executed carefully to ensure the total length of the annulus between the casing and the open hole, as well as the previous casing, is completely filled with sound cement that can withstand long-term exposure to geothermal fluids and temperatures.

However, geothermal wells are often drilled into permeable and under-pressured rock formations, which are susceptible to breakdown and induced losses during cementing. This problem has been found to be particularly severe in the Kenyan geothermal systems of Menengai and Olkaria in the East African Rift Valley (Ng'ang'a, 2014). Attempts to plug every major loss zone with cement during drilling have proved untenable in terms of rig downtime. The recourse is to drill blind (without any fluid returns to the surface), run the casing and cement. It is therefore difficult to achieve a complete filling of the annulus back to the surface during primary cementing, thereby necessitating backfill jobs. The number of backfills varies for each well, depending on the severity of the losses.

Since backfills are conducted through the casing-to-casing annulus, there is a possibility of trapping water between successive cement backfills. When the well comes into production, the trapped water will evaporate and expand at elevated temperatures. Considering a fixed specific volume, at temperatures above 100°C the resultant pressure rise in the water due to a change in temperature is approximately 1.6 MPa for every 1°C rise in temperature (Hole, 2008b). If the vapour pressure exceeds the collapse pressure of the production casing it collapses inwards and chokes the well. Using downhole video cameras, cases of collapsed casing have been discovered in Iceland (Thórhallson, 2003). This leads to tedious, expensive casing repair operations when attempting to restore well integrity.

Formation temperatures of up to 300°C are typical in Menengai. Therefore any trapped water is likely to generate pressures in excess of the collapse pressure rating of the K-55 grade steel casings used. Table 1 shows the collapse pressure of casings used in Menengai (Gabolde and Nguyen, 2006) against the pressure rise in a trapped specific volume of water heated from 100°C to 200°C. Water trapped in the casing-to-casing annulus could possibly come from:

1. Water ingress from surface activity e.g. flooding in the cellar or cleaning around the cellar area with side valves left open. All due caution is exercised during casing cementing in Menengai to prevent water ingress.
2. Free water segregating from cement slurry. The cement slurry should be carefully designed to ensure no free water segregates and settles on top of the cement in the annulus between backfills. In general, the maximum free water should be 0.5%, less in high angle wells (>45°) and zero in horizontal wells or against gas zones (Devereux, 1998).

TABLE 1: Collapse pressure for cemented casings in Menengai wells (grade K-55)

Casing size (in)	Weight (lb/ft)	Collapse resistance (MPa)	Pressure rise in trapped specific volume of water heated from 100°C to 200°C (MPa)
20	94.0	3.6	160
13-3/8	54.5	7.8	160
9-5/8	47.0	26.8	160

Cementing of wells in Menengai Kenya is done via 'through casing' cementing. After running the casing and conditioning the hole, a predetermined volume of slurry is pumped through the casing and displaced into the annulus with a top plug until the plug bumps the float collar. Class A cement blended with bentonite, retarder, fluid loss additives, friction reducer and mica flakes is used for the primary cementing job. If the annulus is not filled up during the primary job, backfills with neat class A cement are done through the casing-to-casing annulus at intervals of 6 to10 hours until the annulus is filled.

1.1 Lithology of Menengai

The lithology of the Menengai caldera area is summarised below and shown in Figure 1 (GDC, 2016):

0-200 m - Pyroclastic and trachyte: The formation comprises mainly unconsolidated pyroclastic material with lithics of trachyte composition. The formation at this zone is unaltered and blocky lava likely poses challenges of drill string vibration and total loss of circulation.

200-400 m - Trachyte and tuff: This zone mainly comprises medium-hard to hard trachytic lavas with major tuff intercalations between the trachyte lava. The tuff at this depth is a marker horizon and appears altered with low temperature clays and zeolites. The trachytic lava at this zone is fractured and altered, hence cave-ins and circulation losses are expected.

400-650 m - Trachyte: This zone is expected to be composed mainly of trachyte. The rocks in this zone are medium-hard to hard with alteration expected to increase with depth. Partial or major circulation losses may be experienced at fracture zones.

650-800 m - Tuff: Reddish brown to grey welded tuff is expected in this zone. The formation is relatively altered and soft. Hence, losses are expected.

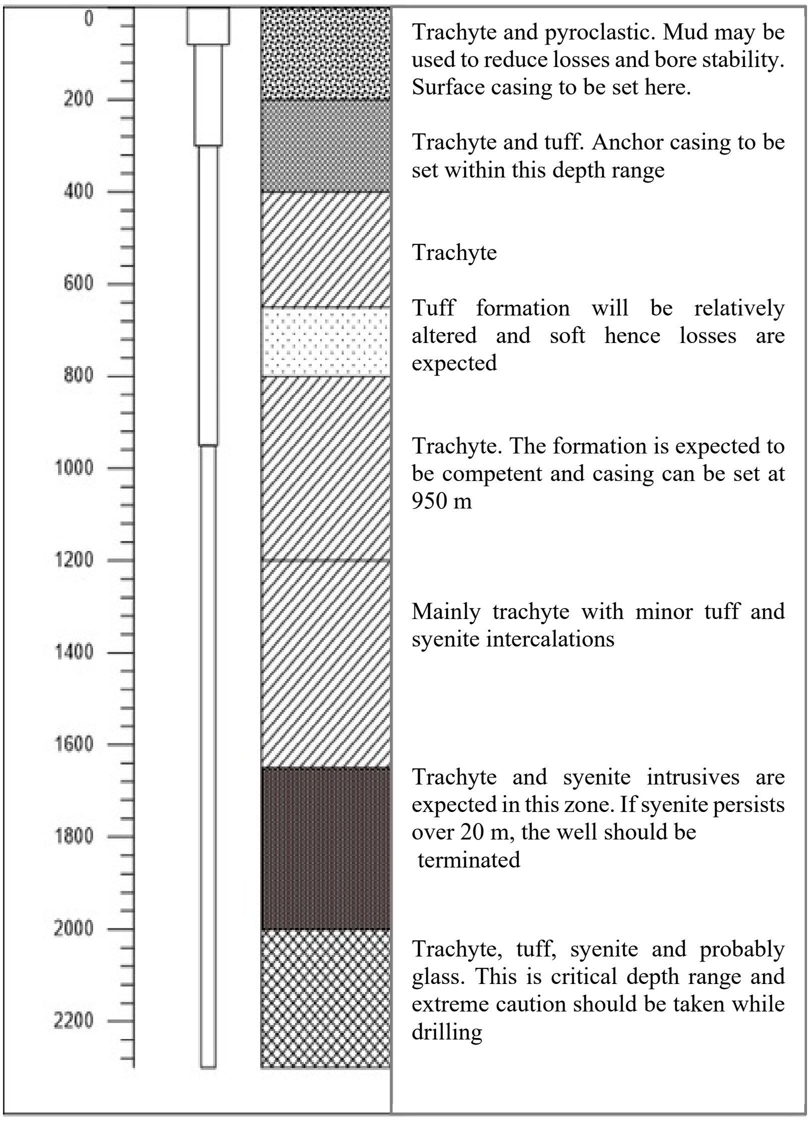

FIGURE 1: Lithology of Menengai (GDC, 2016)

800-1200 m - Trachyte: The rock is mainly trachyte and dark grey, fine grained and sanidine porphyritic lava is expected at this zone with occasional tuff intercalations. The rock shows slight alteration and is medium-hard to hard. Minor to major circulation losses are expected at fracture zones.

1200-1650 m - Trachyte: The rock is mainly trachyte with minor tuff intercalations. The formation is medium-hard to hard and competent in some localities but alteration zones are also probable and cave-ins are to be expected.

1650-2000 m - Trachyte and syenite (intrusives/dykes): The rock is mainly trachyte with syenitic intrusives. The rock could be highly fractured and therefore losses are expected in this zone. Minor syenitic intrusives are also expected in the zone.

2000-2300 m - Trachyte, syenite and glass: This zone consists mainly of trachyte. Syenitic intrusives may be encountered. The formation here is compact and expected to be medium-hard to hard. Minor or partial losses are expected at fracture zones. If the syenite layer is greater than 20 m then drilling should stop as this layer is not permeable and chances of encountering magma are high. Most importantly, glass may be encountered in this zone and it is advisable to stop drilling once this formation is encountered.

2. CEMENTING MATERIALS

2.1 Classification of well cements

Well cements are required to conform to API specification 10, which divides them into eight classes according to the basic manufacturing process for each class, and the application conditions to which it is suited. The eight classes can be summarised as follows (Rabia, 2001; Nelson and Guillot, 2006):

Class A: Intended for use from the surface to a depth of 1,830 m when no special properties are required. It is only available in ordinary sulphate resistance grade.

Class B: Intended for use from surface to 1,830 m when moderate to high sulphate resistance is required. It is available in both moderate sulphate resistance (MSR) and high sulphate resistance (HSR) grades.

Class C: Intended for use from surface to 1,830 m when early strength development is required. It is available in ordinary, MSR and HSR grades.

Class D: Intended for use from 1,830 m to 3,050 m under conditions of moderately high temperatures and pressures. It is available in both MSR and HSR types and is inherently retarded.

Class E: It is intended for use from 3,050 m to 4,270 m under conditions of high temperatures and pressures. It is inherently retarded, and is available in both MSR and HSR grades.

Class F: Intended for use from 3,050 m to 4,880 m under conditions of extremely high temperatures and pressures. It is inherently retarded and is available in both MSR and HSR grades.

Class G and class H: Intended for use as basic well cements as manufactured, or with the addition of retarders and accelerators to cover a wide range of depths and temperatures. They were developed in response to improved technology in slurry acceleration and retardation by chemical means.

2.2 Cement additives

Cement systems employed for well cementing need to endure a wide range of varied conditions, e.g. severe temperatures and pressures, weak or porous formations, corrosive fluids and over-pressured formation fluids. Cement additives are used to modify the behaviour of cement systems to suit these varied conditions i.e. to allow successful placement between the casing and formation, rapid compressive strength development and to provide adequate zonal isolation during the lifetime of the well (Nelson and Guillot, 2006).

According to Nelson and Guillot (2006), cement additives may be classified under eight main categories depending on the slurry property being modified, as follows:

Accelerators: These are chemicals added to cement slurries to shorten the setting time of the cement and/or increase the rate of compressive strength development. Many inorganic salts are accelerators of Portland cement, but chloride salts are the most frequently used. Of these, calcium chloride is the most efficient and economical of all accelerators. It is normally added at concentrations between 2% to 4% by weight of cement (BWOC).

Retarders: These are chemicals that delay the setting time of a cement system, allowing ample time for cement placement while the cement remains in a pumpable state. Lignosulfonate retarders are most commonly used, applied in concentrations ranging from 0.1% to 1.5% BWOC. Others available include sugar, hydroxycarbocylic acid, inorganic compounds and cellulose.

Extenders: These are materials which lower the density of a cement system, increase the yield of the cement, or both. By lowering slurry density they reduce the hydrostatic pressure, thus helping to prevent a breakdown of weak formations and subsequent loss of circulation. Increase in slurry yield leads to better cement economy. Clay extenders like bentonite are the most commonly used in geothermal cementing. Other types include water, sodium silicate, gilsonite, expanded perlite, ceramic microspheres and nitrogen gas.

Weighting agents: These are materials that increase the density of a cement system, thereby increasing the hydrostatic pressure to help counter formation pressure or support weak formations. The most commonly used weighting agents for cement slurries are ilmenite, hematite, barite and manganese tetraoxide.

Dispersants: These are chemicals that reduce the viscosity of a cement slurry, thereby giving a cement system the correct rheological properties for placement in long, narrow annuli. Rabia (2001) describes their mode of action like this: They are mostly solutions of negatively charged polymer molecules that attach themselves to the positively charged sites of the hydrating cement grains. The result is an increased negative on the hydrating cement grains resulting in greater repulsive forces and particle dispersion.

Fluid loss control agents: They are materials that control excessive leakage of the aqueous phase of a cement system to the formation, thereby dehydrating the slurry. Excessive loss of fluid to the formation can affect the setting of the cement. They are mostly made from polymers.

Lost-circulation control agents: These are materials that control the loss of cement slurry to weak or vugular formations.

Specialty additives: Miscellaneous additives, such as antifoam agents, fibres and flexible particles.

FIGURE 2: Vane type sample mixer used by GDC

2.3 Cement slurry properties

Cement slurries are designed with different key properties in mind to meet various application requirements. Test procedures and equipment for testing of well cements are prescribed in API RP 10B. Cement slurry samples for testing are mixed in a vane type mixer like the one shown in Figure 2, whose specifications are defined in API RP 10B.

Density: It is important to use the right slurry density to maintain well control, avoid fracturing weak formations as well as the collapse of the casing during cement placement. Density can be modified with additives, e.g. extenders like bentonite to make it lighter, or weighting agents like barite to make it heavier. Other ways to modify density include the use of hollow glass microspheres or foamed cements. It is measured using a mud balance. In general, the cement density should be a minimum of 0.2 kg/l (1.0 ppg) heavier than the drilling fluid density in the hole at the time of cementing (Ng'ang'a, 2014; Bush and O'Donnel, 2007).

Fluid loss: A pressure differential between the cement and the formation leads to filtration. During and immediately after placement, the aqueous phase of the slurry escapes into the formation, leaving the

FIGURE 3: Fluid loss cell (Fann, 2014)

solids behind. This will affect the setting time, set strength and lead to channelling. An excessive increase in slurry viscosity during placement could also lead to primary cementing failure. A general recommendation for maximum API fluid loss is 100 cc/30 min for casings (Devereux, 1998). Fluid loss control agents are used to control excessive loss of the aqueous phase from cement slurries into the formation. The slurry is conditioned at simulated wellbore conditions and subjected to 1000 psi (6.9 MPa) differential pressure in a standardized heated filter press (Figure 3) for 30 minutes. The filtrate loss is measured across a standard filtration medium (325-mesh) screen supported on a 60-mesh screen. The filtration area is 3.5 in^2. The reported API fluid loss value is the volume of filtrate after 30 minutes multiplied by two (API, 1997).

Free water: This is any water used in excess of that required to completely hydrate the cement and additives. If a slurry is allowed to stand for a period of time before setting, such water will separate from the slurry, migrate upwards and accumulate in pockets or settle at the top of the cement column. In a deviated well this can cause channelling, while during backfill jobs for geothermal wells the water may be trapped between casings and lead to a casing collapse when the well heats up. The slurry is conditioned in an atmospheric consistometer as shown in Figure 4 and transferred to a 250 ml graduated cylinder. It is left to sit static for two hours and any supernatant fluid on top of the slurry is decanted and its volume measured.

FIGURE 4: Atmospheric consistometer used by GDC

The free water is reported as a percentage of the 250 ml test sample volume. In general, the free water should be less than 0.5%, less than that in high angle wells (>45°) and zero in horizontal wells or against gas zones (Devereux, 1998).

Thickening time: This is the length of time a cement slurry remains in a pumpable, fluid state under simulated wellbore conditions of temperature and pressure. It is measured in a pressurized consistometer and recorded in Bearden units (Bc), which is a dimensionless quantity. While the test measures the time to reach 100 Bc, it is generally accepted that the limit of pumpability is reached at 70 Bc (Devereux, 1999). The elapsed time to reach 40 Bc is also measured. The difference between the 100 and 40 Bc times, known as the transition time, is used as an indication of the rate at which slurry changes from a pumpable to unpumpable condition (Ng'ang'a, 2014; Bush and O'Donnel, 2007).

Compressive strength: Compressive strength testing is important since it shows whether the cement can support the casing and subsequent drilling and completion operations. It can be done by either destructive or non-destructive methods. In the destructive method, 2" cement cubes are cast in a standardized mould and subjected to an uniaxial compressive force until failure. This method is used to determine the set strength of the cement. The non-destructive technique uses an ultrasonic cement analyser to measure the real time compressive strength development of the cement sample. Cement strength is determined by measuring the change in velocity of an ultrasonic signal transmitted through the sample as it hardens. As the strength of the cement increases, the ultrasonic signal's transit time through the sample decreases (Chandler Engineering, 2008). This method is particularly helpful in determining when to resume drilling or completion activities after cement placement. For instance, 500 psi (3.5 MPa) is considered adequate compressive strength to support the casing, while 2000 psi is considered the minimum for cement that will be perforated (Devereux, 1999).

Rheology: Nelson and Guillot (2006) describe rheology thus: The science that attempts to determine the intrinsic fluid properties, mainly viscosity, necessary to determine the relationships between the flow rate (shear rate) element and the pressure gradient (shear stress) element that causes fluid movement. For a successful primary cementing job the cementing engineer must first understand the rheological properties of the cement and characterize them properly in order to: Evaluate how practical it will be to mix and pump, optimize mud removal and slurry placement, predict the friction pressures expected during pumping and how the wellbore temperature profile will affect slurry placement. Rheological measurements are done using a coaxial cylinder viscometer after conditioning the slurry for 20 minutes in an atmospheric consistometer. The test fluid is sheared between an outer sleeve, the rotor, and an inner cylinder called the bob. The shear force exerted on the fluid by the sleeve is, in turn, imparted as torque on the bob. The bob is attached to a torsion spring that deflects as torque is applied by the fluid. The sleeve rotates at different pre-selected speeds. Figure 5 shows an illustration of a coaxial cylinder viscometer.

The most commonly used instrument has speeds of 3 rpm, 6 rpm, 100 rpm, 200 rpm, 300 rpm and 600 rpm. However, experience has shown that, for reproducibility of results between different instruments, the tests should not be done at speeds higher than 300 rpm (Nelson and Guillot, 2006).

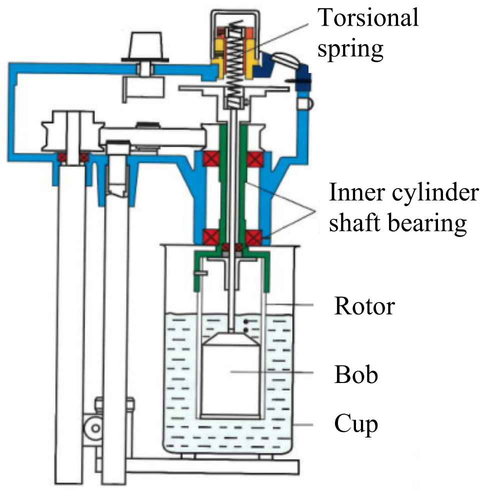

FIGURE 5: Coaxial cylinder viscometer (Nelson and Guillot, 2006)

3. WELL DESIGN AND CEMENTING

3.1 Well design for Menengai

The design for Menengai wells is a regular bore well comprising a 30" conductor casing, 20" surface casing, 13-3/8" anchor casing, 9-5/8" production casing and 7" slotted liners. All the casing strings except the slotted liners are run and cemented back to the surface. The slotted liners usually terminate about two joints above the production casing shoe. Figure 6 shows an illustration of the casing strings for a vertical well in Menengai, with typical casing setting depth ranges.

3.2 Casing cementing techniques

Three different techniques can be utilized for the primary cementing process (Hole, 2008a): 'Through casing' cementing, inner string cementing and reverse circulation cementing.

'**Through the casing' cementing**: In this method, obtained well data is used to determine the total volume of slurry required to completely fill the annulus back to the surface. This volume of cement is then pumped through the casing via a cementing head connected to the top of the casing and displaced into the annulus. Travelling plugs are used to separate the cement slurry from the fluid in the casing, and from the displacement fluid. The major disadvantage of this method is that usually the volume of the casing content exceeds the annulus volume, and therefore a fixed slurry volume is mixed and pumped, the top plug is released and displacement commenced before any cement has reached the annulus.

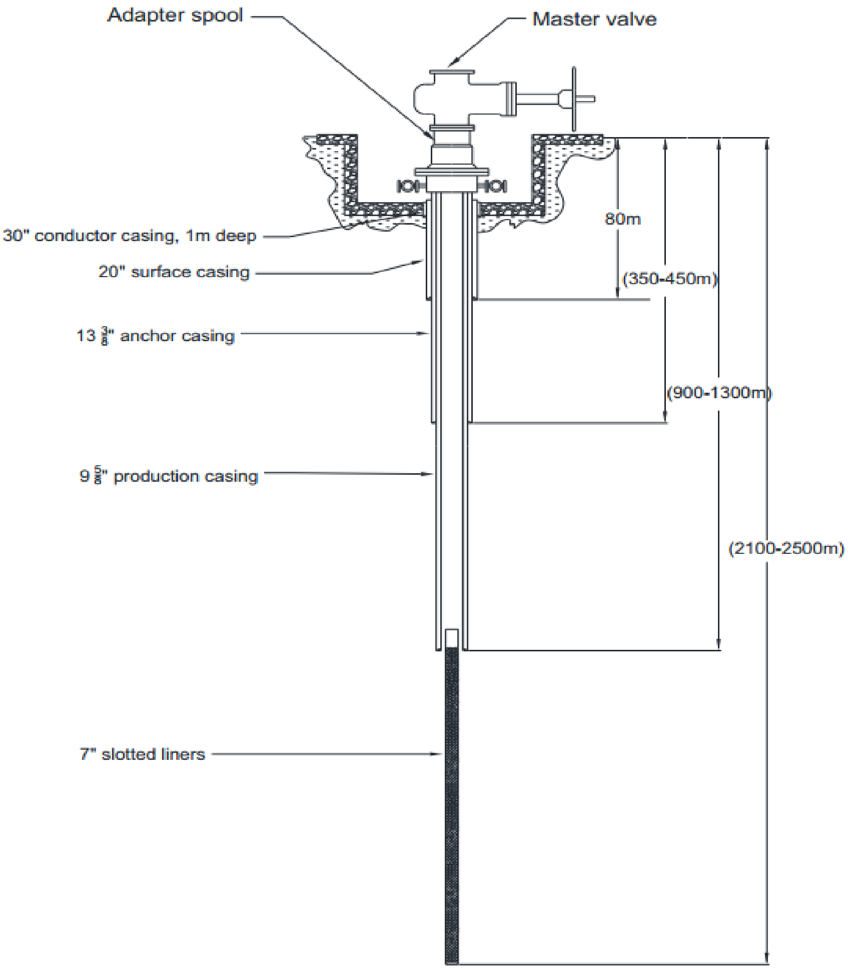

FIGURE 6: Well design for Menengai geothermal wells

This type of cementing can be carried out in one of two different ways i.e. either single-stage or multi-stage primary cementing. The single-stage cementing method, illustrated in Figure 7, is applied on geothermal wells in Menengai area, followed by backfill jobs through the annulus.

Inner string cementing: In this method a cementing string is run inside the casing and stabbed into a receptacle in the float collar. Cement slurry is pumped through the cementing string, through the shoe track (the length of casing below the float collar) into the annulus directly. This method allows cement to be mixed and pumped until good cement returns are received on the surface since it does not require a pre-determined volume to be pumped. Besides, the volume of the cementing string is small relative to the total annulus volume, therefore cement waste is not a big concern. Cement placement and displacement time, as well as the displacement pressure are also reduced. The method is best suited to shallower sections, e.g. surface and intermediate casing strings. For deeper sections, the time it would require to pick up and run the cementing string while the casing is set on the rotary table increases risk of well kicks or hole pack-offs.

Reverse circulation cementing: In this method cement slurry is pumped directly into the annulus, with the displaced fluid being forced back through the casing shoe and the casing to the surface. This method aims at reducing the bottom hole pressure to lower the risk of cement slurry loss during cementing and eliminating the need for top jobs in order to complete the cementing process. It is, however, rarely used because in the event of loss of circulation there are no positive means of ensuring a cemented casing shoe (Hole, 2008a).

3.3 Analysis of backfills done in Menengai

Analysis was carried out on past cementing of the existing productive wells in Menengai, Kenya. This analysis focused on the cementing of the production casings to assess the risk of having trapped water within the casing-to-casing annulus. This is the annular space between the 9-5/8” and 13-3/8” casings, as shown in Figure 8. A substantial amount of water trapped here during cementing is more likely to cause casing damage than, say, water trapped between the 20” and 13-3/8” casings. This is because the 13-3/8” casing is eventually cemented on both sides.

3.3.1 Backfill volume

The volume of a backfill job is important for two reasons. Firstly, if it takes less slurry than the total volume of the casing-to-casing annulus to fill up, it implies that the cement level was already within the casing-to-casing annulus (hence a probable zone of water inclusion is created). Secondly, if a volume less than the casing-to-casing annulus volume is pumped with no returns received, there is a possibility of creating more than one water entrapment point, if the cement level was already within the casing-to-casing annulus. If the backfilling progresses in small batches, each smaller than the total casing-to-casing annulus volume, several water entrapment points are likely to be created.

The volume analysis considers the size of the last two backfills prior to fill-up vis-à-vis the total casing-to-casing annular volume. This would reveal whether any zone(s) of possible water entrapment were introduced. The analysis is as shown in Table 2 (GDC, 2017).

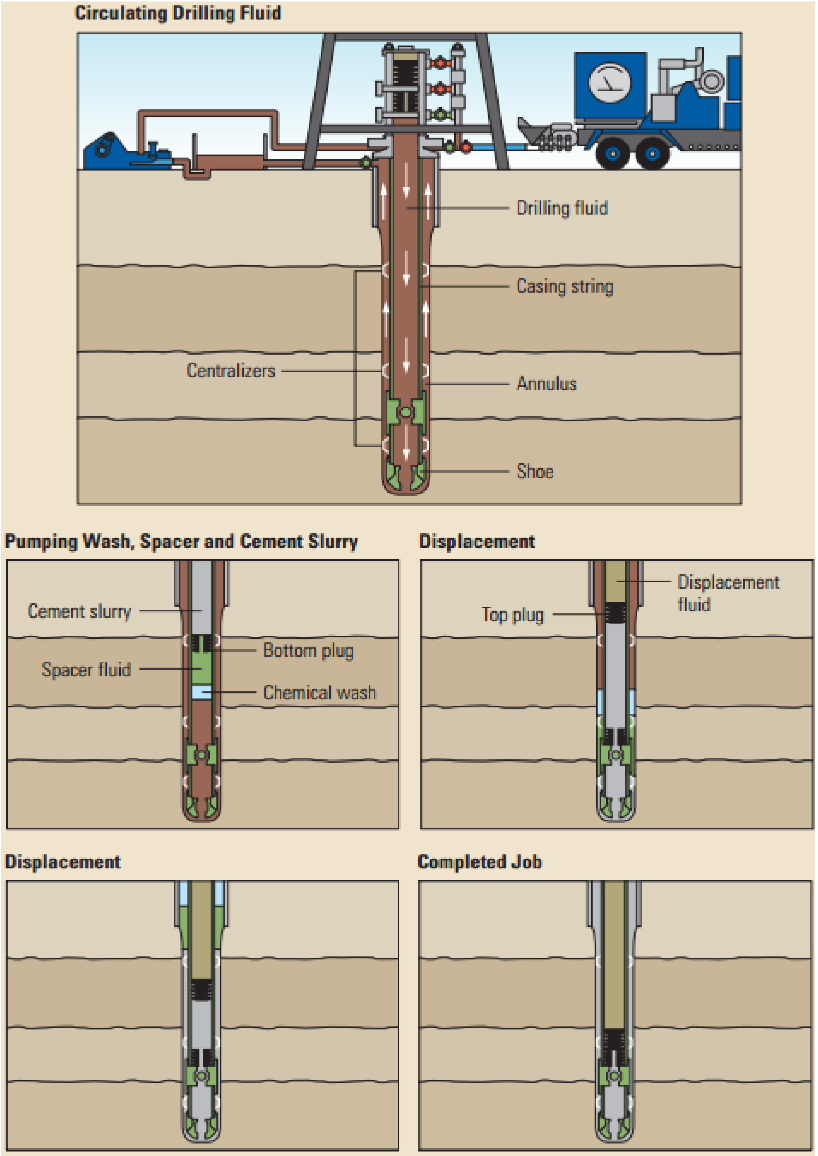

FIGURE 7: Single stage cementing process (Nelson, 2012)

3.3.2 Water/cement ratio

As mentioned in Chapter 1, one possible source of water trapped in the annular space is the free water from the cement slurry. For a particular cement, the amount of free water generated in the slurry is directly related to the water/cement ratio. In the absence of lightweight additives or weighting agents, the slurry density is also directly dependent on the water/cement ratio. Therefore, as shown in Table 2, slurry density was used in the analysis since only neat cement is used for backfill jobs in Menengai wells. Detailed analysis of the effect of water/cement ratio on free water is included in Chapter 5.

4. RHEOLOGICAL MODELS

4.1 Types of flow

Under steady-state conditions, fluids flow in either laminar or turbulent flow. The situation where the flow is no longer completely laminar up to when it is completely turbulent is called transition flow.

4.1.1 Laminar flow

In this type of flow, individual particles of a fluid flowing in a pipe move forward in straight lines parallel to the pipe axis. The velocity of fluid particles across the pipe varies according to their proximity to the pipe walls. Fluid particles in contact with the pipe wall will be at rest, whereas those at the centre of the channel will be moving at the greatest speed (Figure 9). The shape of the velocity profile varies from fluid to fluid depending on the rheological behaviour.

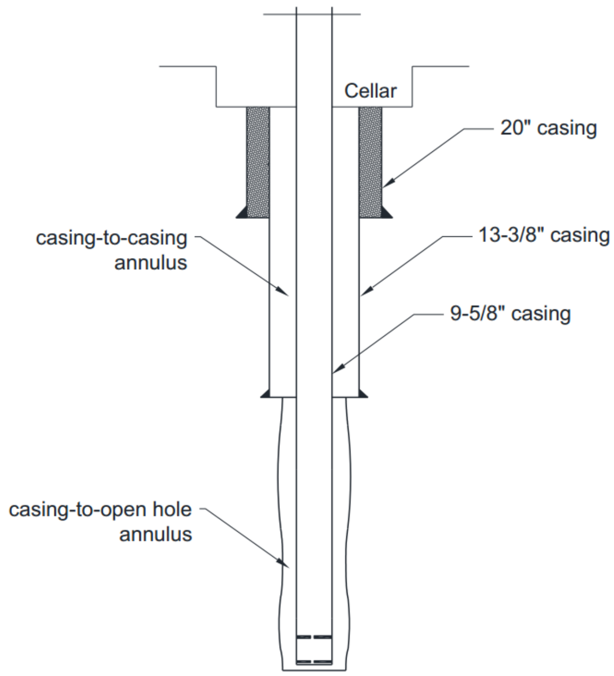

FIGURE 8: Production casing cementing

Fluids flowing at low flow rates exhibit laminar flow.

TABLE 2: Backfill slurry volumes and densities for 9-5/8" production casing cementing

Well no.	Total no. of backfills	Casing-casing annulus volume (m^3)	Vol. of 2nd last backfill (m^3)	Vol. of last backfill (m^3)	Possible water trap zones	ASW[1] in casing-casing annulus (g/cm^3)
MW-01	3	13.4	10.0	7.7	1	1.66
MW-03	4	13.6	10.0	0.4	1	1.65
MW-06	4	13.8	7.5	0.5	1	1.70
MW-07	0	12.0	-	-	0	1.75
MW-09	1	11.8	-	5.0	1	1.80
MW-10A	6	12.7	16.0	13.4	0	1.80
MW-21	5	11.4	23.0	1.0	1	1.80
MW-09A	2	12.7	24.0	10.0	1	1.85
MW-01A	5	13.5	20.0	16.0	0	1.85
MW-20A	3	11.8	20.4	4.3	0	1.80
MW-19A	3	12.3	20.0	8.0	1	1.75
MW-21A	3	12.3	20.5	30.0	0	1.80
MW-17A	4	11.9	14.0	3.0	1	1.80
MW-18A	2	13.7	1.0	1.0	2	1.80
MW-09B	2	11.5	13.0	9.2	1	1.85
MW-13B	3	12.2	10.8	11.0	1	1.80
MW-10B	3	12.0	20.0	15.0	0	1.80
MW-09C	4	10.3	22.8	4.0	1	1.80
MW-12	2	11.1	21.7	17.1	0	1.76
MW-13	2	12.2	22.0	5.6	1	1.72
MW-17*	3	13.6	12.0	12.0	1	1.86
MW-19	2	13.3	20.0	16.1	0	1.82

1: ASW- Average Slurry Weight

4.1.2 Turbulent flow

In this type of flow the fluid particles have velocity components that are not parallel to the pipe wall. Rather than the orderly sliding motion of fluid particles in laminar flow, the particles swirl within the pipe in a rolling motion. The speed of flow increases rapidly away from the pipe walls and becomes fairly constant throughout the main part of the fluid.

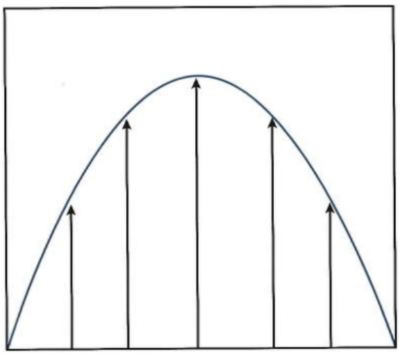

FIGURE 9: Laminar flow (Nelson and Guillot, 2006)

4.2 Viscosity

Viscosity is the measure of a fluid's internal resistance to flow. It is expressed as the ratio of the shear stress, τ, to the shear rate, $\dot{\gamma}$ as shown in Equation 1.

$$\mu = \frac{\tau}{\dot{\gamma}} \qquad (1)$$

The viscosity of a fluid governs the relationship between the friction pressure gradient and the flow rate. A certain pressure (shear stress) is required to make a fluid flow at a certain shear rate. It is therefore necessary to know the viscosity of the fluid in order to be able to calculate the friction pressure drop during pumping, especially for primary cementing jobs. Viscosity usually depends on temperature and pressure but for most fluids used in drilling and cementing it also depends on the shear rate.

4.3 Rheological models

The relationship between shear stress and shear rate in steady laminar flow defines Newtonian and non-Newtonian fluids.

4.3.1 Newtonian fluids

In Newtonian fluids the shear stress, τ, is directly proportional to the shear rate, $\dot{\gamma}$. The relationship is defined by Equation 2 and illustrated in Figure 10.

$$\tau = \mu\dot{\gamma} \qquad (2)$$

The slope of the line represents the viscosity, μ, of the fluid which is a constant that only depends on temperature and pressure. These fluids contain particles no larger than a molecule (Devereux, 1999).

4.3.2 Non-Newtonian fluids

This term covers any fluid whose behaviour deviates from the Newtonian model. In addition to being temperature and pressure dependent, the fluid viscosities can either decrease with shear rate (shear thinning) or increase with shear rate (shear thickening). Three mathematical models are commonly used in the well cementing industry to describe the behaviour of such fluids (Nelson and Guillot, 2006).

- Bingham plastic model;
- Power-law model; and
- Herschel-Bulkley model.

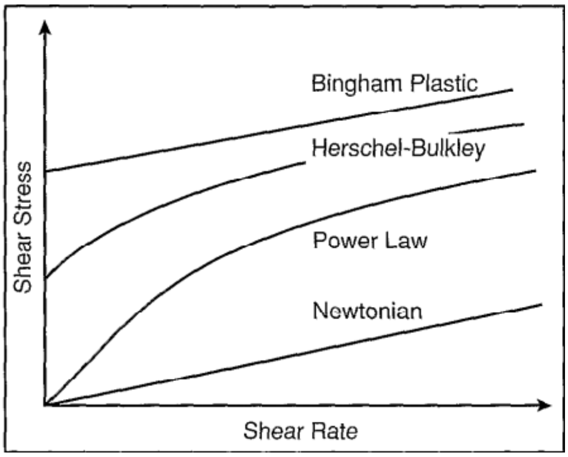

FIGURE 10: Rheological models (Nelson, 1990)

Bingham plastic fluid: Like for Newtonian fluids, the relationship between shear stress and shear rate is linear for Bingham plastic fluids. However, Bingham plastic fluids remain unsheared until the applied stress reaches a minimum value, called the yield stress of the fluid. They are defined by two parameters:

The value of τ for $\dot{\gamma} = 0$, τ_o.
The slope of the straight line, μ_p.

where μ_p is constant and is the plastic viscosity of the fluid, and τ_o is the Bingham yield stress of the fluid. Bingham fluids behave in a manner described by Equations 3 and 4:

$$\tau = \tau_o + \mu_p \dot{\gamma} \qquad \text{when } \tau > \tau_o \tag{3}$$

$$\dot{\gamma} = 0 \quad \text{when } \tau \leq \tau_o$$

or

$$\mu = \mu_p + \frac{\tau_o}{\dot{\gamma}} \tag{4}$$

Bingham plastic fluids require a minimum pressure gradient to initiate flow.

Power-law fluids: They are part of a class known as pseudo-plastic fluids. Like Newtonian fluids, they flow immediately when a pressure gradient is applied. However, for these fluids the relationship between shear rate and shear stress is not linear, as shown in Figure 10.

Power law fluids are described by Equation 5:

$$\tau = k\dot{\gamma}^n \tag{5}$$

where k = Consistency index; and
n = Power-law index. This indicates how much the fluid deviates from Newtonian behaviour.

Herschel-Bulkley fluids: These combine power-law and Bingham plastic behaviours. For flow to commence, the minimum yield stress must be exceeded. Above the yield stress, as with power-law fluids, the shear rate/shear stress relationship follows the power law. Equations 6 and 7 describe Herschel-Bulkley fluids.

$$\tau = \tau_o + k\dot{\gamma}^n \quad \text{when } \tau > \tau_o \tag{6}$$

$$\mu = \frac{\tau_o + k\dot{\gamma}^n}{\dot{\gamma}} \tag{7}$$

The four rheological models described are illustrated by Figure 10.

5. CEMENT SLURRY TEST RESULTS AND ANALYSIS

Cement slurry properties influence the amount of free water generated by the cement as it hydrates, which could be trapped in the annulus. Besides free water, the strength properties of set cement, as well as the ease of mixing and pumping, also largely depend on slurry properties. Tests carried out in Iceland on well cement slurries have shown that (Wallevik et al., 2007):

- Low water-cement ratios produce slurries with faster, early strength development, thus reducing the ‘wait on cement’ time.
- A reduction of the water-cement ratio will also reduce shrinkage and cracking in the set cement.

- Low water-cement ratios give a higher final strength in the set cement.

The rheological properties of plastic viscosity and yield stress are also important because they directly affect the ease of mixing and pumping the slurry.

It is important to determine the fluid loss properties of the slurry used for backfill jobs. Although this is not a cause for concern in the casing-to-casing annulus, it is a critical consideration in the casing-to-open hole annulus. As mentioned in Chapter 2, if the slurry is placed across a permeable formation, loss of filtrate into the formation will dehydrate it. This will affect the setting time, final compressive strength and could lead to channelling.

A suitable slurry for backfilling must therefore strike a good balance of the desirable properties.

Various tests were done to evaluate the suitability of the backfill slurries used so far and improvements were proposed.

5.1 Effect of water/cement ratio and 2% BWOC gel

All materials used in the investigation were those currently used for cementing in the Menengai field as follows:

- Bamburi POWERMAX 42.5 ordinary Portland cement manufactured in Kenya. It is a close approximation of the API class A cement, and is subsequently referred to as such in this report.
- USZ friction reducer (manufactured in China).
- Cementing bentonite (manufactured in China), also referred to as 'gel' in this report.
- G33S friction reducer (manufactured in China).
- Mix water from the rig.

5.1.1 Free water

Laboratory tests were carried out in the GDC cement laboratory to investigate free water properties at different water/cement ratios. The tests were carried out in conformity with the guidelines of API RP 10B (API, 1997), using cement and mix water normally used during cementing. Slurry densities between 1.50 g/cm^3 and 1.85 g/cm^3 were tested under the following conditions:

- Conditioning time: 30 minutes in an atmospheric consistometer.
- Conditioning temperature: 60°C.
- Test duration: 2 hours.
- Test angle: 0°.
- Measuring cylinder: 250 ml x 2 ml divisions.

The results indicated that at higher water/cement ratios (lower density), slurries yielded more free water. From Table 3 it can be seen that only cement slurries with specific gravity of 1.78 g/cm^3 (water/cement ratio < 0.56) and higher met the maximum free water threshold of 0.5%. Neat slurries below this density generated more free water, which could be trapped between casings and lead to well failure.

However, the use of a high-density slurry for backfilling is also likely to aggravate cement losses by breaking down weak formations even further. It is therefore imperative to explore means of lowering the slurry density, while at the same time reducing the excess free water which could segregate at such high water/cement ratios. In this work, bentonite was used as an extender to reduce the free water. The bentonite was pre-hydrated in the mix water. Table 4 shows the effect of bentonite on the free water in Bamburi POWERMAX 42.5 cement for the same density range.

TABLE 3: Volume of free water with class A cement

Slurry specific gravity (g/cm³)	Cement quantity (g)	Mix water quantity (g)	Water/cement ratio	Volume of free water in 250 ml of slurry after 2 hrs (ml)	Percentage free fluid (%)
1.50	438.10	460.40	1.05	75	30.0
1.55	480.23	447.03	0.93	61	24.4
1.60	527.62	431.98	0.82	34	13.6
1.65	569.74	418.61	0.73	16	6.4
1.70	611.87	405.24	0.66	6.0	2.4
1.72	632.93	398.55	0.63	3.1	1.2
1.75	659.26	390.19	0.59	2.2	0.9
1.78	685.58	381.83	0.56	1.2	0.5
1.80	701.38	376.82	0.54	0.5	0.2
1.85	721.01	366.64	0.51	0.0	0.0

TABLE 4: Volume of free water with class A cement and 2% BWOC bentonite (pre-hydrated)

Slurry specific gravity (g/cm³)	Cement quantity (g)	Bentonite - 2% BWOC (g)	Mix water quantity (g)	Water/cement ratio	Free water in 250 ml of slurry after 2 hrs (ml)	Percentage free fluid (%)
1.50	430.25	8.61	459.64	1.07	17.0	6.8
1.55	471.62	9.43	446.20	0.95	12.0	4.8
1.60	518.16	10.36	431.07	0.83	8.0	3.2
1.65	559.53	11.19	417.63	0.75	3.2	1.3
1.70	600.60	12.02	404.18	0.67	1.4	0.6
1.72	621.59	12.43	397.46	0.64	0.6	0.2
1.75	647.44	12.95	389.06	0.60	0.1	0.04
1.78	673.30	13.47	380.65	0.56	0.0	0.0
1.80	688.81	13.78	376.61	0.55	0.0	0.0
1.85	706.05	14.12	366.35	0.52	0.0	0.0

Considering that the maximum free water content should be 0.5% or less (Devereux, 1998), it is clear from Table 4 that the addition of 2% gel to the cement slurry, pre-hydrated in the mix water, would allow the use of a slurry with a lower density of 1.72 g/cm³ (0.2% free water) as opposed to the heavier 1.78 g/cm³ neat slurry (0.5% free water).

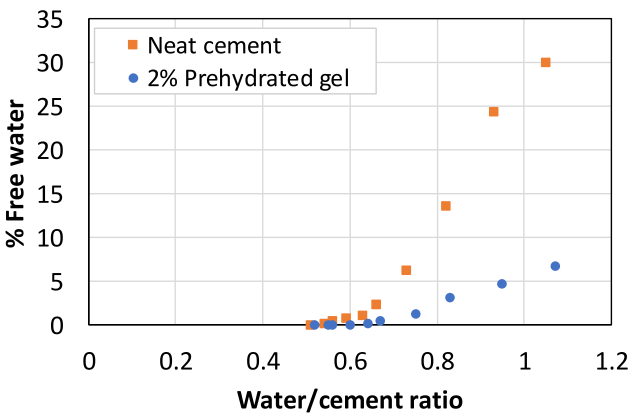

FIGURE 11: Effect of water/cement ratio on the free water in class A cement (neat) and class A cement with 2% bentonite

Figure 11 shows the effect of the water/cement ratio and 2% BWOC gel on free water segregating in the slurry. It is evident that generally, lowering the water/cement ratio reduces the free water content. Moreover, the addition of 2% BWOC gel reduces free water as well. The rate of increase of free water with an increase of water/cement ratio was significantly lower in the slurry with bentonite.

5.1.2 Rheology

Rheology measurements were performed on the slurries presented in Section 5.1.1 to establish the effect of 2% bentonite. Tables 5 and 6 show the rheological properties for neat and blended cements respectively, over the same density range. These tests were carried out according to guidelines in API RP 10B (API, 1997), using a standard coaxial cylinder viscometer.

TABLE 5: Rheological properties of neat class A cement

Specific gravity (g/cm^3)	Average value of ramp-up and ramp-down viscometer readings at each spindle speed				
	300 rpm	**200 rpm**	**100 rpm**	**6 rpm**	**3 rpm**
1.50	9.0	7.5	5.0	3.5	2.0
1.55	11.5	9.0	7.5	5.0	3.5
1.60	19.0	16.5	14.5	9.5	8.0
1.65	24.5	20.5	17.0	11.5	9.0
1.70	30.5	27.0	23.5	15.0	10.5
1.72	48.5	43.5	39.0	17.5	13.5
1.75	63.0	54.5	49.5	21.0	15.0
1.78	76.5	65.0	56.5	23.5	19.5
1.80	84.5	77.5	71.0	28.0	22.5
1.85	93.0	85.5	78.5	31.5	25.0

TABLE 6: Rheological properties of class A cement with 2% BWOC gel

Specific gravity (g/cm^3)	Average value of ramp-up and ramp-down viscometer readings at each spindle speed				
	300 rpm	**200 rpm**	**100 rpm**	**6 rpm**	**3 rpm**
1.50					
1.55					
1.60	27.5	23.5	21.0	12.5	8.5
1.65	46.0	40.5	34.5	17.0	12.0
1.70	64.0	60.0	56.0	22.0	16.5
1.72	118.5	112.0	106.5	38.0	25.5
1.75*	138.5	132.0	125.0	56.5	49.0
1.78*	170.5	164.0	150.5	83.5	75.5
1.80*					
1.85*					

*slurry gelled up during conditioning, unable to run test and/or test results are not accurate

From Table 6 it can be seen that the addition of 2% bentonite to the slurry made it impossible to test for rheology at 1.80 g/cm^3. This is because the slurry became too thick and gelled during conditioning. It implies that, beyond this density, it would present challenges when mixing and pumping.

When using the standard API coaxial cylinder viscometer, the nominal shear rate and shear stress of the cement slurry can be calculated from the instrument's raw data using Equations 8 and 9 (Nelson and Guillot, 2006).

$$\dot{\gamma} = 1.705 \times \Omega \tag{8}$$

and

$$\tau = 0.5109 \times \theta \tag{9}$$

where $\dot{\gamma}$ = Nominal shear rate (1/s);
Ω = Viscometer speed (rpm);
τ = Shear stress (Pa); and
θ = Viscometer reading (instrument degrees).

Using Equations 8 and 9, the shear stress and shear rate values obtained from the raw data are as given in Tables 7 and 8.

TABLE 7: Shear rate and shear stress for neat class A cement

Specific gravity (g/cm³)	**Shear rate $\dot{\gamma}$ (1/s) and shear stress τ (Pa)**									
	300 rpm		**200 rpm**		**100 rpm**		**6 rpm**		**3 rpm**	
	$\dot{\gamma}$	τ	$\dot{\gamma}$	τ	$\dot{\gamma}$	τ	$\dot{\gamma}$	τ	$\dot{\gamma}$	τ
1.50	511.5	4.6	341.0	3.8	170.5	2.5	10.2	1.8	5.1	1.0
1.55	511.5	5.9	341.0	4.5	170.5	3.8	10.2	2.5	5.1	1.8
1.60	511.5	9.7	341.0	8.4	170.5	7.4	10.2	4.8	5.1	4.1
1.65	511.5	12.5	341.0	10.5	170.5	8.7	10.2	5.7	5.1	4.6
1.70	511.5	15.6	341.0	13.8	170.5	12.0	10.2	7.7	5.1	5.4
1.72	511.5	24.8	341.0	22.2	170.5	19.9	10.2	8.9	5.1	6.9
1.75	511.5	32.2	341.0	27.8	170.5	25.3	10.2	10.7	5.1	7.7
1.78	511.5	39.1	341.0	33.2	170.5	28.9	10.2	12.0	5.1	9.9
1.80	511.5	43.2	341.0	39.6	170.5	36.3	10.2	14.3	5.1	11.5
1.85	511.5	47.5	341.0	43.7	170.5	40.1	10.2	16.1	5.1	12.8

TABLE 8: Shear rate and shear stress for blended class A cement (2% BWOC gel)

Specific gravity (g/cm³)	**Shear rate $\dot{\gamma}$ (1/s) and shear stress τ (Pa)**									
	300 rpm		**200 rpm**		**100 rpm**		**6 rpm**		**3 rpm**	
	$\dot{\gamma}$	τ	$\dot{\gamma}$	τ	$\dot{\gamma}$	τ	$\dot{\gamma}$	τ	$\dot{\gamma}$	τ
1.50	511.5	14.0	341.0	12.0	170.5	10.7	10.2	6.4	5.1	4.3
1.55	511.5	23.5	341.0	32.8	170.5	17.6	10.2	8.7	5.1	6.1
1.60	511.5	32.7	341.0	30.6	170.5	28.6	10.2	11.2	5.1	8.4
1.65	511.5	60.5	341.0	57.2	170.5	54.4	10.2	19.4	5.1	13.0
1.70	511.5	70.7	341.0	67.4	170.5	63.9	10.2	28.9	5.1	25.0
1.72	511.5	87.1	341.0	83.8	170.5	76.9	10.2	42.7	5.1	38.6
1.75*										

*Slurry gelled during conditioning

If a Bingham plastic model is assumed for the slurry, the plastic viscosity (μ_p) and yield point (τ_0) for any selected slurry density can be approximated by Equations 10, 11 and 12 (API, 1997).

$$\mu_p = 1.5 \times F \times (\theta_{300} - \theta_{100)}) \tag{10}$$

where μ_p = Plastic viscosity of the slurry in centipoise (cp);
θ_{300} = Instrument reading at 300 rpm;
θ_{100} = Instrument reading at 100 rpm; and
F = Torsion spring factor for the instrument (taken as *F*=1 for the instrument used).

or

$$\mu_p = 0.0015 \times F \times (\theta_{300} - \theta_{100)}) \tag{11}$$

where μ_p = plastic viscosity in Pascal-seconds (Pa·s).

and

$$\tau_0 = 0.4788 \times [(F \times \theta_{300}) - (1000 \times \mu_p)] \tag{12}$$

where τ_0 = Yield point shear stress of the slurry (Pa); and
μ_p = Plastic viscosity (Pa·s)

Using Equations 10, 11 and 12, the calculated plastic viscosity and yield stress values for the slurries are given in Appendix I, Tables 1 and 2.

Figures 12 and 13 show the effects of both the water/cement ratio and 2% BWOC gel on the plastic viscosity and yield stress values of the slurry. It is evident that lowering the water/cement ratio increases both the yield stress and the viscosity. Similarly, the addition of 2% BWOC bentonite increases both the yield stress and the plastic viscosity of the slurry.

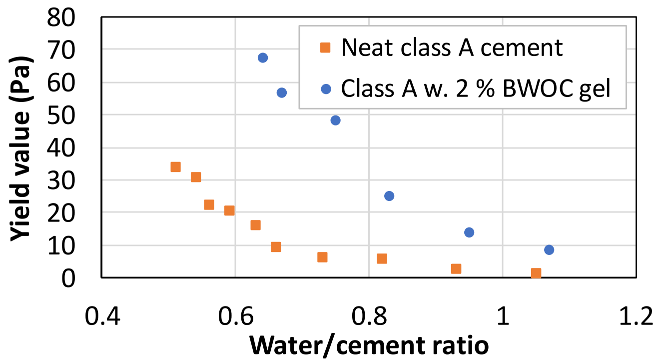

FIGURE 12: Effect of water/cement ratio on yield stress in class A cement (neat) and class A cement with 2% bentonite

5.1.3 Static fluid loss

Fluid loss values for the two cement mixes at 80°C in an API standard static fluid loss cell are shown in Appendix I, Table 3. It is clear that although the addition of 2% gel reduces fluid loss roughly by half for each density, the values still remain higher than the API recommended limit of 100 ml/30 min. As such, neither of the two slurry mixes showed satisfactory fluid loss properties. Rather, both slurries exhibited excessive fluid loss rates, with nitrogen blowing through all the samples within the first 5 minutes of the normal 30 min test duration.

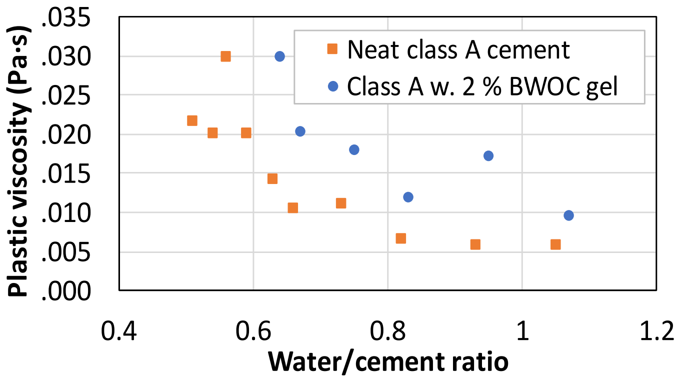

FIGURE 13: Effect of water/cement ratio on plastic viscosity in class A cement (neat) and class A cement with 2% bentonite

In such a scenario, the calculated (as opposed to measured) API fluid loss is given by Equation 13 (Nelson and Guillot, 2006).

$$(q_{API}) = 2V_t\left(\frac{5.477}{\sqrt{t}}\right) \tag{13}$$

where V_t = Volume of filtrate (ml) collected at time t (min).

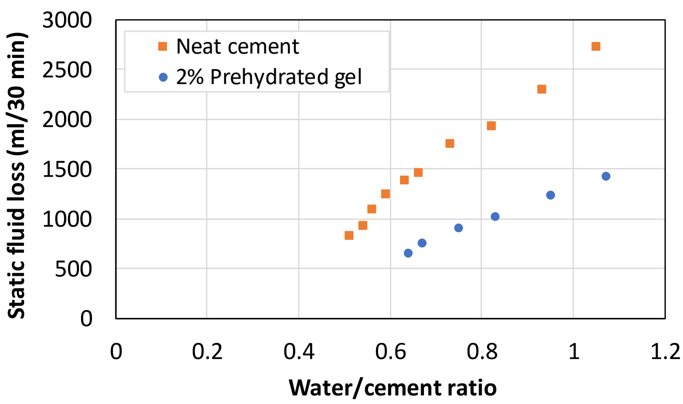

FIGURE 14: Effect of water/cement ratio on static fluid loss in class A cement (neat) and class A cement with 2% bentonite

Nevertheless, it is clear from Figure 14 that lowering the water/cement ratio reduces the static fluid loss rate of the slurry in both cases. The significant reduction of fluid loss rate with the addition of 2% BWOC gel is similarly evident.

5.2 Effect of 2% gel, 0.85% FL and 0.35% FR on slurry properties

More tests were carried out with the objective of modifying the rheological properties and reducing the static fluid loss of the slurries to within acceptable limits. An ideal geothermal cement should have a low yield value and a high plastic viscosity (Wallevik et al., 2004). The addition of 2% bentonite alone at 1.72 g/cm^3 increased the plastic viscosity from 14.3 cp to 30 cp, a 109% increase. The yield stress, on the other hand, rose from 16.4 to 67.3 Pa, a 310% increase. Therefore, the addition of bentonite alone, while improving on the plastic viscosity, raises the yield stress value too much.

In the second set of tests, 0.85% of G33S fluid loss control additive (FL) was added to lower the yield value, while 0.35% USZ friction reducer additive (FR) was added to contain the static fluid loss of Bamburi POWERMAX 42.5 cement. These quantities are similar to those normally used in the primary cementing blend. Slurry densities below 1.70 g/cm^3 were not considered for subsequent testing for the following reasons:

- In Section 5.1 they were found to exceed the maximum free water limit, even with the addition of 2% BWOC bentonite.
- Their static fluid loss rate is very high even with the addition of 2% BWOC bentonite.
- They have high water/cement ratios, implying lower final set strength and slow compressive strength development, according to similar studies done in Iceland (Wallevik et al., 2007).

According to Nelson and Guillot (2006), the extension efficiency of bentonite can be greatly enhanced if it is pre-hydrated in mix water before cement addition. This implies that 0.5% BWOC pre-hydrated bentonite would have a similar effect as 2% BWOC dry-blended bentonite. Besides, as can be seen in Figure 15, research has shown that increasing the bentonite content lowers the compressive strength of the cement sheath (Nelson and Guillot, 2006). The least possible amount of bentonite to achieve desired results should therefore be used.

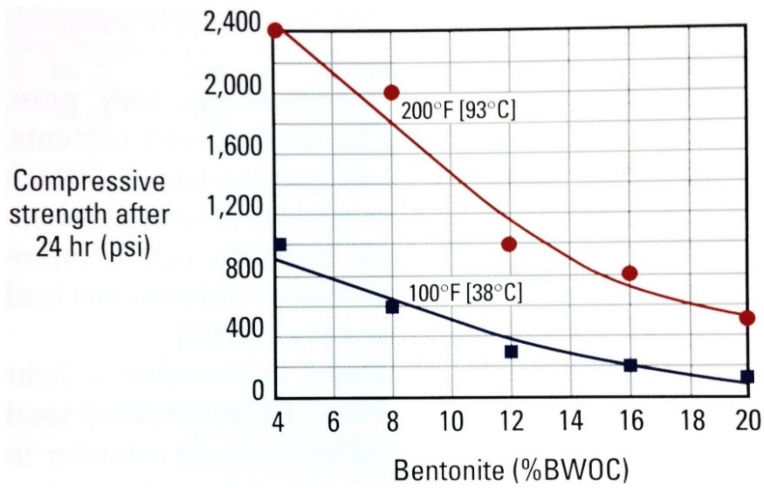

FIGURE 15: Effect of bentonite on compressive strength (Nelson and Guillot, 2006)

The tests incorporating the friction reducer and fluid loss control additives were carried out in two parts. In one mix, additives including 2% bentonite were dry-blended with cement. In the second mix, additives including 0.5% bentonite, were pre-hydrated in the mix water. The main aim was to establish if 0.5% pre-hydrated bentonite would be as effective as 2% dry-blended bentonite.

5.2.1 Free water

Table 9 shows the results of free water tests when the three additives are used together, both in dry-blended and pre-hydrated cases. It is evident from the table that in both cases the free water was successfully eliminated in the slurry at the water/cement ratios under consideration.

TABLE 9: Free water content of blended cement

	Dry blended cement (2% gel, 0.85% FL and 0.35% FR; all BWOC)						
Specific gravity (g/cm^3)	**Cement (g)**	**Gel (g)**	**FL (g)**	**FR (g)**	**Mix water (g)**	**Water/cement ratio**	**Free water (ml/2 hr)**
1.70	598.39	11.97	5.09	2.09	399.56	0.67	0.0
1.72	617.96	12.36	5.25	2.16	393.02	0.64	0.0
1.75	643.53	12.87	5.47	2.25	385.32	0.60	0.0
1.80	684.65	13.69	5.82	2.40	371.64	0.54	0.0
1.85	725.77	14.53	6.17	2.54	357.96	0.50	0.0
	Pre-hydrated (0.5% gel, 0.85% FL and 0.35% FR; all BWOC)						
Specific gravity (g/cm^3)	**Cement (g)**	**Gel (g)**	**FL (g)**	**FR (g)**	**Mix water (g)**	**Water/cement ratio**	**Free water (ml/2 hr)**
1.70	606.51	3.03	5.16	2.12	400.28	0.66	0.0
1.72	626.34	3.13	5.32	2.19	393.77	0.63	0.0
1.75	652.24	3.26	5.54	2.28	386.12	0.59	0.0
1.80	693.92	3.47	5.90	2.43	372.48	0.54	0.0
1.85	735.60	3.68	6.25	2.57	358.85	0.50	0.0

5.2.2 Rheology

When using the standard coaxial cylinder viscometer, API (1997) states that: *Repeatability of data taken at shear rates less than 10.2 s^{-1} is often poor. Readings at below 10.2 s^{-1} may be omitted from the test, except when measuring gel strength.* Nelson and Guillot (2006) also point out that 6 rpm and 3 rpm readings are not very accurate, or may be affected by wall slip. By disregarding readings at these two speeds, all the slurries were found to follow a true Bingham Plastic model as evident in Figure 16 plotted using values from Tables 3 and 4, Appendix II.

The rheological properties of the two cement blends are shown in Appendix II, Tables 1 and 2. The plastic viscosity and yield stress values were determined using Equations 10 and 12 for a Bingham Plastic model.

Figures 17 and 18 show the combined effects of the water/cement ratio and additives on the rheological properties of the cement slurry.

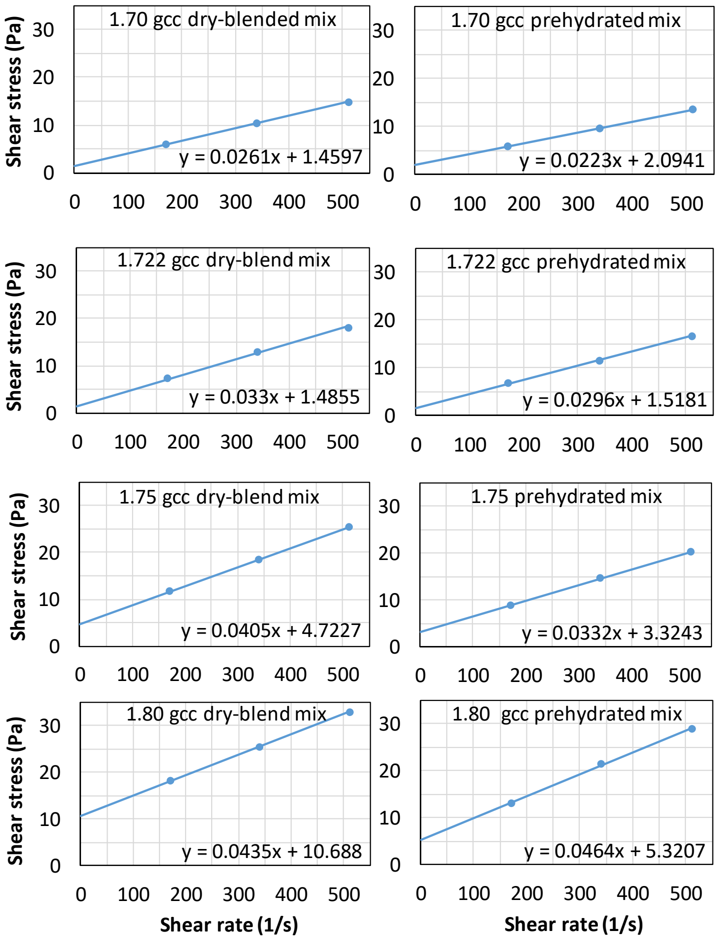

FIGURE 16: Shear stress/shear rate plots for dry-blended and pre-hydrated slurries

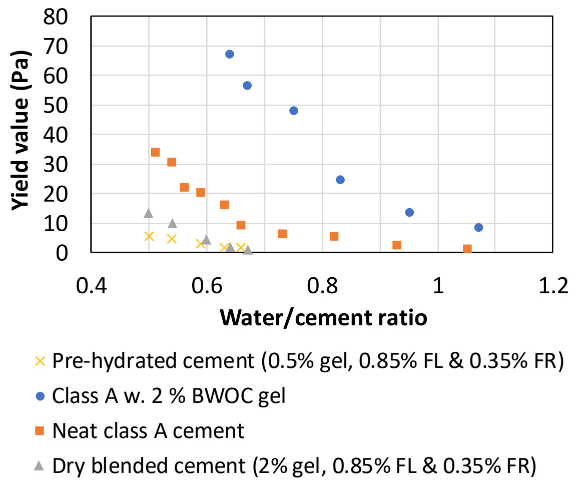

FIGURE 17: Effect of water/cement ratio on yield stress

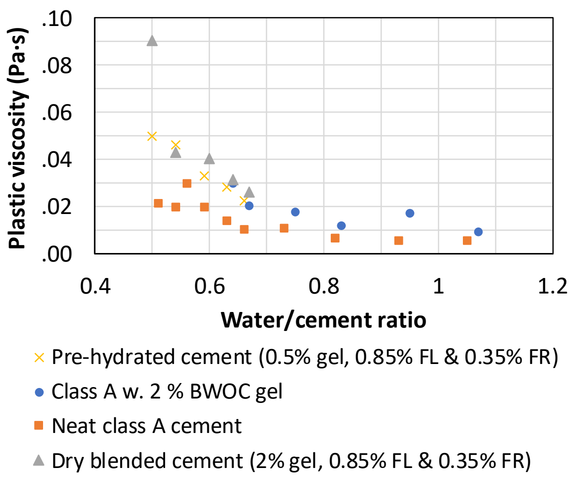

FIGURE 18: Effect of water/cement ratio on plastic viscosity

5.2.3 Static fluid loss

Table 3, Appendix II shows the results of fluid loss tests for the slurry mix containing 2% gel and the one containing 0.5% gel, both including fluid loss control additives. The water/cement ratios used are shown in Table 9, Section 5.2.1. From Figure 19 below, it is evident that there is only a marginal difference in the static fluid loss rate between the two slurry blends. Similarly, it is clear from Table 9 that free water was completely eliminated in the two blends for the densities under consideration. This shows that 0.5% BWOC pre-hydrated bentonite is as effective as 2% BWOC dry-blended bentonite in modifying these two properties.

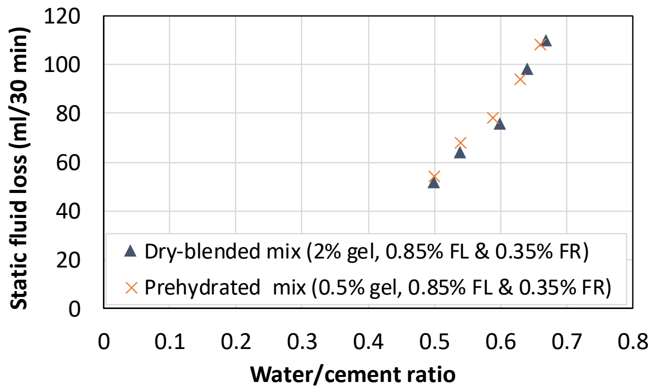

FIGURE 19: Effect of w/c on class A cement with dry blended additives and class A cement with pre-hydrated additives

6. DISCUSSION

From the lithology of the Menengai caldera presented in Chapter 1, it is evident that massive loss of circulation is to be expected, particularly at depths from 0 m to 1200 m where the cemented casing strings are set. An analysis of the cement systems normally used for cement backfill jobs revealed that improvements are required to reduce the free water and the static fluid loss rate of the slurry.

The water/cement ratio affects the plastic viscosity and yield stress of the cement slurry. Generally, reducing the water/cement ratio led to an increase in both the plastic viscosity and the yield stress of the slurry, regardless of the cement mix in question. Likewise, the addition of 2% BWOC bentonite, pre-hydrated in the mix water, resulted in an increase in both parameters. The effect of bentonite was found to be more pronounced on the yield value than on plastic viscosity. Moreover, 0.5% pre-hydrated bentonite was found to be as effective as 2% dry-blended bentonite.

The addition of 0.35% FR in addition to bentonite cancelled out the effect of bentonite on the yield stress of the cement slurry. Generally, the yield stress values were marginally lower when additives were pre-hydrated than when they were dry-blended. This was due to a better homogeneity of the mix, rendering the additives more effective. Low yield stress values are desirable in the slurry for ease of mixing.

Slurry with a lower water/cement ratio was found to have lower free water content and static fluid loss rate. This held true for neat slurry and the 2% pre-hydrated bentonite blend. The increase in free water content with an increase in water/cement ratio is non-linear. Due care should therefore be exercised during mixing and pumping to not deviate too much from the designed density. In addition, the introduction of 2% pre-hydrated bentonite helped to drastically reduce both the free water content and the static fluid loss. The addition of 0.85% FL reduced the fluid loss rate further.

An analysis of past cement backfill jobs done on Menengai wells showed that there is generally a low risk of having trapped water in the production casing annulus. The batch volumes used vis-à-vis the casing annulus volume mostly reduced this risk to a single possible zone of water inclusion. In addition, the free water analysis revealed that, at the slurry densities employed, there was generally very low risk of free water segregation. Exceptions are in the early wells MW01, MW03 and MW06 where low density slurries were used for backfill jobs. However, even where the risk of having trapped water exists, Hole (2008b) states that a large volume of trapped water would be required to deform the pipe to failure. Nevertheless, the best practice is to avoid trapping any water at all.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

1. Performing cement backfills in batches larger than the casing-to-casing annulus volume greatly reduces the risk of trapping water in the casing-to-casing annulus. This could be free water from the cement slurry or water ingress into the annulus from surface activity.
2. The free water content of the cement used for backfilling in Menengai needs to be closely monitored to reduce the risk of trapping water between casings.
3. The addition of 2% BWOC bentonite to the cement, while reducing the free water content, is not a viable solution. Bentonite alone raises the yield value of the slurry, making it difficult to mix and pump at a reasonably low water/cement ratio (high density), which is ideal for a good compressive strength of set cement. Moreover, the addition of bentonite alone does not reduce the static fluid loss of the cement to agreeable levels.
4. Pre-hydrating bentonite in the mix water instead of dry-blending increases its extension efficiency. It was found that 0.5% BWOC pre-hydrated bentonite is as effective as 2% BWOC dry-blended bentonite. This is advantageous both in terms of saving on cost of bentonite and it produces a better homogeneity of the mix. Increasing the amount of bentonite also lowers the compressive strength of cement.

7.2 Recommendations

1. Cement slurries used for backfill jobs in Menengai require to have their free water, fluid loss and rheological properties modified with additives. Using 0.5% bentonite, 0.85% USZ fluid loss additive and 0.35% G33S friction reducer with Bamburi POWERMAX 42.5 cement gives the slurry better plastic viscosity, lowers the yield value and reduces the static fluid loss and free water contents to acceptable limits. The three additives are therefore recommended as a minimum for backfill slurries. However, the additive ratios need to be verified and adjusted as necessary if either the cement brand or additives are changed.

2. It is recommended for the additives to be pre-hydrated in the mix water at least 30 min before cement mixing to ensure homogeneity. Pre-hydration also makes it practical to use blended cement for backfilling. Dry blending operations take an average of eight hours and extra workers, but a pre-hydration operation would require less people and much less time.
3. There is need to include lightweight aggregates in cements to lower the water/cement ratio without increasing the density. Weak and fractured formations encountered during drilling in Menengai area call for the use of lightweight but high viscosity slurries (e.g. in Iceland typically 1.65 to 1.70 g/cm^3 is used, as opposed to 1.72 to 1.85 g/cm^3 in Menengai) to avoid fracturing and inducing excessive cement losses. Lower water/cement ratios also reduce the shrinkage and cracking of the set cement. Otherwise, it is recommended to maintain the current low water/cement ratios in backfill slurries to retain other benefits. Though the density remains high, the considerably higher plastic viscosity of the blended mix is likely to reduce the rate of slurry loss to the formation, thereby reducing the number of backfills and overall time spent on cementing the casings. Relatively high compressive strength of the set cement will also be maintained.
4. The use of inner-string cementing is recommended for primary jobs on the surface and anchor casings where it is advantageous over the current single stage plug cementing. This will allow the placement of more cement slurry in the annulus within less time, and attempts could be made to pump until the cement returns are received during the primary job. However, the full advantage of this method can only be realised if lightweight slurries are used to avoid induced cement losses.
5. The volume of backfill jobs should always exceed the respective casing-to-casing annulus volume or until cement returns are received on the surface, whichever comes first. This will ensure that zones of possible water entrapment in the casing annulus are minimal. However, the cement slurry used must have zero free water and precaution should be exercised to prevent ingress of any water into the annulus.

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NOMENCLATURE

BWOC	= By weight of cement;
API	= American Petroleum Institute;
RP	= Recommended practice;
MSR	= Moderate sulphate resistance;
HSR	= High sulphate resistance;
cp	= Centipoise;
Pa	= Pascal;
Pa·s	= Pascal-seconds;
FL	= Fluid loss control additive;
FR	= Friction reducer additive;
Gel	= Bentonite;
ppg	= Pounds per gallon;
rpm	= Revolutions per minute; and
min	= Minutes.

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APPENDIX I: Effect of water/cement ratio and 2%BWOC gel on slurry properties

TABLE 1: Rheological properties of neat class A cement

Specific gravity (g/cm^3)	**Average value of ramp-up and ramp-down viscometer readings at each spindle speed**					**Plastic viscosity μ_p (cp)**	**Yield point τ_0 (Pa)**
	300 rpm	**200 rpm**	**100 rpm**	**6 rpm**	**3 rpm**		
1.50	9.0	7.5	5.0	3.5	2.0	6.0	1.4
1.55	11.5	9.0	7.5	5.0	3.5	6.0	2.6
1.60	19.0	16.5	14.5	9.5	8.0	6.7	5.9
1.65	24.5	20.5	17.0	11.5	9.0	11.2	6.4
1.70	30.5	27.0	23.5	15.0	10.5	10.5	9.6
1.72	48.5	43.5	39.0	17.5	13.5	14.3	16.4
1.75	63.0	54.5	49.5	21.0	15.0	20.2	20.5
1.78	76.5	65.0	56.5	23.5	19.5	30	22.3
1.80	84.5	77.5	71.0	28.0	22.5	20.2	30.9
1.85	93.0	85.5	78.5	31.5	25.0	21.7	34.1

TABLE 2: Rheological properties of class A cement with 2% BWOC gel

Specific gravity (g/cm^3)	**Average value of ramp-up and ramp-down viscometer readings at each spindle speed**					**Plastic viscosity μ_p (cp)**	**Yield point τ_0 (Pa)**
	300 rpm	**200 rpm**	**100 rpm**	**6 rpm**	**3 rpm**		
1.50 1.55 1.60 1.65 1.70 1.72 1.75* 1.78* 1.80* & 1.85*	27.5 46.0 64.0 118.5 138.5 170.5	23.5 40.5 60.0 112.0 132.0 164.0	21.0 34.5 56.0 106.5 125.0 150.5	12.5 17.0 22.0 38.0 56.5 83.5	8.5 12.0 16.5 25.5 49.0 75.5	9.7 17.2 12.0 18.0 20.3 30	8.5 13.8 24.9 48.1 56.6 67.3

*slurry gelled up during conditioning, unable to run test

TABLE 3: Static fluid loss results

Calculated API static fluid loss for neat class A cement										
Specific gravity (g/cm^3)	**0.5 min**	**1.0 min**	**2.0 min**	**5.0 min**	**7.5 min**	**10 min**	**15 min**	**25 min**	**30 min**	**Fluid loss (ml/30 min)**
1.50	140ml	200ml	Blow out at 1 min 39 seconds, 321 ml collected							2734.9
1.55	135ml	190ml	Blow out at 1 min 55 seconds, 292 ml collected							2306.3
1.60	125ml	177ml	218ml	Blow out at 2 min 11 seconds, 261 ml collected						1933.1
1.65	98ml	156ml	198ml	Blow out at 2 min 23 seconds, 248 ml collected						1758.1
1.70	84ml	125ml	176ml	Blow out at 2 min 30 seconds, 212 ml collected						1467.4
1.72	81ml	124ml	171ml	Blow out at 2 min 37 seconds, 205 ml collected						1387.1
1.75	78ml	115ml	163ml	Blow out at 2 min 48 seconds, 192 ml collected						1255.7
1.78	72ml	102ml	140ml	Blow out at 3 min 05 seconds, 177 ml collected						1103.2
1.80	70ml	95ml	134ml	Blow out at 3 min 19 seconds, 156 ml collected						937.5
1.85	42ml	83ml	120ml	Blow out at 3 min 20 seconds, 140 ml collected						839.2
Calculated API static fluid loss for class A cement with 2% BWOC gel										
Specific gravity (g/cm^3)	**0.5 min**	**1.0 min**	**2.0 min**	**5.0 min**	**7.5 min**	**10 min**	**15 min**	**25 min**	**30 min**	**Fluid loss (ml/30 min)**
1.50	92ml	142ml	190ml	Blow out at 3min 12seconds, 233ml collected						1425.5
1.55	89ml	138ml	177ml	Blow out at 3min 46seconds, 219ml collected						1235.0
1.60	77ml	105ml	138ml	Blow out at 4min 03seconds, 188ml collected						1022.4
1.65	53ml	89ml	106ml	Blow out at 4min 11seconds, 169ml collected						904.3
1.70	45ml	74ml	97ml	Blow out at 4min 19seconds, 144ml collected						758.5
1.72	38ml	66ml	71ml	Blow out at 4min 32seconds, 127ml collected						652.8
1.75 1.78 1.80 1.85	Slurry gelled on conditioning									

APPENDIX II: Effect of 2% gel, 0.85% FL and 0.35% FR on slurry properties

TABLE 1: Rheology properties for dry-blended cement (2% gel, 0.85% FL and 0.35% FR)

Specific gravity (g/cm^3)	**Average value of ramp-up and ramp-down viscometer readings at each spindle speed**					**Plastic viscosity μ_p (cp)**	**Yield point τ_0 (Pa)**
	300 rpm	**200 rpm**	**100 rpm**	**6 rpm**	**3 rpm**		
1.70	29.0	20.5	11.5	3.0	2.0	26.3	1.3
1.72	35.5	25.5	14.5	3.5	2.5	31.5	1.9
1.75	50.0	36.0	23.0	5.5	3.5	40.5	4.5
1.80	64.5	50.0	35.5	7.0	3.5	43.5	10.1
1.85	119.0	89.0	58.5	12.5	8.0	90.7	13.5

TABLE 2: Rheology properties for pre-hydrated cement (0.5% gel, 0.85% FL and 0.35% FR)

Specific gravity (g/cm^3)	**Average value of ramp-up and ramp-down viscometer readings at each spindle speed**					**Plastic viscosity μ_p (cp)**	**Yield point τ_0 (Pa)**
	300 rpm	**200 rpm**	**100 rpm**	**6 rpm**	**3 rpm**		
1.70	26.5	19.0	11.5	2.0	1.5	22.5	1.9
1.72	32.5	22.5	13.5	4.0	2.5	28.5	1.9
1.75	39.5	29.0	17.5	3.5	2.5	33.0	3.1
1.80	56.5	42.0	25.5	5.5	3.5	46.5	4.8
1.85	62.0	45.5	28.5	6.5	4.5	50.2	5.6

TABLE 3: Shear rate and shear stress for dry-blended cement (0.5% gel, 0.85% FL and 0.35% FR)

Specific gravity (g/cm^3)	**Shear rate $\dot{\gamma}$ (1/s) and shear stress τ (Pa)**									
	300 rpm		**200 rpm**		**100 rpm**		**6 rpm**		**3 rpm**	
	$\dot{\gamma}$	τ	$\dot{\gamma}$	τ	$\dot{\gamma}$	τ	$\dot{\gamma}$	τ	$\dot{\gamma}$	τ
1.70	511.5	14.8	341.0	10.4	170.5	5.9	10.2	1.5	5.1	1.0
1.72	511.5	18.1	341.0	13.0	170.5	7.4	10.2	1.9	5.1	1.3
1.75	511.5	25.5	341.0	18.4	170.5	11.7	10.2	2.8	5.1	1.8
1.80	511.5	32.9	341.0	25.5	170.5	18.1	10.2	3.6	5.1	1.8
1.85	511.5	60.8	341.0	45.5	170.5	29.9	10.2	6.4	5.1	4.1

TABLE 4: Shear rate and shear stress for pre-hydrated cement (0.5% gel, 0.85% FL and 0.35% FR)

Specific gravity (g/cm^3)	**Shear rate $\dot{\gamma}$ (1/s) and shear stress τ (Pa)**									
	300 rpm		**200 rpm**		**100 rpm**		**6 rpm**		**3 rpm**	
	$\dot{\gamma}$	τ	$\dot{\gamma}$	τ	$\dot{\gamma}$	τ	$\dot{\gamma}$	τ	$\dot{\gamma}$	τ
1.70	511.5	13.5	341.0	9.7	170.5	5.9	10.2	1.0	5.1	0.8
1.72	511.5	16.6	341.0	11.5	170.5	6.9	10.2	2.0	5.1	1.3
1.75	511.5	20.2	341.0	14.8	170.5	8.9	10.2	1.8	5.1	1.3
1.80	511.5	28.9	341.0	21.4	170.5	13.1	10.2	2.8	5.1	1.8
1.85	511.5	31.8	341.0	23.2	170.5	14.6	10.2	3.3	5.1	2.3

TABLE 5: Static fluid loss in blended cement with fluid loss control additive

	Dry blended cement (2% Gel, 0.85% FL & 0.35% FR; all BWOC)									
Specific gravity (g/cm^3)	**Volume of filtrate collected at API prescribed intervals**									**API fluid loss (ml)**
	0.5 min	**1.0 min**	**2.0 min**	**5.0 min**	**7.5 min**	**10.0 min**	**15.0 min**	**25.0 min**	**30.0 min**	
1.70	10.0ml	14.0ml	17.0ml	25.0ml	29.0ml	34.0ml	40.0ml	51.0ml	55.0ml	110.
1.72	9.0ml	12.0ml	14.0ml	22.0ml	26.0ml	29.0ml	34.0ml	44.0ml	49.0ml	98.0
1.75	5.0ml	8.0ml	11.0ml	16.0ml	19.0ml	23.0ml	28.0ml	36.0ml	38.0ml	76.0
1.80	4.0ml	6.0ml	9.0ml	13.0ml	16.0ml	19.0ml	22.0ml	29.0ml	32.0ml	64.0
1.85	3.0ml	5.0ml	7.0ml	10.0ml	13.0ml	15.0ml	18.0ml	24.0ml	26.0ml	52.0
Pre-hydrated (0.5% gel, 0.85% FL and 0.35% FR; all BWOC)										
Specific gravity (g/cm^3)	**0.5 min**	**1.0 min**	**2.0 min**	**5.0 min**	**7.5 min**	**10.0 min**	**15.0 min**	**25.0 min**	**30.0 min**	**API fluid loss (ml)**
1.70	8.0ml	11.0ml	15.0ml	22.0ml	28.0ml	32.0ml	39.0ml	49.0ml	54.0ml	108.
1.72	7.0ml	10.0ml	14.0ml	20.0ml	25.0ml	28.0ml	35.0ml	44.0ml	47.0ml	94.0
1.75	4.0ml	7.0ml	10.0ml	16.0ml	18.0ml	21.0ml	26.0ml	35.0ml	39.0ml	78.0
1.80	2.0ml	6.0ml	8.0ml	13.0ml	16.0ml	18.0ml	22.0ml	29.0ml	34.0ml	68.0
1.85	2.0ml	4.0ml	7.0ml	10.0ml	12.0ml	15.0ml	19.0ml	24.0ml	27.0ml	54.0

The reported API fluid loss value is the collected volume at end of test duration times two (API,1997).