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Universal Fluid System Utilizing Sustainable Materials

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Abstract

This study presents an innovative and sustainable water-based fluid system designed for use in both drilling and wellbore cementing operations. The system addresses a critical challenge in drilling and cementing: the incomplete displacement of drilling mud by cement. By functioning first as a drilling fluid and then transitioning into a cementing fluid, this dual-purpose solution ensures reliable zonal isolation in the wellbore.

The primary component of the drilling mud is blast furnace slag, a sustainable material used as the main weighting agent. To enhance the rheological properties and reduce fluid loss, the formulation includes various chemical additives. An activator was identified to facilitate the transition of the fluid from a liquid state to a solid state. The performance of the solidified fluid was assessed through Ultrasonic Cement Analyzer (UCA) and Unconfined Compressive Strength (UCS) tests.

The results demonstrated excellent rheological properties and effective fluid loss control in the drilling fluid prior to activation. Stability tests revealed a SAG factor of 0.50, indicating optimal suspension stability. Upon activation, the fluid transitions from a liquid to a solid state within minutes to hours. Notably, the system exhibits a period of low viscosity before rapidly solidifying into a high-strength material. Within approximately 5 hours, the fluid achieves a compressive strength exceeding 500 psi, which further increases to over 1,300 psi after 24 hours, as measured by the UCA. Importantly, the activated fluid system showed no free water separation.

This dual-purpose fluid system simplifies the transition between drilling and cementing operations with a straightforward activation process. The drilling fluid exhibits superior rheological stability, fluid loss control, and suspension characteristics. Upon activation, it transforms into a high-strength solid suitable for zonal isolation and wellbore cementing. This innovative approach offers significant potential for diverse drilling and cementing applications.

Introduction

Conventional drilling fluid(Apaleke et al., 2012) systems cannot solidify into a high-strength material, and any residual drilling fluid left behind can create pathways for communication between different zones. This can ultimately compromise the wellbore's structural integrity. Two strategies can be considered to tackle this issue:

Transforming Traditional Water-Based Drilling Fluids: This method focuses on altering conventional water-based drilling fluids to enable them to solidify into a cement-like material. Typically, these fluids use barite ($BaSO_4$) as the main component, which remains unreactive in water. Consequently, such fluids do not harden into a strong solid after drilling, instead staying in a liquid state or dehydrating to form a weak filter cake due to fluid loss into the surrounding formations.

Utilizing Portland Cement for Drilling: This alternative involves employing Portland cement as the drilling fluid. Unlike traditional water-based fluids, Portland cement reacts chemically with water to produce solid gels, such as calcium silicate hydrate (C-S-H)(Santra et al., 2007). Over time, these reactions form a durable and high-strength cement structure, providing enhanced wellbore stability.

By adopting the second approach, it is possible to tune the properties of the drilling fluid, allowing it to transition into a solid state and provide better zonal isolation when employed in cementing operations.

By utilizing slag as a sustainable alternative, the Universal Fluid System (UFS) aims to reduce environmental impact and promote an eco-friendlier approach. These pozzolanic materials mitigate the carbon footprint associated with traditional cement usage, making the UFS a more sustainable choice for drilling and cementing operations. The exploration of alkali-activated slag systems for cement applications has been extensively explored. However, the development of a slag-based fluid system that exhibits field-ready properties for both drilling and cementing purposes is seldom documented. This manuscript presents the creation of a comprehensive fluid package that tackles various challenges, including fluid rheology, fluid loss, cement thickening time, strength development, and slurry stability. The implementation of this technology has the potential to transform field drilling and cementing processes, thereby enhancing the sustainability of wellbore operations.

Experimental

Materials

Blast furnace slag (New Cem Slag Cement, Grade 120) was obtained from Holcim, while fly ash was provided by Lafarge. Lime (ACS reagent grade) was sourced from Sigma, and soda ash was supplied by M-I SWACO, a Schlumberger company. Lignosulfonate was procured from Beauregard, and xanthan gum was supplied by CP Kelco Biological Co., Ltd. The fluid loss control additive, identified as a modified starch and referenced in prior studies, was acquired from Chemstar Inc. Additionally, silica fume was sourced from Elkem Materials Inc., and reagent-grade sodium hydroxide (≥98%) was supplied by Sigma-Aldrich.

Characterization

Rheological behavior

The rheological properties of the various mud systems were assessed using a Model 35 rheometer (Fann Instrument Company). Rheology tests were conducted after hot rolling the sample for 16 hours at each specific temperature. Data were collected at several rotational speeds—600, 300, 200, 100, 6, and 3 revolutions per minute (rev/min), corresponding to shear rates of 1022, 511, 341, 170, 10, and 5 s^{-1}, respectively. The plastic viscosity (PV), yield point (YP), and low shear yield point (LSYP) were calculated using the relevant equations.

$$PV = \theta_{600} - \theta_{300} \ (mPa \cdot s) \quad \textbf{(1)}$$

$$YP = 2\theta_{300} - \theta_{600} \ (lb/100ft^2) \quad \textbf{(2)}$$

$$LSYP = 2\theta_3 - \theta_6 \ (lb/100ft^2) \quad \textbf{(3)}$$

The values of θ_3 θ_6, θ_{300} and θ_{600} correspond to the dial readings at rotational speeds of 3 rev/min, 6 rev/min, 300 rev/min, and 600 rev/min, respectively. Gel strength refers to the shear stress measured at a low shear rate after the mud system has been sheared at a high shear rate and allowed to rest for a period. In this study, gel strength was measured both after 10 seconds and 10 minutes of setting.

Filtration Loss

The fluid loss measurement was conducted using the high-temperature high-pressure filter press. The HTHP tests were conducted at 160 °F at a different pressure of 500 psi for 30 mins according to API RP 13B-1 (2023). The volume of fluid loss after 30 mins was recorded and the thickness of filter cake was measured.

Sag test

The fluid was poured into a glass container and allowed to rest for 16 hours at 160°F. After the sample was loaded into the container, it was placed into a high-pressure cell at 100 psi. The density of the fluid was measured at three different levels (top, middle, and bottom) as well as the initial density before the 16-hour setting.

$$Sag\ factor = \frac{\rho_{bottom}}{\rho_{top}+\rho_{bottom}} \quad \textbf{(4)}$$

Thickening time

The thickening time was measured using the M290 HPHT Consistometer (Fann Instrument), following the procedure outlined in API RP 10B-2 (2013). The sample was heated from room temperature to 160°F, while the pressure was gradually increased from ambient pressure to 2000 psi over a 30-minute period.

Ultrasonic Cement Analyzer (UCA) analysis

The Ultrasonic Cement Analyzer (UCA) Model 304 was employed to monitor the strength development over a 7-day period. The UFS-LT was heat-rolled for 16 hours at 160°F and subsequently activated with an activator. The samples were heated from room temperature to 160°F within 30 minutes, while the pressure was gradually increased from 1 atm to 2000 psi.

Unconfined compressive strength test

The unconfined compressive strength (UCS) test of the cement was performed using a Forney Compression Testing Machine. The UFS-LT was first prepared and hot-rolled at 160°F for 16 hours. Afterward, the activator was added and thoroughly mixed with the UFS to initiate activation. The mixture was then poured into molds, which were placed in capped plastic containers and cured in a water bath at 160°F. The compressive strength of the samples was measured at designated time intervals.

Results

Formulation for drilling fluid

The water-based drilling fluid system consists of a combination of solid materials, water, and various chemicals. Fluid rheology and fluid loss control are crucial factors in formulating the drilling fluid system. A modified starch-based fluid loss control additive was utilized to manage fluid loss. Additionally, a lignosulfonate dispersing retarder was employed due to the small size of the slag particles, which could easily form a high-viscosity slurry paste, particularly in the presence of the viscosifier Xanthan Gum. The formulation of the UF system, used as a drilling fluid before activation, is provided in

Table *1*. Soda ash was incorporated as a pH adjuster for acid gas applications in future field operations. Xanthan gum acts as a viscosifier, while MS1 is the fluid loss control additive, and silica fume serves as a low-end rheology modifier (Liu et al., 2023). The fluid is mixed following these steps:

1. Add DI water to the fluid container.
2. Dissolve NaCl in the DI water and mix for 5 minutes.
3. Add the dry blend of all solid additives to the water.
4. Mix for 30 minutes at 12,000 RPM.
5. The resulting formulation is referred to as UFS-LT.

Table 1 *Formulation UFS-LT for drilling fluid testing*

Materials	Weight (g)
DI Water	140
NaCl	14
SLAG120	200
Soda Ash	1
Xanthan Gum	0.3
MS1(fluid loss control)	3
Retarder	4
Silica fume	5

Results

Formulation for drilling

The data presented in **Table 2** indicates that at 120 °F, the rheological properties of UFS-LT (before hot rolling, BHR) are higher compared to UFS-LT (after hot rolling, AHR). Upon increasing the temperature from 120 °F to 160 °F, there is a noticeable reduction in the DR reading values under higher shear rate conditions. However, under low shear conditions, the DR reading remains consistent with the value measured at 120 °F. At 160 °F, UFS-LT (AHR) shows a plastic viscosity (PV) of approximately 29 centipoise and a yield point (YP) of around 22 lb/100 ft^2. Additionally, the low shear yield point (LSYP) at 160 °F is measured at 7 lb/100 ft^2, demonstrating the drilling mud's ability to effectively suspend materials.

Table 2 Rheology(FANN® Model 35) of UFS-LT after hot rolling (AHR) for 16hrs at 160°F, and then measured at 120 °F and 160 °F

RPM	DR(AHR) @120°F	DR(AHR) @160°F
600	111	80
300	69	51
200	53	46
100	34	26
6	8	9
3	7	8
10 s	10	9
10 min	18	18
30min	21	25
PV, cp	42	29
YP, lb/100 ft^2	27	22
LSYP,lb/100 ft^2	6	7

Fluid loss control

Table 3 HTHP fluid loss test of UFS-LT testing after 16hrs hot rolling at 160 °F

Fluid loss (mL)	4.8
Fluid loss*2 (mL), API	9.6
Thickness of filter cake (inches)	4/32

As shown in **Table 3**, an HTHP fluid test was performed at 160°F under a differential pressure of 500 psi (following API conditions). The results indicate that the UFS-LT exhibited very low fluid loss, measuring only 9.6 mL, and produced a filter cake thickness of 4/32 inches. Several traditional fluid loss additives were evaluated, including a 2-acrylamido-2-methylpropane sulfonic acid (AMPS)-based copolymer, cellulose and its derivatives, PAA-based block polymers, and various modified starch polymers. Among these, it was found that the nonionic modified starch polymer was compatible with the system containing slag particles. This polymer formed a thin filter cake with the fine slag particles, effectively sealing the filter paper surface. Moreover, nonionic starch contributed to a synergistic effect by enhancing the viscosity of the fluid system, thus reducing the need for additional viscosifier (Xanthan gum) in this case. In this dispersed system, lignosulfonate, with its negative charge, bonds to the positively charged sites on the slag particle surface. Nonionic starch likely binds through hydrogen bonding with the hydroxyl groups on the slag particle surface, forming a three-dimensional structure of particle-starch-particle. This structure aids in filter paper plugging and the formation of a thin filter cake. Due to its abundance of hydroxyl groups and oxygen atoms with lone pairs of electrons, along with its non-linear molecular structure, nonionic starch easily forms a composite with the filter paper, resulting in low permeability. In contrast, other polymers may be less effective at controlling fluid loss, as they do not form similar three-dimensional structures.

SAG test

As shown in

Table *1* and **Table 2**, the drilling mud displays a density between approximately 14.48 and 15.08 pounds per gallon (ppg), while maintaining a stable SAG factor of around 0.51. This stability indicates minimal sagging, reflecting the effective suspension of particles. The high stability of the system can be attributed to several key factors. First, the small size of the slag particles prevents settling, contrary to what Stock's law would predict. Second, the high viscosity of the system generates significant drag forces, which hinder the descent of particles. Third, the dispersant lignosulfonate, which adsorbs onto the particles, imparts a negative charge, resulting in a strong negative surface potential that enhances electrostatic repulsion and further stabilizes the particles. These combined factors contribute to the overall stability of the fluid system, preventing sagging even under static conditions. These characteristics highlight the effectiveness and reliability of this drilling fluid formulation.

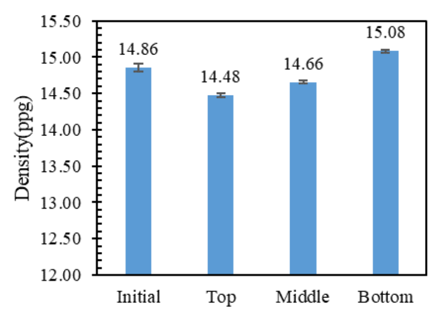


Figure 1 SAG test at 160 °F after hot rolling (AHR) for 16hrs at 160 °F

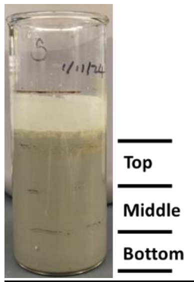
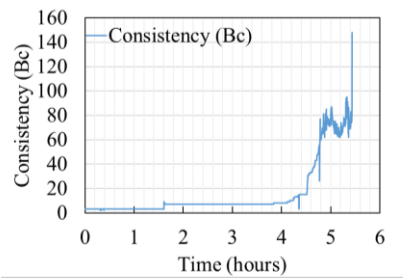
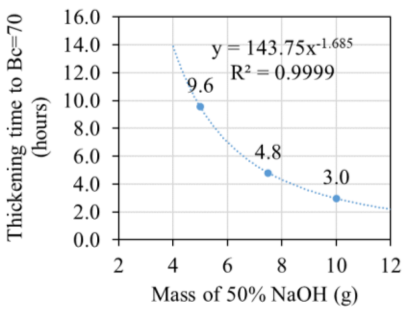


Figure 2 SAG test (16 hours static setting at 160 °F) after hot rolling for 16hrs at 160 °F

SAG Activated Universal Fluid Used as Cementing



(a)



(b)

Figure 3 (a) consistency history for activated formulation for cement; (b) thickening time (Bc=70) as a function of mass of 50% NaOH(aq) added to UFS-LT; Test conditions: Ramp time = 30 min from RT to 160°F, P =2000 psi

Figure 3(a) presents the consistency curves of activated UFS-LT. The sample was heated from room temperature to 160°F, while pressure was increased from ambient to 2000 psi over a 30-minute period. The consistency data shows that the activated OPT-UFS maintains a low Bc (<30) for approximately 4.5 hours, providing sufficient time for fluid pumping during cementing operations. Following this period, there is a sharp increase in consistency values, which corresponds to the final phase of geopolymer formation—geopolymer condensation. This process leads to the formation of strong inorganic polymer gel networks, resulting in higher consistency within the UF system. The extended fluid state is due to the addition of lignosulfonate. Without this lignosulfonate retarder, fluidity is lost rapidly, as observed in other alkaline-activated systems (Palacios et al., 2021). **Figure 3** (b) illustrates the thickening time (Bc=70) as a function of the amount of aqueous NaOH solution added to the UF system, showing an exponential relationship with the sodium hydroxide content. These results indicate that thickening time can be easily adjusted by varying the NaOH quantity, facilitating fluid preparation, transportation, and use in well cementing. This Right Angle Set Cement (RAS) behavior enhances the ease of deployment and helps prevent gas migration during cementing operations.

Rheology of the activated UFS-LT

Table 4 Rheology (FANN® Model 35) of activated UFS-LT for cement at 160 °F

RPM	DR (160°F)
600	75
300	44
200	32
100	90
6	6
3	5
10 s	7
10 min	16
30 min	50
PV, cp	31
YP, lb/100 ft^2	13

The rheological properties of the activated universal fluid, UFS-LT, at room temperature and 160°F are summarized in **Table 4**. At 160°F, UFS-LT exhibits a Plastic Viscosity (PV) of approximately 31 centipoise (cp) and a Yield Point (YP) of about 13 lb/100 ft². These values underscore the fluid's favorable rheological behavior, making it well-suited for both injection and operational applications.

API HTHP fluid loss test of the activated UFS-LT

Table 5 HTHP (160 °F, ΔP=1000 psi) fluid loss results of activated UFS-LT

Formulation	Activated UFS-LT	Activated UFS-LT
Filtration media	325 mesh SS screen	325 mesh SS screen + filter paper
Fluid loss (mL)	81.6 ml API	5.8 ml API
Thickness of filter cake (inches)	1'1/2	3/32

To evaluate the fluid loss performance of the activated Universal Fluid System Low-Temperature (UFS-LT) under high-temperature and high-pressure (HTHP) conditions, an API fluid loss test was conducted at 160°F with a differential pressure of 1000 psi. The results, summarized in **Table 5**, reveal that using the traditional API standard measurement for cement fluid loss control resulted in a fluid loss of approximately 81.6

mL. This higher fluid loss is due to the 325-mesh screen size, which allows particles smaller than 44 microns to pass through, while the D90 of the slag particles is only 28 microns. This indicates that at least 90% of the particles can pass through the 325-mesh screen.

In contrast, when a filtration medium consisting of a 325-mesh stainless steel screen combined with filter paper (retaining particles down to 2.7 microns) was used, the fluid loss was significantly reduced, and a thin filter cake was formed. This is because over 90% of the particles, with a D10 of 4 microns, are unable to penetrate the filter paper. As a result, a low-permeability filter cake is created, supported by fluid loss control additives in the system.

Importantly, in the UFS-LT fluid test activated by NaOH, incorporating filter paper closely simulates practical field conditions. Before activation, the UFS-LT comes into contact with the reservoir, and the thin filter cake is designed to remain in place, as it naturally solidifies over time. These findings highlight the activated UFS-LT's effectiveness in controlling fluid loss, even under demanding HTHP conditions.

Compressed strength test of the activated UFS-LT

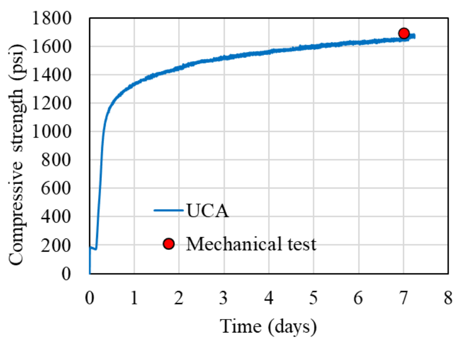


Figure 4 Compressive strength (from UCA and mechanical test) of activated UFS-LT for cement; 2000 psi, 160 °F.

According to the UCA results in **Figure 4**(a), the cement achieved a strength of 500 psi in approximately 5 hours. Furthermore, the UCA test demonstrated that the compressive strength exceeded 1000 psi within one day(Duan et al., 2022; Oh et al., 2010) These findings confirm that UFS-LT is highly suitable for oil well construction, meeting the required strength standards. The results highlight that introducing concentrated sodium hydroxide into the universal fluid system, with a high water-to-binder ratio of 0.7, promotes favorable strength development and facilitates the transition from liquid to solid phases. An incubation period is observed during which compressive strength remains low, marking the initiation of geopolymerization as precursors and monomers begin to form.

In summary, the activated universal fluid (cement) formulation exhibits the following properties at 160 °F:

- Plastic Viscosity (PV): 31 cp, ensuring ease of pumping under high shear rates.
- Yield Point (YP): 13 lb/100 ft².
- HTHP Fluid Loss: 5.8 mL using API with filter paper.
- Thickening Time: Approximately 4.8 hours for consistency (Bc) to reach 70, demonstrating excellent waiting-on-cement (WOC) performance.
- Compressive Strength: UCA and USC tests indicate a strength of 1600 psi at 7 days, with 500 psi achieved in 5 hours based on UCA measurements.

These characteristics highlight the system's strong performance in cementing applications. Additional improvements, such as lowering the water content or refining the slag's particle size distribution, could further enhance its effectiveness.

Conclusions

A universal fluid system (UFS-LT) utilizing fine SLAG particles has been developed, serving as a drilling fluid prior to activation and transforming into a cementing fluid post-activation. In its non-activated state, the UFS-LT fluid demonstrates exceptional fluid loss control, achieving ultra-low levels and forming a thin filter cake. The presence of retarder within the formulation allows the UF to maintain its liquid state for a minimum of 20 days at a temperature of 160°F. To activate the UFS-LT fluid, the fluid UFS-LT transitions into gel networks within 5 hours under static conditions. The compressive strength develops rapidly, reaching 1318 psi after just one day of curing, showcasing its potential for use in well-cementing operations. The cement slurry, when activated, exhibits a distinctive right-angle-set behavior during the thickening time test. The consistency remains at a low level (Bc<10) for an extended period and then rapidly increases to 100 Bc within a few minutes. This behavior has been reported to aid in balancing the total hydrostatic pressure of the cement column until the setting process begins(Prabhakar et al., 2019; Santra et al., 2007).

References

Apaleke, A.S., Al-Majed, A., Hossain, M.E., 2012. Drilling Fluid: State of The Art and Future Trend. Presented at the North Africa Technical Conference and Exhibition, OnePetro. https://doi.org/10.2118/149555-MS

Duan, W., Zhuge, Y., Chow, C.W.K., Keegan, A., Liu, Y., Siddique, R., 2022. Mechanical performance and phase analysis of an eco-friendly alkali-activated binder made with sludge waste and blast-furnace slag. Journal of Cleaner Production 374, 134024. https://doi.org/10.1016/j.jclepro.2022.134024

Liu, Y., Lu, C., Hu, X., Shi, C., 2023. Effect of silica fume on rheology of slag-fly ash-silica fume-based geopolymer pastes with different activators. Cement and Concrete Research 174, 107336. https://doi.org/10.1016/j.cemconres.2023.107336

Oh, J.E., Monteiro, P.J.M., Jun, S.S., Choi, S., Clark, S.M., 2010. The evolution of strength and crystalline phases for alkali-activated ground blast furnace slag and fly ash-based geopolymers. Cement and Concrete Research 40, 189–196. https://doi.org/10.1016/j.cemconres.2009.10.010

Palacios, M., Gismera, S., Alonso, M.M., d'Espinose de Lacaillerie, J.B., Lothenbach, B., Favier, A., Brumaud, C., Puertas, F., 2021. Early reactivity of sodium silicate-activated slag pastes and its impact on rheological properties. Cement and Concrete Research 140, 106302. https://doi.org/10.1016/j.cemconres.2020.106302

Prabhakar, A., Lee, N., Ong, K.C.G., Zhang, M., Moon, J., Cheng, A., Kong, K.H., 2019. Enhancing the Gel Transition Time and Right-Angle-Set Property of Oil Well Cement Slurries by Incorporating CSA Cement and Gypsum. Presented at the International Petroleum Technology Conference, OnePetro. https://doi.org/10.2523/IPTC-19224-MS

Santra, A., Reddy, B.R., Antia, M., 2007. Designing Cement Slurries for Preventing Formation Fluid Influx After Placement. Presented at the International Symposium on Oilfield Chemistry, OnePetro. https://doi.org/10.2118/106006-MS