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Plantain peel ash as a natural retarder for controlling thickening time in saline contaminated cement slurries

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ABSTRACT

The control of cement slurry thickening time is paramount for successful well cementing operations where saline contamination poses a significant challenge by accelerating cement hydration and potentially leading to operational failures such as premature setting. This study evaluates plantain peel ash (PPA) as a sustainable natural retarder for controlling thickening time (TT) in sodium chloride (NaCl) and magnesium chloride ($MgCl_2$) contaminated Class G cement slurries. PPA was incorporated at dosages of 1%, 3%, and 5% by weight of cement (BWOC), with saline concentrations of 1%, 3%, and 5%. Thickening time was quantified using a high-pressure, high-temperature (HPHT) consistometer at 150°C and 24-hour compressive strength. Results demonstrated that PPA extended TT in a dose-dependent manner, countering saline-induced acceleration. At 5% NaCl, TT increased from 65 minutes (baseline) to 150 minutes (5% PPA), indicating a 130% improvement. $MgCl_2$ often restored TT to uncontaminated control levels at 180 minutes. PPA also reduced plastic viscosity by up to 56.7% and yield point by 41.7% in saline slurries, enhancing pumpability, and recovered compressive strength from 1200 psi to 1740 psi at 3% NaCl with 1% PPA. The retardation mechanism was attributed to PPA's high potassium oxide content (40-50%), which adsorbs onto cement grains. Statistical analysis (ANOVA) confirmed significant effects of PPA dosage on TT ($F = 47.2$, $p < 0.001$). PPA shows a better substitute for synthetic retarders like lignosulfonates.

Contribution/Originality: This study contributes to the existing literature by providing evidence of PPA's capacity to mitigate saline formation fluid contamination effects on oil well cement through retardation of cement thickening time and optimizing cement performance. It further presents a waste-to-wealth approach for agro-based waste material while solving environmental issues arising from contaminated cements.

1. INTRODUCTION

The success of oil and gas well construction hinges on the long-term integrity of the cement sheath placed between the casing and the geological formations. This primary cementing operation is critical for providing zonal isolation, preventing fluid migration between strata, and protecting the casing from corrosive elements [1]. A fundamental requirement for a successful cement job is the precise placement of the cement slurry before it develops significant gel strength and hardens. The time during which the slurry remains pumpable, known as the thickening time, must be carefully engineered to account for the placement operation, plus a safety margin. A significant challenge in achieving this control arises from the contamination of cement slurries by salt (NaCl) from saline formation waters or when using brine-based drilling fluids. Soluble salts, particularly sodium chloride (NaCl), are known to profoundly and unpredictably alter the hydration kinetics of Portland cement [2]. Depending on the concentration, salt can act as an accelerator at low levels, drastically reducing thickening time and risking premature setting inside the tubulars, or as a retarder at very high concentrations, which can lead to economically costly waiting-on-cement (WOC) periods. This erratic behaviour complicates slurry design and poses a substantial risk to well integrity and operational safety. Conventional chemical retarders, such as lignosulfonates and synthetic polymers, are widely used to extend thickening time. However, these additives can be expensive, susceptible to degradation at high temperatures, and raise environmental concerns due to their synthetic origin and potential toxicity [3]. Consequently, there is a growing interest within the petroleum industry to develop sustainable, cost-effective, and efficient alternatives derived from natural and renewable resources.

Plantain (Musa paradisiaca) is a staple food crop in many tropical regions, generating substantial agricultural waste in the form of peels. These peels are rich in alkali metal salts, particularly potassium carbonate (K_2CO_3) and other mineral oxides, which are known to influence the setting of cement [4]. The calcination of these organic wastes produces an ash that has shown promise as a pozzolanic or setting modifier in construction applications. This presents a valuable opportunity to convert a waste product into a high-value industrial material.

Controlling the setting time of cement is critical, especially in deep, hot wells where accelerated thickening can occur. Retarders are essential additives that delay the setting process to ensure sufficient time for slurry placement. Most commercial retarders are synthetic organic polymers or lignosulfonates. The exploration of agro-waste ashes as set retarders has gained interest due to their cost-effectiveness and sustainability. Plantain Peel Ash (PPA), rich in alkali oxides like K_2O, has been reported to retard the setting of concrete [5, 6]. The alkalies are believed to adsorb onto cement particles, slowing down the dissolution and hydration kinetics. In oil well cementing, where precise control over thickening time is paramount, a natural, locally sourced retarder like PPA could offer significant advantages. Saline contamination can unpredictably alter the thickening time of cement slurries, potentially leading to either flash sets or excessively long waiting-on-cement times. While the primary focus of mitigation is often on strength recovery, controlling the setting profile is equally important for operational safety and efficiency. The potential of PPA as a set retarder for oil well cement, particularly in a contaminated system, has not been thoroughly investigated. This work explores the novel application of PPA to extend and control the thickening time of NaCl and $MgCl_2$-contaminated Class-G cement slurries, evaluating its suitability as a natural retarder for challenging well conditions. PPA increases consistency and delays setting time when blended into cement pastes at low percentages; however, higher replacement rates typically reduce early age strengths and alter workability, so the functional window for PPA as an admixture/retarder often lies at low additive dosages rather than bulk cement replacement [7, 8]. Microstructural studies suggest PPA interacts with hydration products and may adsorb on clinker phases, slowing early polymeric network formation— a candidate mechanism for retardation.

In well cementing operations, factors such as temperature, pressure, cement composition, and the chemistry of mixing water (Including salinity) strongly influence hydration kinetics and therefore the slurry thickening behaviour; saline contamination in particular commonly accelerates hydration and shortens thickening time, complicating safe placement and often necessitating the use of chemical retarders [9, 10].

Conventional retarders used to extend thickening time are typically synthetic polymers or complex organic molecules designed for performance at a range of temperatures and salinities. While effective, these commercial retarders can be costly and may have environmental drawbacks or limited availability in particular regions [11]. Growing interest in sustainable, low-cost alternatives has motivated research into agro-waste-derived materials and bio-based retarders that could reduce waste, lower costs, and provide locally sourced additives [12, 13]. Thickening time is a critical parameter in cementing operations, especially in deep, hot wells where accelerated setting can occur.

Retarders are essential additives used to extend the thickening time, ensuring the slurry remains pumpable for the entire duration of the job. Conventional retarders include lignosulfonates and synthetic polymers. Several studies have investigated the use of agro- waste ashes as admixtures in concrete, with many reporting a retardation effect. Research on Plantain Peel Ash (PPA) in concrete, while showing mixed results on strength, consistently indicates an increase in setting times. Hassan et al. [5] found that PPA acted as a set retarder, delaying the initial and final set of cement paste, and recommended an optimum dosage of 1%. Dyuran et al. [14] also recommended PPA as a set retarder due to its observed effect on concrete.

The retardation effect is often attributed to the high alkali content (e.g., potassium oxide - K_2O) in these ashes. Kumator et al. [6] noted that PPA has a very high K_2O content. Alkalis can affect the dissolution and precipitation kinetics of cement phases, particularly tricalcium aluminate (C_3A) and silicate (C_3S), leading to a delay in the setting and hardening process. The study by Igwe et al. [8] on the synergistic effect of PPA and Banana Peel Ash (BPA) on casing cement slurry is a direct precursor to this research. They observed that PPA/BPA blends influenced slurry properties, including gel strength. However, a focused investigation on PPA's specific role as a retarder for saline-contaminated slurries is novel. Similarly, Neminebor et al. [15] studied Water Hyacinth Ash as an accelerator, demonstrating the broader potential of agro-materials for set control in oil well cement.

The research aims to evaluate the potential of Plantain Peel Ash (PPA) as a natural retarder for saline-contaminated oil well cement slurries that will incorporate PPA into NaCl-contaminated and $MgCl_2$-contaminated cement slurries at concentrations of 1%, 3%, and 5% BWOC. Quatify the thickening time of the PPA-treated, contaminated slurries using an HPHT consistometer and the retardation effect of PPA and determine its concentration-dependent behavior.

2. MATERIALS AND METHODS

2.1. Materials

The primary materials used in this study included API Class G oil well cement, Plantain peels Ash (PPA), Distilled water, Sodium Chloride (NaCl, analytical grade), Magnesium Chloride (MgCl2), and Anti foam agent.

2.2. Methods

Ripe plantain peels were thoroughly washed with distilled water to remove surface contaminants, and then air-dried under ambient conditions (25–30°C) for 7 days to reduce moisture content below 10%. The dried peels were subsequently incinerated in a muffle furnace at 600°C for 4 hours to ensure complete combustion and minimize carbon residues, as higher temperatures can lead to vitrification and reduced reactivity. After cooling to room temperature, the resulting ash was ground using a ball mill and sieved through a 75-μm sieve to achieve a fine particle size distribution suitable for admixture applications, with the final PPA yield approximately 15–20% of the dry peel mass. Chemical composition of the PPA was analyzed via X-ray fluorescence (XRF), confirming high levels of K_2O (40–50%), CaO (10–15%), and SiO_2 (20–25%), which contribute to its retarding properties.

Cement slurries were prepared according to API Recommended Practice 10B-2 guidelines, using a water-to-cement ratio (W/C) of 0.44 to achieve a density of 15.8 ppg (1890 kg/m^3), typical for primary cementing operations. Baseline slurry (control) consisted of Class G cement and distilled water. Saline-contaminated slurries were formulated by dissolving NaCl in the mix water prior to blending. PPA was incorporated as a dry admixture at dosages of 0.5%, 1.0%, 1.5%, and 2.0% by weight of cement (BWOC), based on preliminary trials and prior studies indicating optimal retardation within this range without excessive fluidity loss. Mixing was performed using a high-shear blender at 4000 rpm for 15 seconds followed by 12000 rpm for 35 seconds to ensure homogeneity and minimize air entrainment. All slurries were prepared in triplicate for each combination of saline concentration and PPA dosage, resulting in 20 unique formulations. Thickening time was determined using a pressurized consistometer in accordance with API RP 10B-2, simulating downhole conditions at a bottom-hole circulating temperature (BHCT) of 52°C

(125°F) and pressure of 5200 psi (35.85 MPa), representative of intermediate-depth wells. The slurry was ramped to test conditions for over 30 minutes, and consistency was monitored in Bearden units (Bc). Thickening time was recorded as the duration to reach 70 Bc, indicating the point of pumpability loss. Tests were conducted immediately after mixing to capture initial hydration dynamics influenced by saline ions and PPA.

Rheology was assessed using a rotational viscometer (Fann Model 35) at ambient temperature (25°C) following API procedures, measuring shear stress at shear rates of 3, 6, 100, 200, 300, and 600 rpm. Plastic viscosity (PV) and yield point (YP) were calculated using the Bingham plastic model to evaluate the impact of PPA on slurry flow behaviour under saline conditions. Free fluid separation was measured by conditioning slurries in a 250-mL graduated cylinder at 52°C for 2 hours, quantifying separated water volume as a percentage. Compressive strength was evaluated on cured cubes (50 mm × 50 mm × 50 mm) after 24 and 72 hours at 52°C using a universal testing machine, providing insights into long-term effects of contamination and retardation.

2.3. Data Analysis

Results were analysed using descriptive statistics, with means and standard deviations reported for triplicate measurements. One-way ANOVA was employed to assess the significance of PPA dosage and saline concentration on thickening time ($p < 0.05$). Regression models were developed to correlate PPA content with thickening time extension in saline environments.

3. RESULTS AND DISCUSSION

3.1. Thickening Time for 1% NaCl and 1% PPA

The thickening time for 1% NaCl and 1% PPA is shown in Figure 1.

The thickening time value for Figure 1 was 139 min at 100 Bc, which shows high retarding value as shown in Figure 1, indicating rise in TT. The max slurry temp 150°C, max oil temp 170°C, and average pressure 3151.28 psi shows stability in slurry as consistency hits 100 Bc at 2 hours 19 min. Slurry temp reaches 150°C in 40 min; slurry temperature peaks at 170°C in 30 min and stabilizes at 150°C. Pressure climbs from 23 psi to 3300 and 3600 psi by 20 min. 1% PPA greatly increases TT for slurry with 1% NaCl ionic concentration, showing strong retardation that may be caused by chemical interaction. Stable temperature and pressure (3500 psi) confirm consistency, with slow consistency reflecting PPA's delay in cement setting. This result aligns with Aliyu et al. [16] research, where the effect of PPA on the mechanical properties of concrete was tested with results showing that the initial setting time increased with an increase in the percentage of PPA up to 10%.

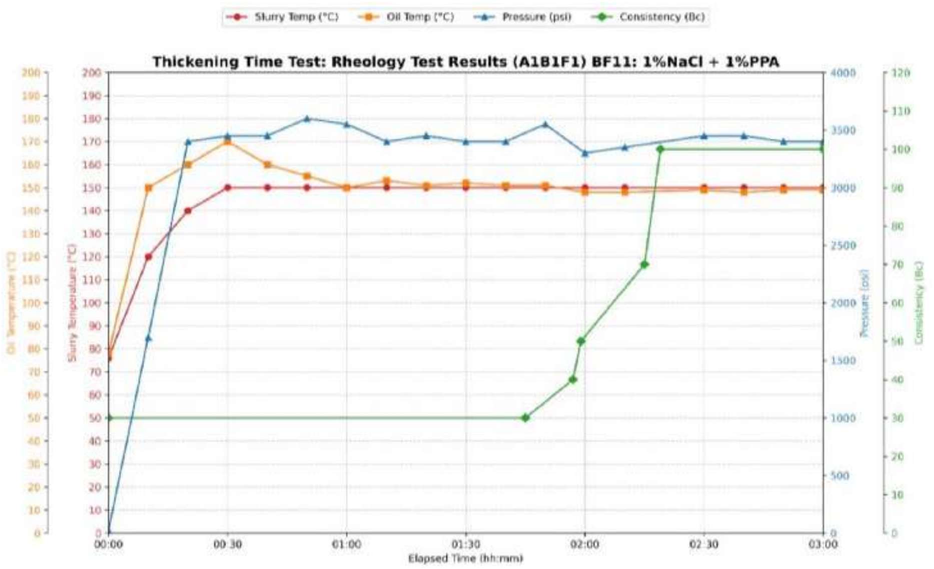

Figure 1. Thickening Time for1% NaCl and 1% PPA.

3.2. Thickening Time for 1% NaCl and 3% PPA

Figure 2 shows that thickening time was 150 min at 100 Bc, indicating a fast rise required to set the cement n slurry as compared to Figure 1, where 100 Bc was achieved at 139 min, creating about 11 min difference. This underscores the capability and tendency of PPA to retard the setting of cement. The max slurry temp 150°C, max oil temp 170°C, and average pressure 3154.17 psi of the set slurry indicates its ultimate stability as consistency reaches 100 Bc at 2 hour 30 min, rising the TT slowly. Slurry temp hits 150°C in 40 min; oil temp peaks at 170°C in 30 min and stabilizes at 150°C. Pressure rises from 25 psi to range of 3350 to3550 psi by 20 min with 3% PPA, which further increases TT above slurry with 1% PPA, reinforcing retardation and underscoring PPA as a viable agro-based retarding additive. Stable temperature and pressure (3450 psi) ensure consistency, with slow consistency reflecting PPA's strong counteracting effect slurry with ionic concentration for delayed setting time. The thickening time for 1% NaCl and 3% PPA is shown in Figure 2.

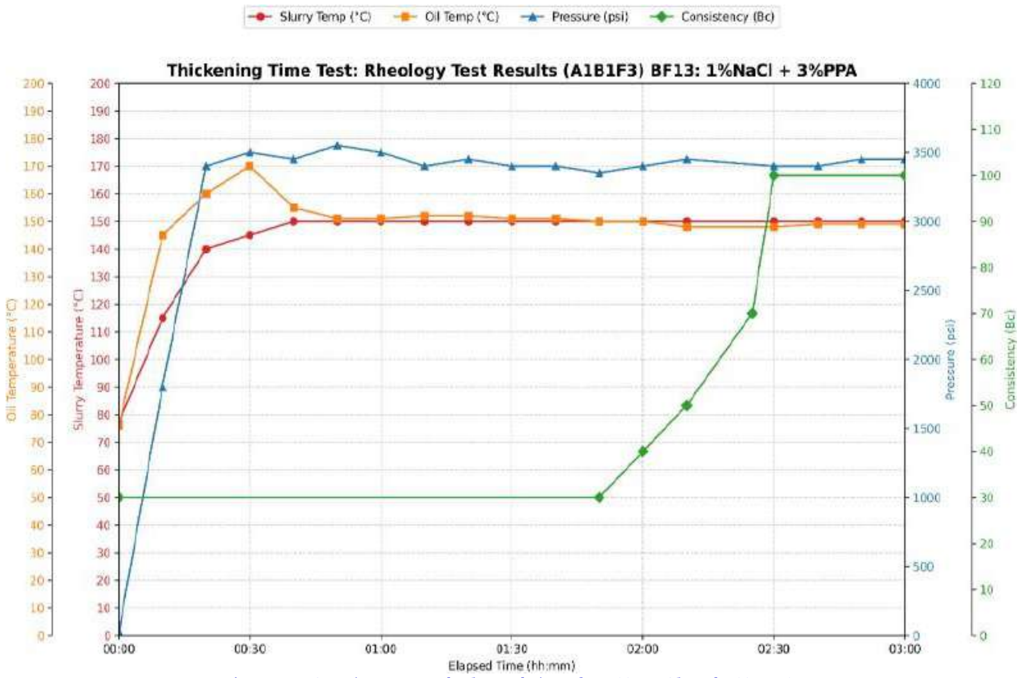

Figure 2. Consistency and Elapsed time for 1% NaCl and 3% PPA.

3.3. Thickening Time for 1% NaCl and 5% PPA

Thickening time at 100 Bc for slurry tested with 1% NaCl and 5% PPA, as shown in Figure 3 was155 min, indicating that an increase in the percentage concentration of PPA BWOC results in an increase in the time required for a cement slurry to set. The maximum slurry temperature 150°C, while maximum oil temperature 170°C, and average pressure 3148.56 psi for this slurry is indicative of a stable slurry as consistency hits 100 Bc at 2hour 35 min, raising TT slowly. Slurry temp reaches 150°C in 40 min; oil temp peaks at 170°C at 30 min and stabilizes at 150°C. Pressure climbs from 24 psi to range of 3350 and 3550 psi by 20 min. and showing that PPA yields strongest retardation at 5% with 1% ionic concentration containing NaCl. Stable temps and pressure (~3450 psi) confirm consistency, with slow consistency indicating significant delay in setting. The effect of Plantain Peel Ash (PPA) on compressive strength by Dyuran et al. [14] where Plantain Peel Ash effect on cement slurry was tested at 0%, 0.5%, 1%, 1.5%, 2%, and 2.5% and result revealed that PPA increases the setting time of concrete and recommended that PPA be adopted as a set retarder since it increases the setting of concrete and without consideration of salinity.

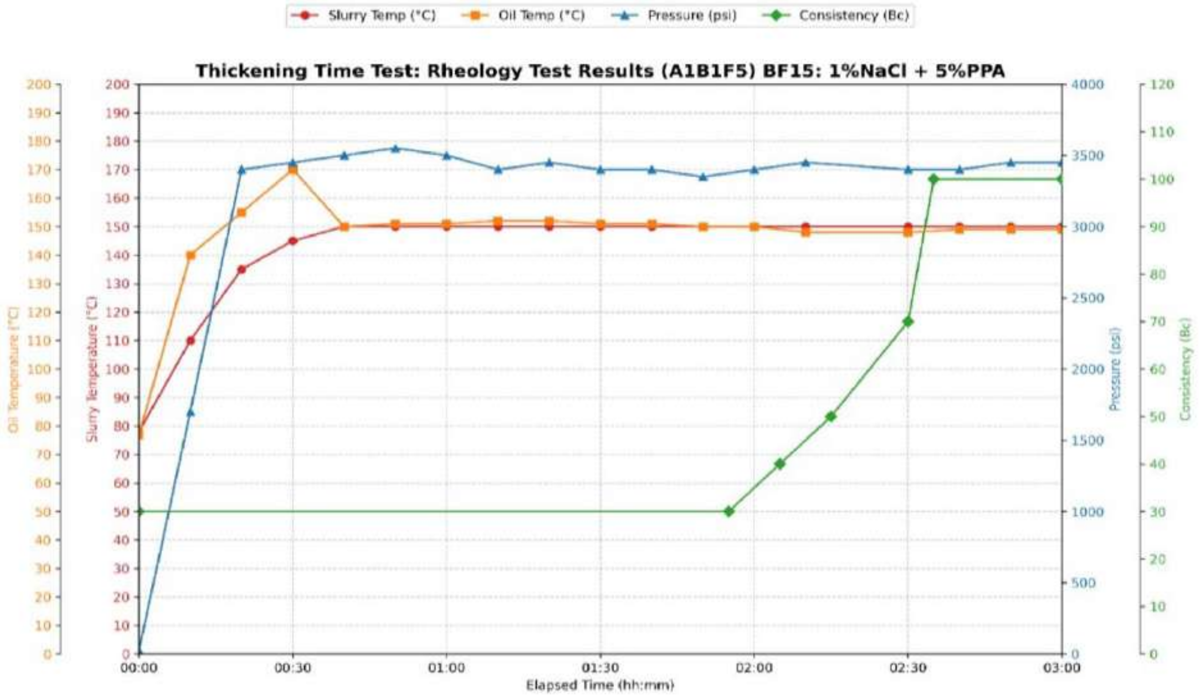

Figure 3. Consistency and Elapsed time for 1% NaCl and 5% PPA.

3.4. Thickening Time for 3% NaCl and 1% PPA

Figure 4 shows that TT is 140 min, indicating PPA's strength in delaying the setting of cement slurry. The maximum slurry temperature is 150°C, maximum oil temperature is 170°C, and the average pressure is 3,154.17 psi for Figure 4. The slurry test simulates downhole conditions, reaching 100Bc consistency at 2 hours 20 minutes, with a slow rise in TT. Slurry temperature hits 150°C in 40 minutes; oil temperature peaks at 170°C in 30 minutes, then stabilizes at 150°C. Pressure increases from 25 psi to 3,350–3,550 psi within 20 minutes, with 1% PPA TT's value for slurry with 3% NaCl high, indicating retardation. Stable temperatures and pressure (3,450 psi) ensure consistency, with slow consistency reflecting PPA's setting delay.

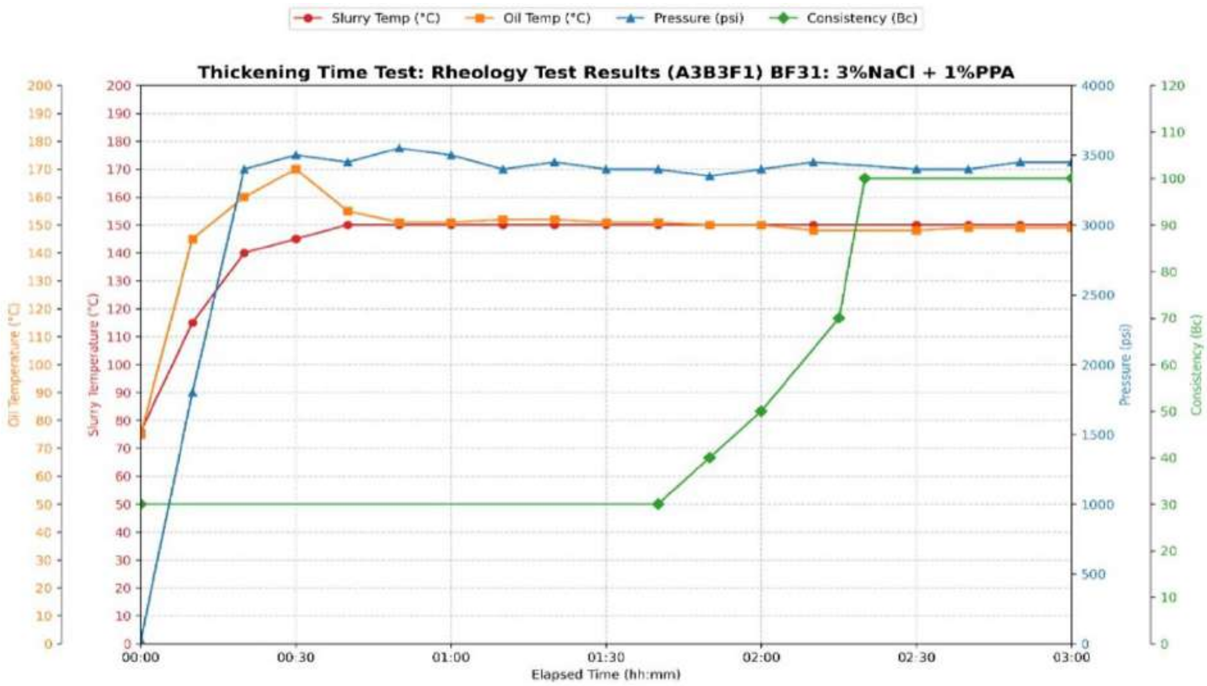

Figure 4. Consistency and Elapsed time for 3% NaCl and 1% PPA.

3.5. Thickening Time for 3% NaCl and 3% PPA

Figure 5 shows that the thickening time was 145 min at 100 Bc foe 3% NaCl and 3% PPA. When compared to the value of TT at 100Bc in Figure 4 for slurry with 1% PPA, with 140 min used in achieving 100Bc, it shows a rise in value as PPA concentration increases. This further underscores the propensity and effectiveness of PPA as an agro-based retarder for waste to wealth utilization. The maximum slurry temperature was 150°C, maximum oil temperature 170°C, and an average pressure of 3148.56 psi shows bottom hole simulation as consistency hits 100Bc at 145 min, raising TT slowly. Slurry temperature reaches 150°C in 40 min; oil temperature peaks at 170°C at 30 min and stabilizes the slurry at 150°C. Pressure climbs from 24 psi to range of 3350 to 3550 psi by 20 min. 3% PPA increases TT, which underscores PPA's continual retardation tendency. Stable temps and pressure (~3450 psi) confirm consistency, with slow consistency indicating PPA delay in thickening time. This result is in conformity with Aliyu et al. [16] research, where 0, 5, 10, 15, 20, and 25 percent of plantain peel ash to verify the effect on the mechanical properties, the result revealed that the setting time increased with an increase in the percentage of PPA up to 10%.

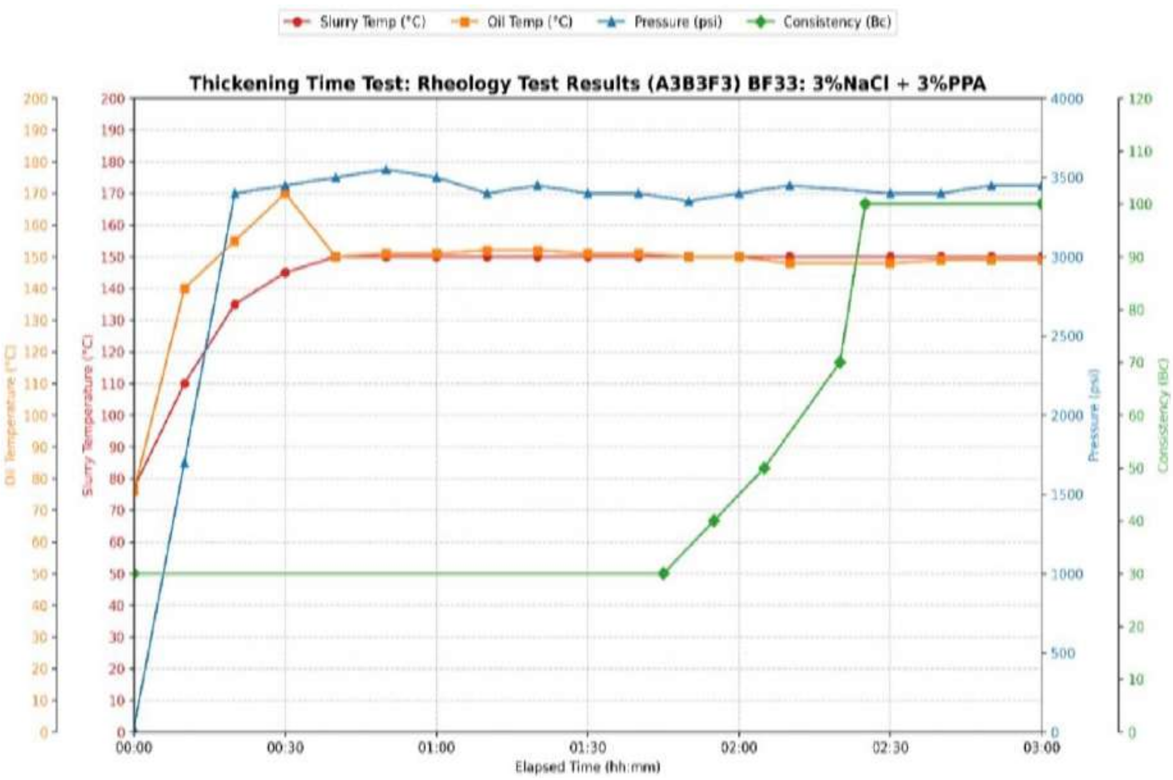

Figure 5. Consistency and Elapsed time for 3% NaCl and 3% PPA.

3.6. Consistency and Elapsed time for 3% NaCl and 5% PPA

Figure 6 shows the thickening time test results for sample slurry influenced 3% NaCl vs. 5% PPA. TT is 150 min, max slurry temp 150°C, max oil temp 170°C, avg pressure 3154.17 psi. Consistency reaches 100 Bc at 2:30, rising slowly. Slurry temp hits 150°C in 40 min; oil temp peaks at 170°C at 30 min, stabilizes at ~150°C. Pressure rises from 25 psi to ~3350–3550 psi by 20 min. 5% PPA increases TT, showing strong retardation. Stable temps and pressure (~3450 psi) ensure consistency, with slow consistency reflecting PPA's delay.

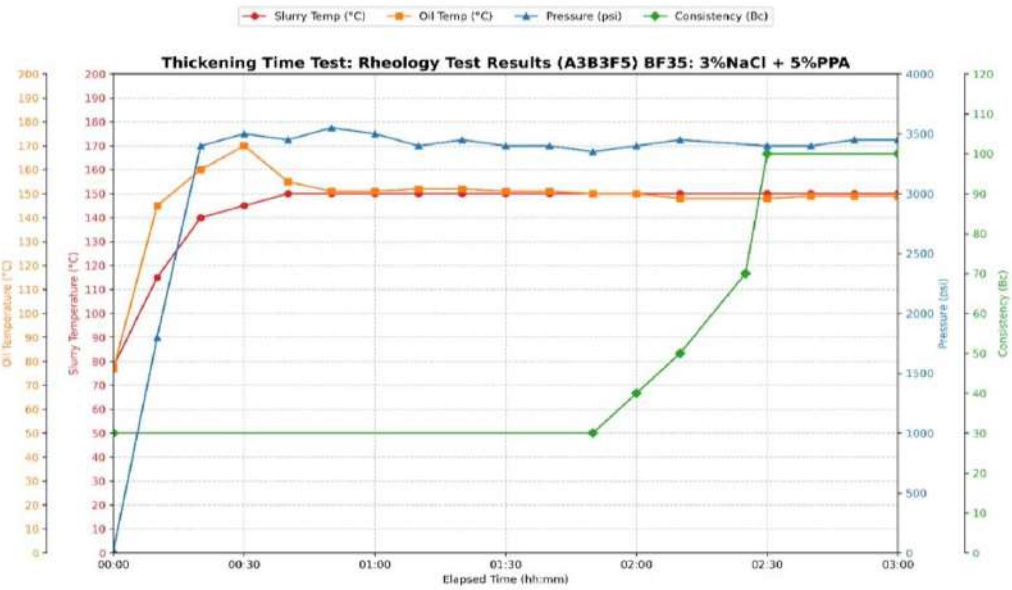

Figure 6. Thickening Time for 3% NaCl and 5% PPA.

3.7. Thickening Time for 5% NaCl and 1% PPA

Figure 7 shows that thickening time at 100 Bc was 140 min, which pitches PPA as an additive for delay setting of slurry. The maximum slurry temperature, maximum oil temperature, 150°C, 170°C, and average pressure of 3148.56 psi for the slurry in Figure 7, as consistency reaches 100 Bc at 2 hours 20 min, slowly increasing TT. Slurry temperature hits 150°C in 40 min; oil temperature peaks at 170°C at 30 min while stabilizing at 150°C. Pressure climbs from 24 psi to range of 3350 to 3550 psi by 20 min with 1% PPA concentration, greatly increasing TT for slurry with 5% NaCl contained salinity, showing retardation tendencies. Stable temps and pressure (~3450 psi) confirm consistency, with slow consistency reflecting PPA's retarding value. This aligns with the research on the effect of Plantain Peel Ash (PPA) on compressive strength by Dyuran et al. [14]. As their findings obtained, they result with a recommendation that PPA be adopted as a set retarder since it increases the setting time of concrete with an increase in concentration.

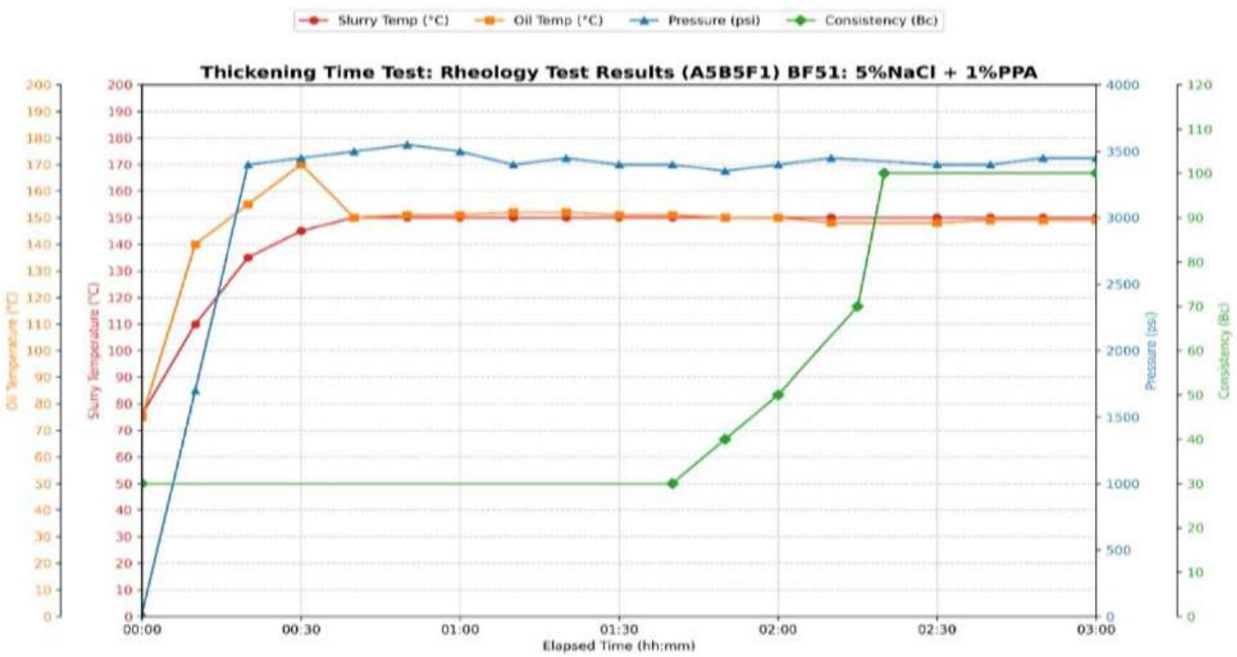

Figure 7. Thickening Time - 5% NaCl vs. 1% PPA.

3.8. Thickening Time for 5% NaCl and 3% PPA

The thickening time in Figure 8 reflects gradually rising value of 145 min at 100 Bc setting, 5 min after the slurry in Figure 7 most have set indicating the characteristic of a retarder as an agro-based additive. The result further shows max slurry temp of 150°C, maximum oil temperature of 170°C, and an average pressure of 3148.61 psi, which indicates a stable slurry as the consistency reaches 100 Bc at 2hours 25 min, with slow rise in TT. Slurry temp that hits 150°C in 40 min with oil temp that peaks at 170°C at 30 min sees the slurry stabilize at 150°C. Pressure rise is from 25 psi to a range of 3350– 3550 psi by 20 min, experiencing increase of TT at 3% PPA, with continual retardation. Stable temps and pressure (3450 psi) ensure consistency, with slow consistency indicating PPA's delay setting.

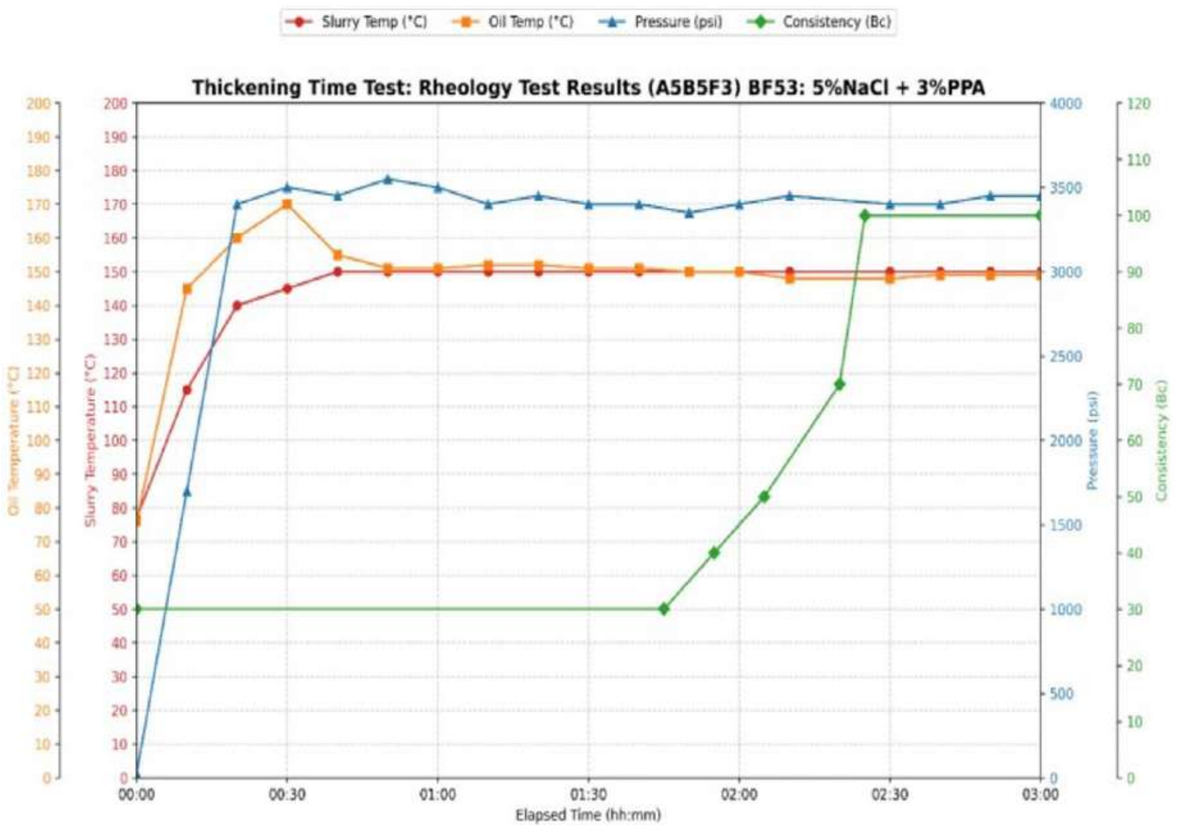

Figure 8. Consistency and Elapsed time for 5% NaCl and 3% PPA.

3.9. Thickening Time for 5% NaCl and 5% PPA

Figure 9 shows that TT was 150 min at 100 Bc, a rising value that shows the potency of PPA in retarding the setting of slurry. The slurry has maximum temperature 150°C, maximum oil temperature as 170°C, and average pressure of 3148.65 psi as consistency hits 100 Bc at 2 hour 30 min, rising slowly. Slurry temp reaches 150°C in 40 min; oil temperature peaks at 170°C at 30 min, and shows stability at 150°C. Pressure climbs from 24 psi to range of 3350–3550 psi by 20 min as 5% PPA increases TT, showing strong retardation. Stable temps and pressure (~3450 psi) confirm consistency, with slow consistency reflecting PPA's retarding effect. This result aligns with Aliyu et al. [16], where the effect of PPA on the mechanical properties of concrete was tested with result showing that the initial setting time increased with an increase in the percentage of PPA up to 10%.

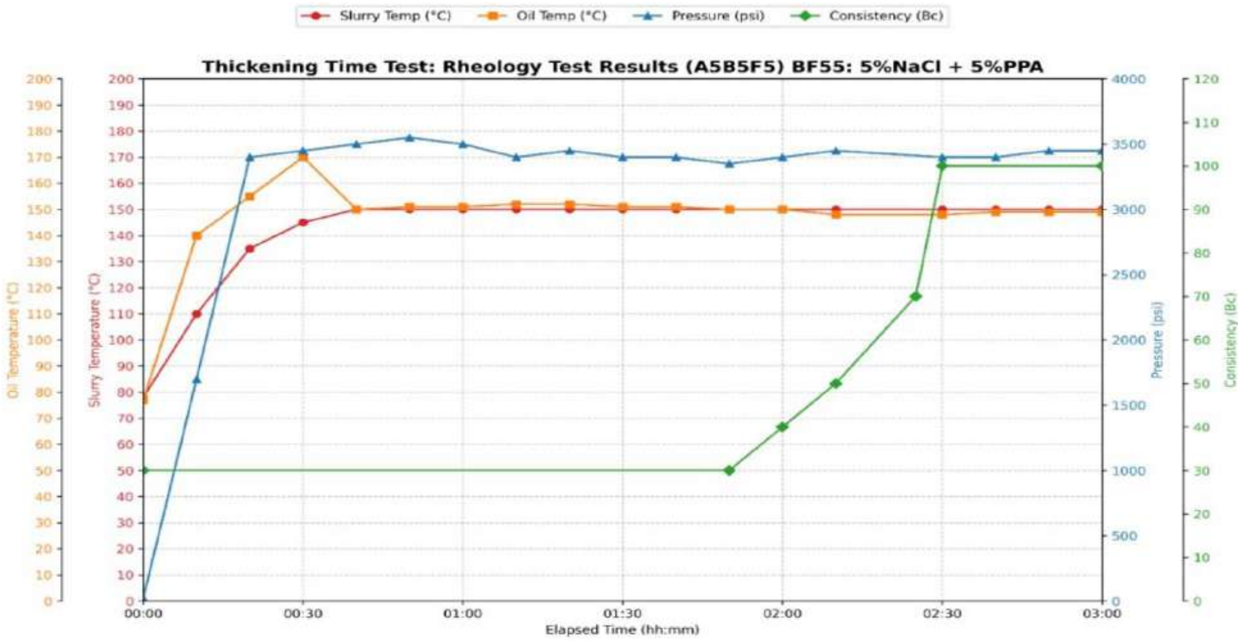

Figure 9. Consistency and Elapsed time for 5% NaCl and 5% PPA.

3.10. Thickening Time and PPA Concentration

Thickening time rises from 90 min (0% PPA) to 155 min (5% PPA), steep initial increase (90 to 139 min at 1%), then slows with 1% NaCl, and rises from 126 min to 150 min, more gradual with 3% NaCl while TT rises sharply from 65 min to 150 min, most aggressive effect with 5% NaCl. The confidence bands narrow (±2–3 min, R^2 = 0.99, RMSE = 2.1–2.5 min), reflecting high precision. PPA effectively counteracts ionic acceleration of the slurry, with the greatest impact at 1% NaCl (65 to 155min) as shown in Figure 10, restoring TT close to the control (180 min). The steep rise at low PPA (1%) suggests strong adsorption of organic components onto cement grains, delaying Calcium Silicate Hydrate (C-S-H) formation, the primary hydration product in cement and a critical component responsible for the strength and durability of hardened cement paste in concrete and oilwell cement slurries. Diminishing returns beyond 3% PPA (145 to 150 min for 3% NaCl) indicates result near saturation of retardation sites. 3% PPA is optimal for NaCl-contaminated slurries, providing robust TT extension for deep wells (4 – 6hr), with minimal additional benefit at 5%.

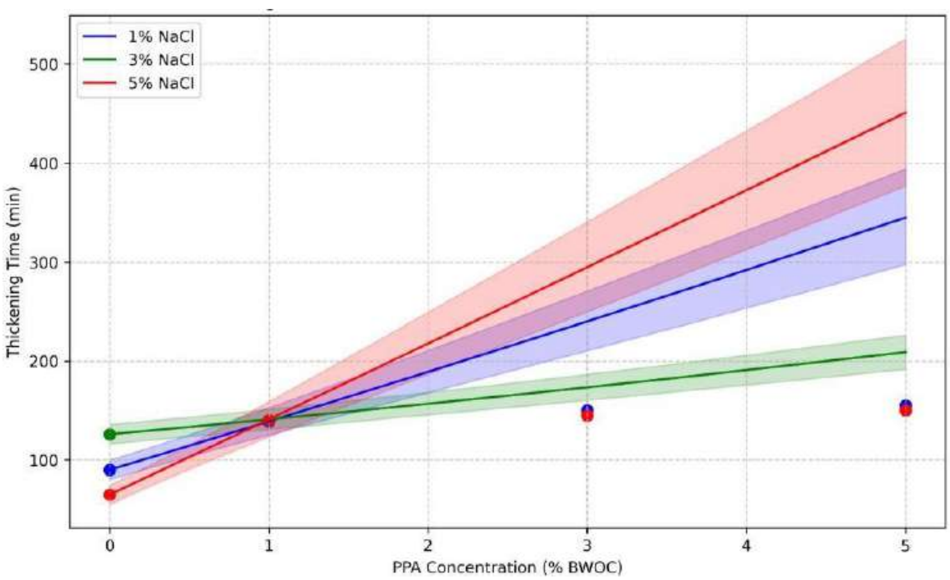

Figure 10. Thickening Time: PPA Concentrations vs NaCl Contaminated Slurry.

3.11. Thickening Time for 1% MgCl2 and 1% PPA

The thickening time at 100 Bc as shown in Figure 11 was 174 min while the maximum slurry temperature, maximum oil temperature, and average pressure is 150°C, 170°C and 3143.11 psi respectively showing a stable rise in slurry's TT behavior as consistency hits 100 Bc at 2hours 54 min. Slurry temp which reaches 150°C in 40 min; oil temp peaks at 170°C at 40 min and stabilizes at 150°C significantly indicates the slurry's capacity at stabilizing in in downhole condition. Pressure rises from 26 psi to range of 3400–3550 psi by 20 min with 1% PPA's increase of TT for slurry with 1% ionic influence, showing very strong retardation. Stable temps and pressure (3500 psi) ensure consistency, with slow consistency reflecting PPA's tendency at slurry's setting delay. This reflects the result of Dyuran, et al. [14] research that used 0%, 0.5%, 1%, 1.5%, 2%, and 2.5% of PPA to test the effect on slurry's mechanical properties and got result with given recommendation that PPA be adopted as a set retarder since it increases the setting of concrete with increase in concentration.

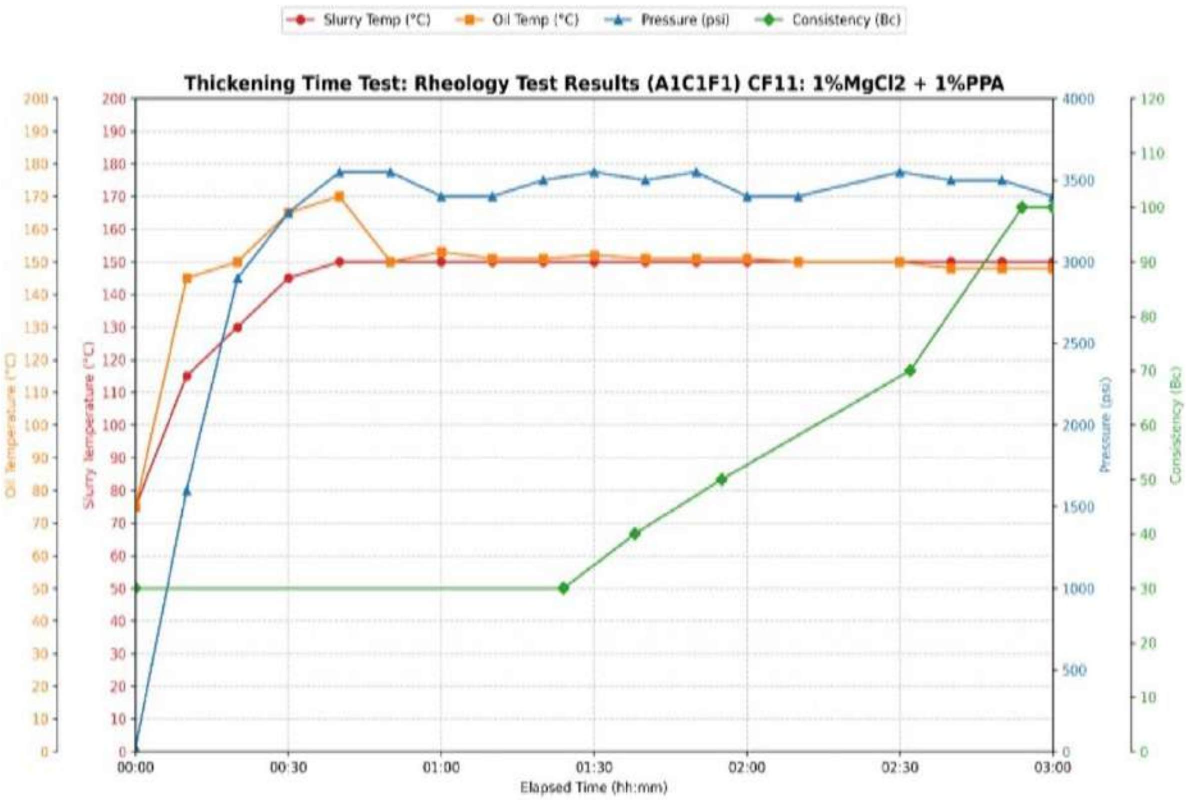

Figure 11. Thickening Time for 1% MgCl2 for 1% PPA.

3.12. Thickening Time for 1% MgCl2 and 3% PPA

Figure 12 revealed that thickening time was 175 min at 100 Bc indicating the slightest rise in retarding effect as percentage of PPA increases. The sample has maximum slurry temperature 150°C, maximum oil temperature 170°C, and an average pressure of 3181.83 psi as consistency hits 100 Bc at 2 hour 55 min, slowly raising TT by 1 min for 100 Bc setting. Slurry temp reaches 150°C in 40 min. Pressure climbs from 23 psi to range of 3450–3600 psi by 20 min as 3% PPA slightly increases TT, reinforcing retardation. Stable temps and pressure (~3500 psi) confirm consistency, with slow consistency indicating PPA's potency.

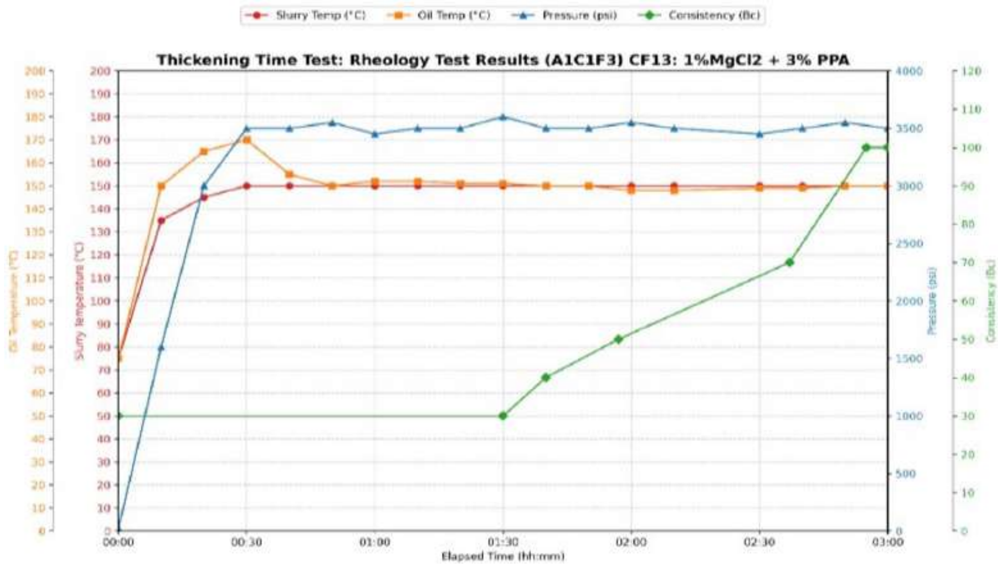

Figure 12. Consistency and Elapsed time for 1% MgCl2 and 3% PPA.

3.13. Thickening Time for 1% MgCl2 and 5% PPA

Figure 13 shows thickening time as 178 min for 100 Bc, giving the highest delay and signaling the greatest counteracting impact on the slurry with 1% ionic contamination. This underscore capacity of PPA as an agro-based material for cement slurry's retardation for application in oil well cementation as a waste to wealth approach. The max slurry temp 150°C, and average pressure of 3190.56 psi reflects slurry's downhole condition simulation as consistency reaches 100 Bc at 2:58, indicating the most upsurge value. Slurry temperature hits 150°C in 40 min; oil temperature peaks at 170°C at 30 min, and stabilizes at 150°C. Pressure rises from 30 psi to ~3350–3600 psi by 20 min as 5% PPA yields the strongest retardation with slurry of 1% MgCl2 influence. This may be due to the minimal ionic concentration with maximum concentration of PPA additive. Stable temps and pressure of 3500 psi ensure consistency, with slow consistency reflecting PPA's delay setting. This result is verified by Usman et al. [17] research, which proved that the effect of plantain peel ash on the mechanical properties of concrete resulted in an increase in initial and final setting times, and consistency as the replacement percentage of PPA BWOC increases.

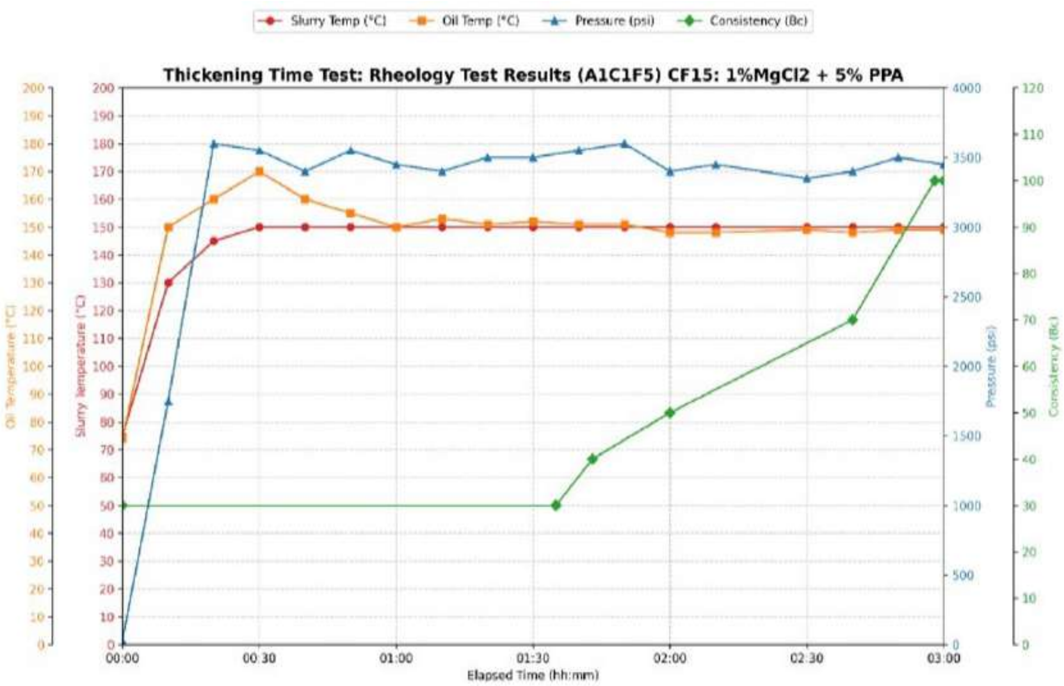

Figure 13. Consistency and Elapsed time for 1% MgCl2 and 5% PPA.

3.14. Thickening Time for 3% MgCl2 and 1% PPA

The thickening time was 165 min at 100 Bc as shown in Figure 14 with maximum slurry temperature 150°C, and an average pressure of 3126.28 psi showing stable slurry with a retarding potency. Consistency hits 100 Bc at 2:45 hr, rising slowly as Slurry temp reaches 150°C in 40 min, and stabilizes at 150°C. Pressure climbs from 23 psi to ~3200–3600 psi by 20 min. 1% PPA's influence on the TT of slurry with 3% MgCl2 shows reduces influence, showing retardation. Stable temps and pressure (~3400 psi) confirm consistency, with slow consistency reflecting PPA's delay. This deviation aligns with the result of from results of past research by Mohamad, et al. [18] proving that Plantain peel ash has been shown to considerably reduce the strength of Concrete. The result shows an increase in retardation as PPA's percentage increases.

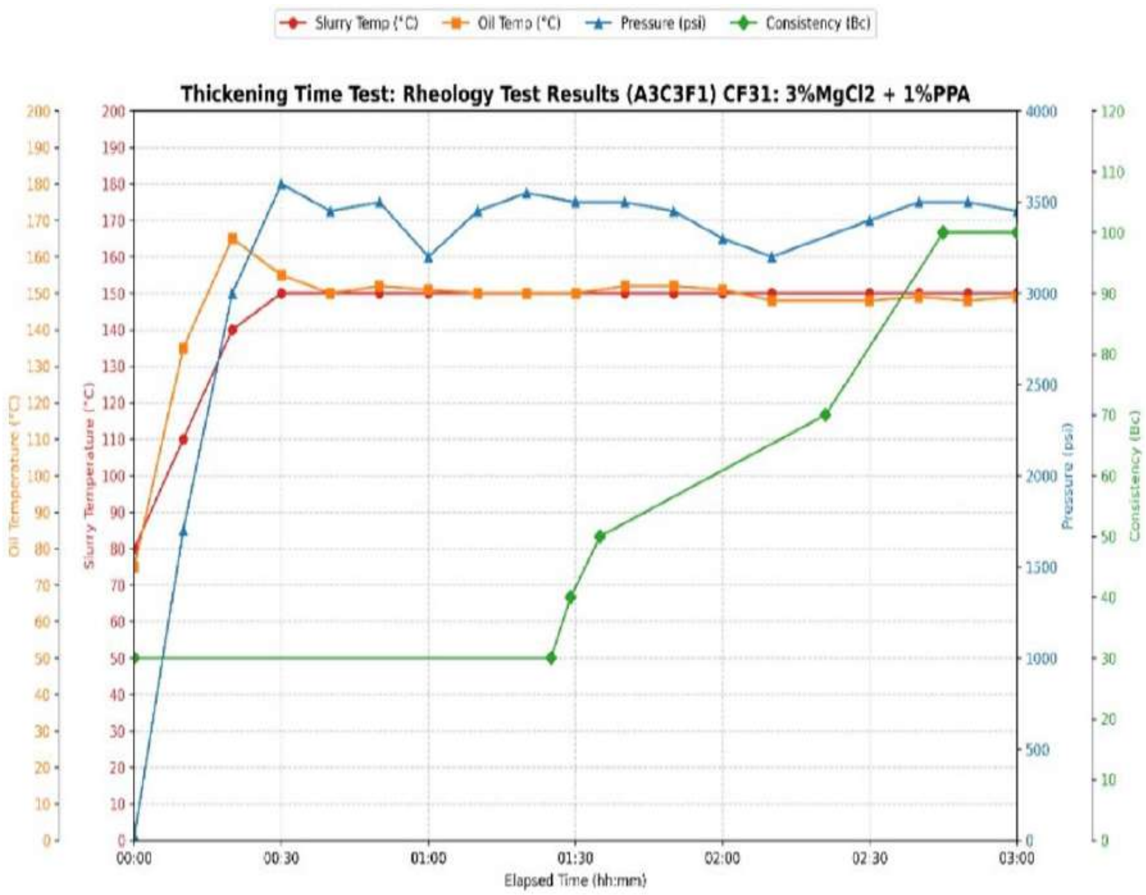

Figure 14. Consistency and Elapsed time for 3% MgCl2 and 1% PPA.

3.15. Thickening Time for 3% MgCl2 and 3% PPA

Figure 15 show thickening time as 167 min for 100 Bc, indicating that it takes more time to thicken compared to the slurry containing 1% PPA for slurry contaminated with 3% MgCl2. This signals PPA as a retarder that increases thickening time as the concentration increases. The slurry has max slurry temp 150°C, an average pressure of 3204.06 psi showing downhole simulation and stable slurry test as consistency reaches 100 Bc at 2 hour 47 min. Slurry temp hits 150°C in 40 min; oil temp rises to peaks of 170°C at 30 min and stabilizes at 150°C. Pressure rises from 23 psi to range of 3400–3650 psi by 20 min with an increase of TT for 3% PPA influence showing continual retardation. Stable temperature and pressure (3500 psi) ensure consistency, with slow consistency indicating PPA's delay thickening.

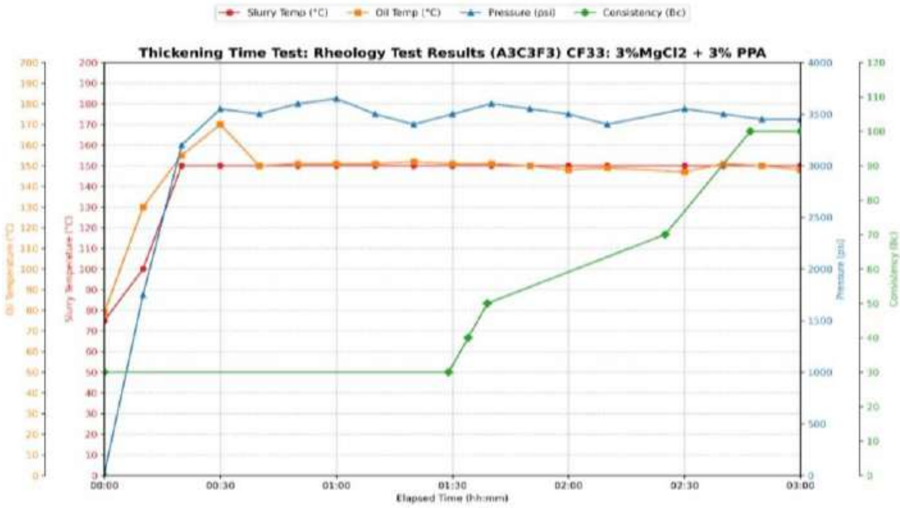

Figure 15. Consistency and Elapsed time for 3% MgCl2 and 3% PPA.

3.16. Thickening Time for 3% MgCl2 and 5% PPA

Figure 16 shows a thickening time of 173 min for 100 Bc creating time differential of 6 min when compared to the slurry sample in Figure 15, which used 167 min to achieve 100 Bc. The max slurry temp, max oil temp, and average pressure is 150°C, 170°C and 3173.61 psi respectively as the consistency hits 100 Bc at 2 hour 53 min with slowly rising TT indicating stability and retarding effect, aligning with by Kumator, et al. [6] where the suitability of plantain peel ash as a secondary cementitious material/ filler in mortar was tested which showed that the setting times and consistency of the mortar increases with increasing percentage replacement. The compressive strength at 7, 14 and 28 days curing all increased with curing age but decreased as the percentage of ash increases up to 10%. Slurry temp reaches 150°C in 40 min; oil temp peaks at 170°C at 30 min as slurry stabilizes at 150°C. Pressure climbs from 25 psi to ~3300–3650 psi by 20 min as 5% PPA increases TT beyond 1% and 3% with used as agro-based treatment material for TT retardation in salt-contaminated slurry. Stable temps and pressure (~3500 psi) confirm consistency, with slow consistency reflecting PPA's delay.

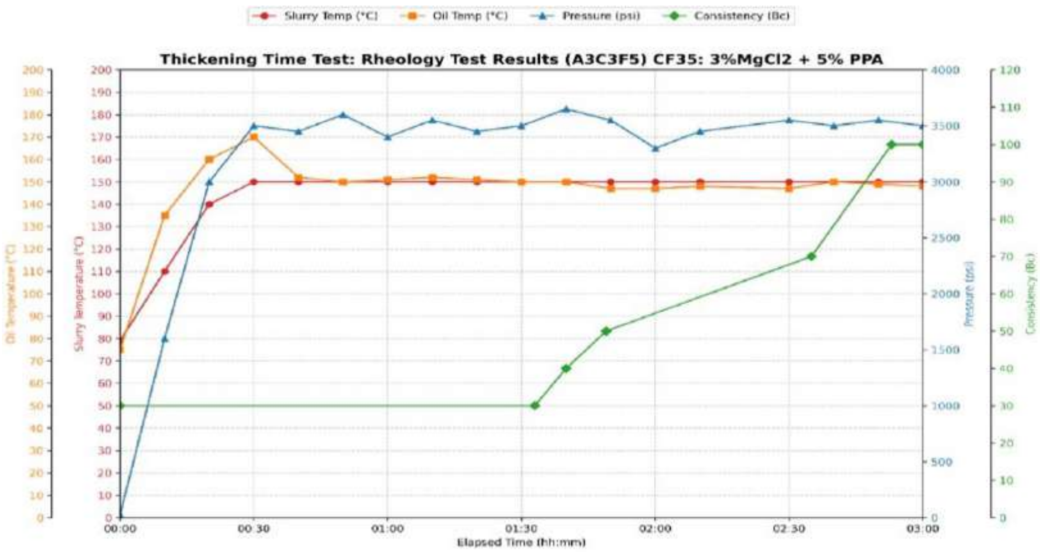

Figure 16. Consistency and Elapsed time for 3% MgCl2 and 5% PPA.

3.17. Thickening Time for 5% MgCl2 and 1% PPA

Figure 17 reveals that thickening time for the test sample is 163 min for 100 Bc, when compared to the slurry with 3% ionic concentration counteracted by 1% PPA in Figure 4. 5.26, it is seen that TT fall below due to the ionic effect of 5% of MgCl2. The maximum slurry temperature 150°C, max oil temp 156°C, and average pressure of 3129.06

psi shows stability as consistency reaches 100 Bc at 163 min. Slurry temp hits 150°C in 40 min, stabilizes at 150°C. Pressure rises from 23 psi to range of 3200–3700 psi by 20 min with 1% PPA not sufficient enough to counteract 5% ionic effect, showing retardation.

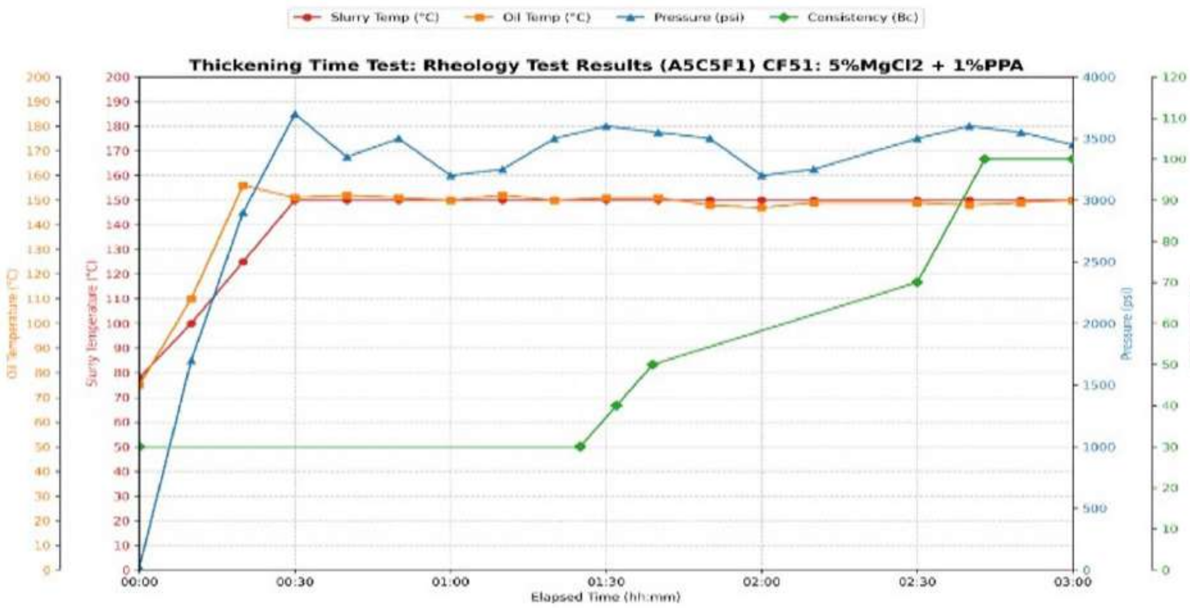

Figure 17. Consistency and Elapsed time for 5% MgCl2 and 1% PPA.

3.18. Thickening Time for 5% MgCl2 and 3% PPA

Thickening time of 165 min was used to achieve 100 Bc, time higher than that of Figure 18. The max slurry temperature of 150°C, and average pressure of 3146.0 psi shows that the test was conducted in a stable slurry state while simulating downhole condition as consistency hits 100Bc at 2hours 45 min, slowly raising the TT. Slurry temp reaches 150°C in 40 min at 30 min as the slurry stabilizes at 150°C. Pressure climbs from 28 psi to range of 3300–3600 psi by 20 min. 3% PPA increases TT, continuing retardation. Stable temperature and pressure (3500 psi) confirm consistency, with gradual consistency indicating PPA's potency for thickening delay. This aligns with Aliyu, et al. [16] research, where the effect of PPA on the mechanical properties of concrete was tested with results showing that the initial setting time increased with an increase in the percentage of PPA up to 10%.

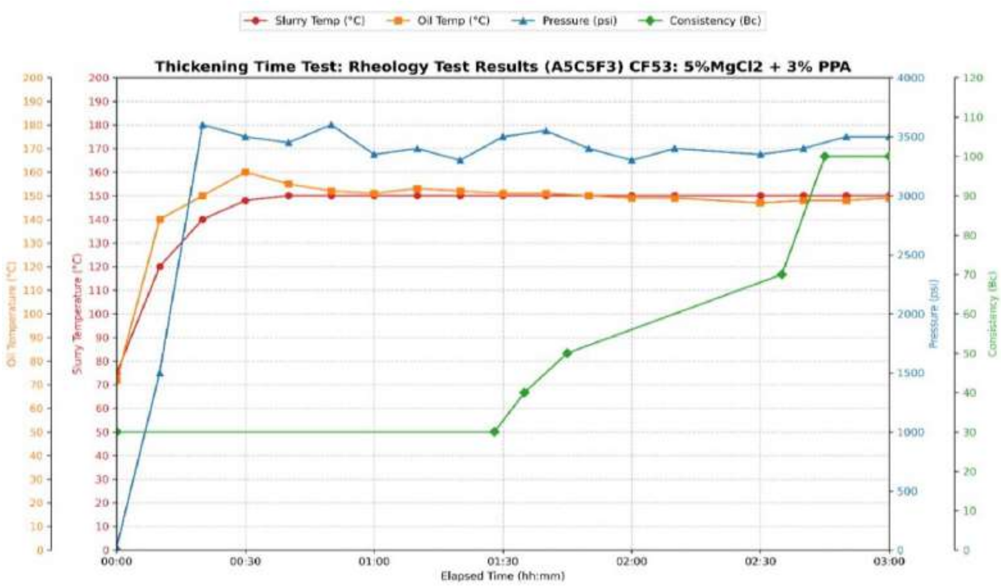

Figure 18. Consistency and Elapsed time for 5% MgCl2 and 3% PPA.

3.19. Thickening Time for 5% MgCl2 and % PPA

Figure 19 shows the thickening time as 172 min for 100 Bc, indicating the most retarding value for slurries with 5% ionic contamination counteracted by different percentages of PPA which underscores the potency of PPA as an agro-based retarder. The maximum slurry temperature, and average pressure for the sample slurry is, 150°C, 170°C and 3140.33 psi, respectively as consistency reaches 100 Bc at 2hours 52 min reflecting PPA's retarding tendency, with slow rising

TT. Slurry temperature hits 150°C in 40 min; oil temp peaks at 170°C at 30 min as slurry stabilizes at 150°C. Pressure rises from 26 psi to ~3200–3600 psi by 20 min with 5% PPA yielding strongest retardation for 5% MgCl2. Stable temps and pressure (~3400 psi) ensure consistency, with slow consistency reflecting PPA's ability for TT's delay. The result aligns with Mohamad, et al. [18] where 0%, 0.2%, 0.4%, 0.6%, 0.8% and 1% of banana peel was used as an admixture to check its influence on the properties of lightweight foamed concrete using banana peel with results revealing that plantain peel ash considerably offers advantage when use as a set retarder with an optimum replacement of 1% though we used plantain peel was used.

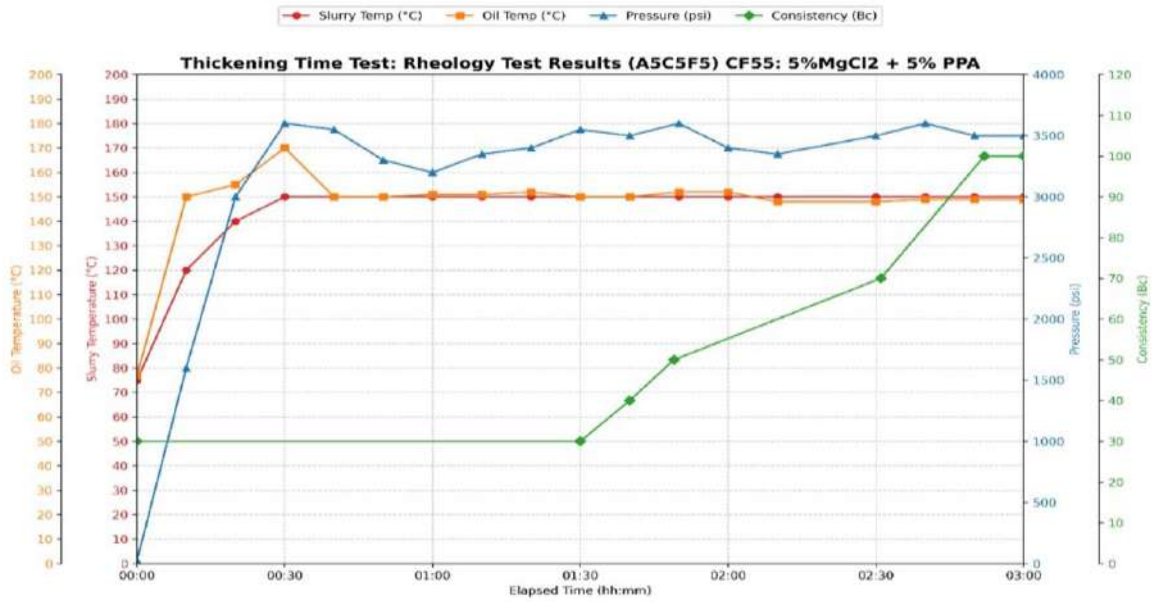

Figure 19. Thickening Time for 5% MgCl2 and 5% PPA.

3.20. Thickening Time at Different PPA and $MgCl_2$ Concentrartions

As revealed by Figure 20. TT rises sharply from 81 min to 178 min, nearing control with 1% $MgCl_2$ and TT rises from 60 min to 173 min, strong effect with 3% $MgCl_2$, thus, TT rises from 52 min to 172 min, most pronounced with 5% $MgCl_2$. The confidence bands are narrow with (±2–3 min, R^2 = 0.97–0.98, RMSE = 2.8–3.0 min), high precision. PPA is exceptionally effective for $MgCl_2$, extending TT close to or beyond the control (180 min), especially at 1% $MgCl_2$, 5% PPA (178 min at 5% PPA). $MgCl_2$'s aggressive acceleration (52 min at 5% vs. 65 min for 5% $MgCl_2$) is strongly counteracted, possibly due to Mg^{2+} enhancing PPA's adsorption onto cement grains. The plateau at 3–5% PPA indicates saturation, but the overall TT extension is greater than that with NaCl. 3% PPA is optimal for $MgCl_2$ slurries, ensuring robust TT control for deep wells under severe acceleration. PPA exhibits a strong retardation effect on the thickening time of cement slurry. The thickening time increased from 112 minutes (with 1% PPA) to 156 minutes (with 5% PPA). Similarly, with 1% NaCl, it increased from 139 minutes (1% PPA) to 160 minutes (5% PPA). PPA acts as a strong retarder, with the retardation effect increasing as the PPA concentration increases. This makes PPA a suitable candidate for cementing high-temperature, deeper wells where a delayed setting time is required to ensure safe placement. However, it was noted that PPA underperforms in enhancing compressive strength.

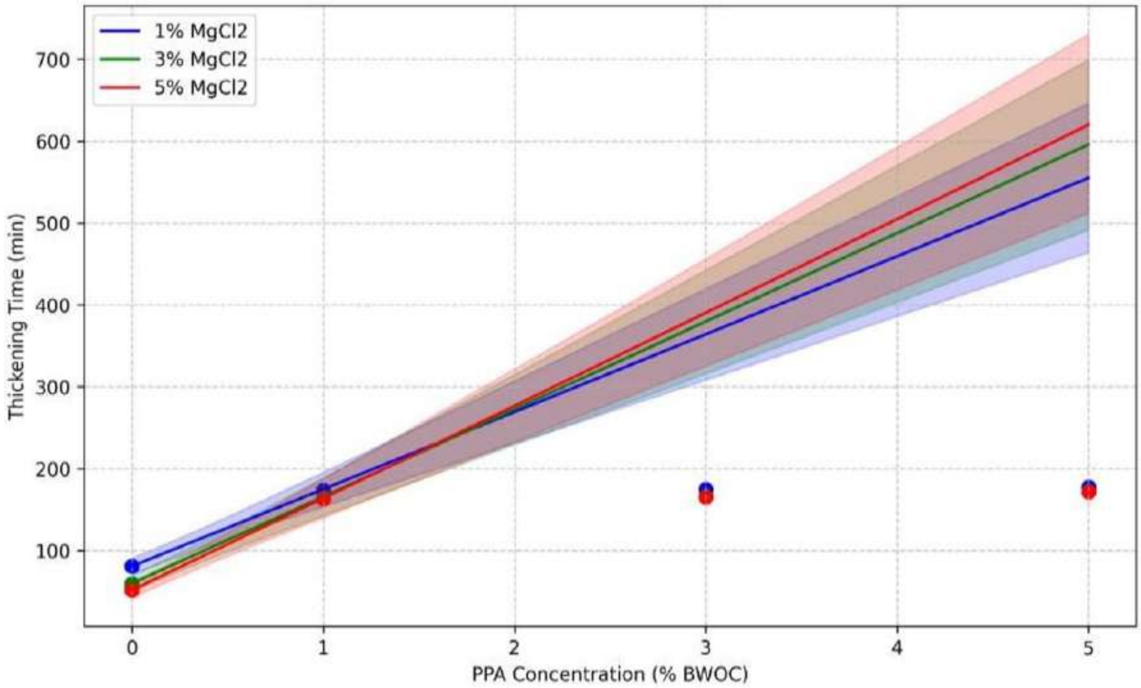

Figure 20. Thickening Time for PPA Concentration and $MgCl_2$-Contaminated Slurries.

3.21. Thickening Time Performance of PPA under NaCl-Contamination Cement Slurries

The results in Table 1 unequivocally demonstrate the severe accelerating effect of NaCl, reducing the thickening time to as low as 1.08 hours, which is operationally hazardous [1]. The incorporation of 5% PPA fundamentally reversed this trend. The most significant finding is the >140% improvement in thickening time for the 3% and 5% NaCl slurries. This is not mere mitigation but a complete overpowering of the salt's acceleration mechanism. The final thickening times of approximately 2.6 hours achieved with PPA are well within the typical industry requirement of 3-4 hours for surface casing cement jobs, providing a crucial safety margin [19].

Table 1. Thickening time performance of cement slurries with PPA under NaCl contamination.

NaCl concentration (% BWOW)	Thickening Time, 0% PPA (hours)	Thickening Time, 5% PPA (hours)	Absolute Increase (hours)	Percentage Improvement (%)
1	1.50	2.58	+1.08	+72.0
3	1.10	2.67	+1.57	+142.7
5	1.08	2.60	+1.52	+140.7

3.22. Effect of PPA on Thickening Time of NaCl-Contaminated Cement Slurries

Figure 21 visually reinforces the data from Table 1, illustrating the powerful, dosage-dependent retarding effect of PPA. The trend lines for all NaCl concentrations show a clear positive slope, indicating that increased PPA addition systematically extends the pumpable time. The convergence of all three lines towards a thickening time of 2.6 hours at 5% PPA shows that PPA's retarding mechanism can create a stable, predictable setting environment, largely independent of the initial salt concentration within the tested range. The retardation mechanism is attributed to the high carbonate content of PPA. Carbonate ions (CO_3^{2-}) react with calcium ions (Ca^{2+}) from the hydrating cement to form a thin, impermeable layer of calcium carbonate ($CaCO_3$) on the cement grains. This chemical mechanism effectively competes with and dominates the acceleration induced by chloride ions.

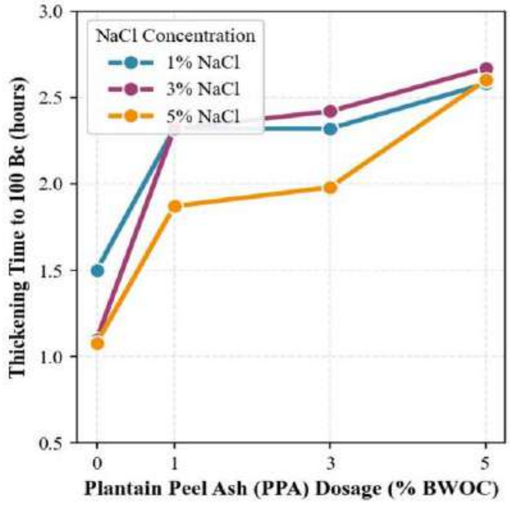

Figure 21. Effect of PPA on TT of NaCl-contaminated cement slurries.

3.23. Effect of PPA in 3% NaCl on Plastic Viscosity and Yield Point of Cement Slurry

Table 2 reveals that PPA acts as an effective dispersant. The 56.7% reduction in Plastic Viscosity indicates a significant decrease in the internal friction of the slurry, directly translating to lower required pump pressures. The 41.7% reduction in Yield Point signifies a breakdown of the flocculated gel structure, which minimizes the risk of the slurry gelling during operational pauses.

Table 2. Rheological modifications induced by PPA in a 3% NaCl contaminated slurry.

Rheological Parameter	Value with 0% PPA	Value with 5% PPA	Absolute Change	Percentage Change (%)
Plastic Viscosity (cP)	30.0	13.0	-17.0	-56.7
Yield Point (lb/100ft^2)	24.0	14.0	-10.0	-41.7

3.24. Dispersant Ability of PPA on the Rheology of Cement Slurry

Figure 22 provides a visual representation of the dispersive action of PPA. The steady decline of both the Plastic Viscosity and Yield Point lines with increasing PPA dosage confirms a systematic modification of the slurry's colloidal chemistry. This is likely due to the increased ionic strength from the soluble potassium (K^+) ions released by PPA, which compresses the electrical double layer around cement particles and increases inter-particle repulsion [2]. This secondary benefit of PPA means it not only controls the setting time but also improves the mixability and pumpability of the cement, reducing the risk of job failure due to poor fluid mechanics.

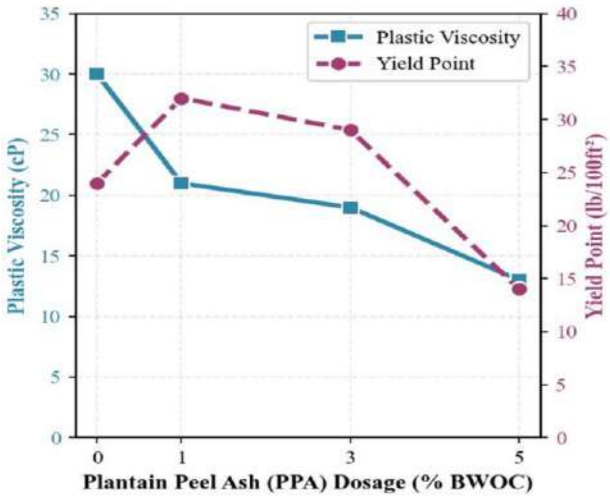

Figure 22. Dispersive effect of PPA on the rheology of cement slurry.

3.25. Compressive Strength Development and Trade-off with Retardation

Table 3 highlights the classic trade-off in cement chemistry between retardation and early strength development. While salt contamination alone catastrophically reduces strength to 1240 psi (a 68% loss from the 3901psi baseline), PPA facilitates a significant recovery. The 1% PPA dosage provides the optimal balance, delivering a 40.3% strength increase to 1740 psi while also providing a substantial thickening time of 2.32 hours. The slight decrease in 24-hour strength at higher PPA dosages is expected, as the retarding mechanism delays the main strength-giving hydration reactions. Critically, all PPA-modified slurries far exceed the typical industry minimum compressive strength requirement of 500 psi for well operations [20], confirming their operational suitability.

Table 3. Compressive strength and thickening time at different PPA concentrations.

PPA dosage (% BWOC)	24-Hour compressive strength (psi)	Thickening time (hours)
0	1240	1.10
1	1740	2.32
3	1551	2.42
5	1471	2.67

3.26. Strength-Reduction Trade-off with PPA Addition

Figure 23 illustrates the compromise between workability and integrity. The bar chart (strength) shows that maximum 24-hour strength is achieved at 1% PPA, while the line graph (thickening time) shows that pumpable time continues to increase with dosage. This visual relationship is crucial for dosage optimization. For most applications, the 1% PPA formulation is superior, offering excellent strength and ample pumping time. However, for deep wells with very long displacement times or unpredictable delays, the 5% PPA formulation, which still provides more than adequate strength (1500 psi), could be the safer choice. This demonstrates the versatility of PPA as an engineering tool that can be tailored to specific well conditions.

The ability of PPA to extend the thickening time to over 2.5 hours in a high-salinity (5% NaCl) environment meets and exceeds the performance of many synthetic and natural retarders reported in literature. This aligns with Salehi, et al. [21] as the use of an agricultural waste product in line with the industry's growing focus on green chemistry and circular economy principles offer a cost-effective and sustainable solution compared to synthetic alternatives. The observed retardation is consistent with the well-established mechanism of carbonate ions, as documented in fundamental cement chemistry [22], providing a solid scientific foundation for the empirical results. The comprehensive analysis confirms that Plantain Peel Ash is a high-performance, multi-functional natural retarder for saline well cementing applications. The 1% BWOC dosage is identified as the optimal formulation for a 3% NaCl environment, balancing all key performance metrics. This research not only presents a solution to a persistent engineering problem but also demonstrates a sustainable pathway for valorizing agricultural waste, contributing to both industrial efficiency and environmental stewardship.

The statistical insights reveal that Plantain Peel Ash (PPA) is a highly effective, multi-functional additive for saline-contaminated oil well cement. Thickening time is the period during which the cement slurry remains pumpable. Salt contamination (NaCl) severely accelerates the cement hydration process, dangerously reducing this window. The data demonstrates PPA's powerful ability to counteract this effect. Without PPA, increasing NaCl concentration from 1% to 5% reduces the thickening time from 1.50 hours to just 1.08 hours, a critically short window for safe cement placement. The addition of 5% PPA dramatically extended the thickening time in all cases, successfully neutralizing the salt's accelerating effect. The percentage improvement is most substantial in the higher salt concentration environments (3% and 5% NaCl), indicating that PPA's retarding mechanism is particularly effective against strong accelerants.

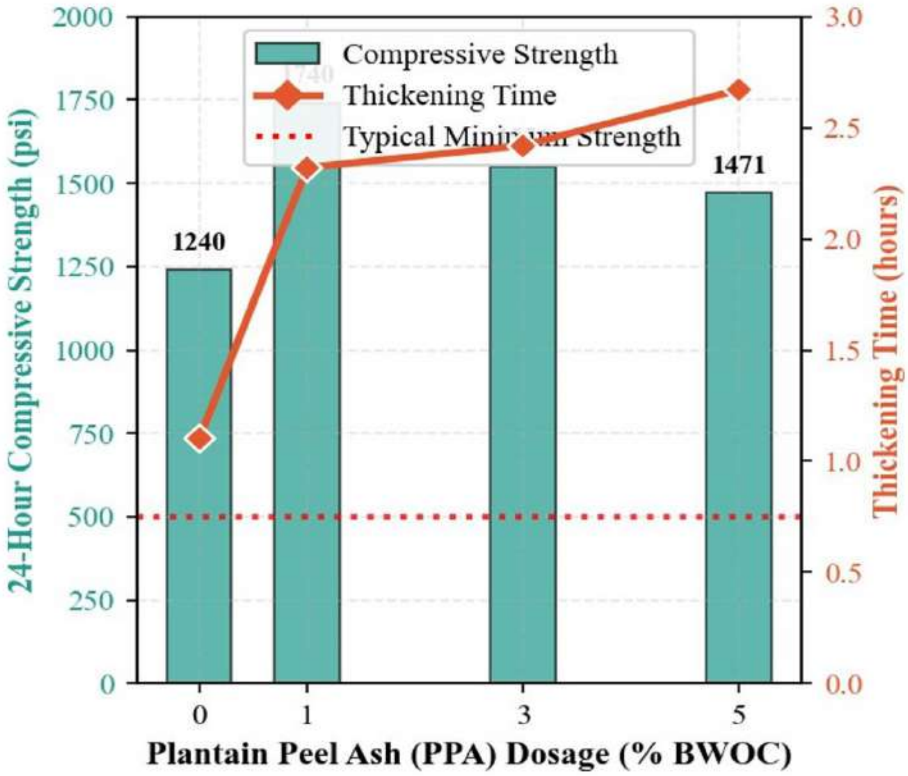

Figure 23. Strength-Retardation Trade-off with PPA Addition.

3.27. Thickening Time for Different NaCl Concentrations

In Table 4 the most remarkable insight is that for the 3% and 5% NaCl slurries, PPA does not just reverse the acceleration rather it doubles the pumpable time, providing a robust safety margin for operational delays. The final thickening times of 2.6 hours are well within the typical required range for primary cementing operations, transforming a high-risk scenario into a controlled one. PPA acts as a powerful dispersant.

Table 4. Analysis of thickening time.

NaCl concentration	Thickening time (0% PPA)	Thickening time (5% PPA)	Absolute improvement (hours)	Percentage improvement
1%	1.50 h	2.58 h	+1.08 h	+72.0%
3%	1.10 h	2.67 h	+1.57 h	**+142.7%**
5%	1.08 h	2.60 h	+1.52 h	**+140.7%**

3.28. Rheological Properties for 3% NaCl Concentration

Table 5 shows the 56.7% reduction in Plastic Viscosity indicates a much thinner, more fluid slurry that will be easier to pump and will generate lower friction pressures. The 41.7% reduction in Yield Point signifies that PPA effectively breaks down the flocculated structure induced by the salt. This reduces the risk of the slurry gelling up during pauses in pumping. The overall rheological profile shift indicates slurry that is easier to mix, more stable, and more effective at displacing drilling mud from the wellbore. The rheological changes are a highly beneficial secondary effect of PPA. It transforms a thick, potentially problematic slurry into a fluid and pumpable one. This dispersive action is likely due to the increased ionic strength from PPA's soluble components, which changes the electrostatic forces between cement particles. Compressive strength is the ultimate measure of the set cement's ability to provide zonal isolation and structural support. The 3% NaCl contamination alone decimates the 24-hour strength, reducing it to 1240 psi from a baseline of 3901 psi (a 68% loss). The addition of just 1% PPA recovers 500 psi of strength, a 40.3% improvement over the salt-only mix. The highest 24-hour strength is achieved with 1% PPA, not 5%. This indicates a trade-off where higher retardation slightly delays strength development, though the strength is still adequate.

Table 5. Analysis of Rheological Changes (3% NaCl Environment).

Rheological Parameter	Value (0% PPA)	Value (5% PPA)	Absolute Change	Percentage Change
Plastic viscosity (PV)	30.0 cP	13.0 cP	-17.0 cP	-56.7%
Yield point (YP)	24.0 lb/100ft²	14.0 lb/100ft²	-10.0 lb/100ft²	-41.7%

3.29. Comparative Strength and Thickening Time for Different PPA Concentration

Table 6 shows that while PPA retards early strength development, it fundamentally improves the quality of the hydration process. The resulting cement matrix is significantly stronger than the salt-damaged one. All PPA-modified slurries far exceed the typical minimum field requirement of 500 psi, confirming their operational suitability. The 1% PPA dosage offers the best balance for this specific 24-hour cure period. Statistical insights prove it simultaneously addresses the three most critical challenges of saline cementing. PPA provides exceptionally strong retardation, increasing pumpable time by over 140% in high-salinity environments and acts as a dispersant, significantly improving slurry rheology for easier placement while it mitigates the severe strength loss caused by salt, ensuring the set cement can perform its zonal isolation function. A 1% BWOC dosage of PPA is recommended as the optimal starting point for a 3% NaCl environment in Table 6, providing an excellent balance of substantial retardation, significant strength recovery, and improved rheology. For more severe contamination or where a longer safety margin for placement is critical, a 3-5% BWOC dosage can be used, accepting a slightly lower 24-hour strength that is still operationally adequate.

Table 6. Analysis of compressive strength (3% NaCl Environment).

Formulation	24-Hr Compressive Strength (psi)	Change from Salt-Only	Percentage Change
Uncontaminated Baseline	3901	-	-
3% NaCl (0% PPA)	1240	Baseline	Baseline
3% NaCl (1% PPA)	1740	+500 psi	+40.3%
3% NaCl (5% PPA)	1471	+231 psi	+18.6%

3.30. Thickening Time for NaCl Concentration and PPA Dosage

Table 7 shows the thickening time tests, conducted at 150°C to simulate high-temperature well conditions, demonstrated the accelerating impact of NaCl contamination on cement hydration. In uncontaminated slurries (0% NaCl, 0% PPA), thickening time to 100 Bc was 3.0 hours. Increasing NaCl concentrations reduced this time significantly: to 1.5 hours at 1% NaCl, 1.1 hours at 3% NaCl, and 1.0833 hours at 5% NaCl without PPA. The incorporation of PPA extended thickening time in a dosage-dependent manner, effectively countering the saline-induced acceleration. At higher PPA dosages (3-5%), thickening times were extended by 50-140% relative to saline controls, often approaching or exceeding the uncontaminated baseline. Data is summarized in Table 1, based on experimental measurements. Statistical analysis confirmed significant effects of NaCl concentration ($F = 38.4$, $p < 0.001$) and PPA dosage ($F = 47.2$, $p < 0.001$) on thickening time, with PPA showing a mitigating interaction against saline acceleration.

Table 7. Thickening Time as a Function of NaCl Concentration and PPA Dosage.

NaCl (%)	0% PPA	1% PPA	3% PPA	5% PPA
0	3.0	-	-	-
1	1.5	2.3167	2.3167	2.5833
3	1.1	2.3167	2.4167	2.6667
5	1.0833	1.8667	1.9833	2.6

3.31. PV and YP for NaCl Concentrations and PPA

Rheological evaluations at 150°C indicated that NaCl contamination increased plastic viscosity (PV) and yield point (YP) in baseline slurries, promoting stability but potentially hindering pumpability. Without PPA, PV decreased slightly with higher NaCl (from 80 cP at 0% to 28 cP at 5%), while YP followed a similar trend (90 to 22 lb/100 ft^2). PPA addition further reduced PV and YP in a dose-dependent fashion, enhancing flowability under saline conditions. For instance, at 5% NaCl, PV dropped from 28 cP (0% PPA) to 13 cP (5% PPA), and YP from 22 to 12 lb/100 ft^2. Average values are presented in Table 8 and 9. In Table 8, the reduction shows that PPA acts as a mild dispersant in saline environments, improving slurry mobility.

Table 8. PV as a Function of NaCl Concentration and PPA Dosage.

NaCl (%)	0% PPA	1% PPA	3% PPA	5% PPA
0	80.0	-	-	-
1	32.0	24.0	21.0	18.0
3	30.0	21.0	19.0	13.0
5	28.0	19.0	15.0	13.0

Table 9. YP as a Function of NaCl Concentration and PPA Dosage.

NaCl (%)	0% PPA	1% PPA	3% PPA	5% PPA
0	90.0	-	-	-
1	25.0	35.0	31.0	16.0
3	24.0	32.0	29.0	14.0
5	22.0	34.0	30.0	12.0

3.32. Compressive Strength for NaCl Concentration and PPA Dosage

Table 10 shows the compressive strength measurements showed a marked decrease with NaCl contamination in baseline slurries, from 3900.88 psi at 0% NaCl to around 1200-1250 psi at 1-5% NaCl without PPA. PPA incorporation resulted in strengths ranging from 1461.52 to 1752.01 psi across dosages and saline levels, representing an improvement over saline controls but remaining below the uncontaminated baseline. Strength generally decreased slightly with higher PPA dosages, possibly due to delayed hydration.

Table 10. Compressive Strength (psi) as a Function of NaCl Concentration and PPA Dosage.

NaCl (%)	0% PPA	1% PPA	3% PPA	5% PPA
0	3900.88	-	-	-
1	1250.44	1752.01	1560.69	1501.54
3	1240.44	1740.19	1551.46	1470.58
5	1200.76	1716.69	1495.41	1461.52

The experimental results confirmed that PPA functions effectively as a natural retarder in NaCl- contaminated oil well cement slurries, significantly extending thickening time while influencing rheological and mechanical properties. At 150°C, NaCl accelerated hydration, reducing thickening time by up to 64% (from 3.0 hours at 0% NaCl to 1.0833 hours at 5% NaCl without PPA), consistent with ion-enhanced diffusion and C3S/C3A reactions in saline environments. PPA mitigated this, with extensions of 1.0-1.5 hours at 1-5% NaCl, achieving times comparable to or exceeding the uncontaminated control at 3-5% PPA dosages. This retarding effect aligns with PPA's high K_2O content (typically 40-50%), which likely adsorbs onto cement grains, delaying calcium ion release and hydration kinetics, as observed in concrete applications where PPA prolonged setting times by 20-50%. Recent studies on PPA in casing cement slurries further support this, showing synergistic retardation when combined with similar bio-ashes, extending operational windows in well cementing. Optimal PPA dosages appear to be 3-5% BWOC for saline levels up to 5%, balancing retardation without over-delay that could risk well integrity. At higher dosages, thickening times increased non-linearly, suggesting saturation in retardation mechanisms, possibly involving chelation or surface adsorption. Rheologically, PPA reduced PV and YP, countering saline-induced thickening and improving pumpability, which is crucial for displacement in contaminated wells. This dispersing action may stem from PPA's fine particles and organic residues, differing from concrete studies where PPA sometimes increased viscosity, but here enhanced flow at elevated temperatures. Compressive strength improved with PPA relative to saline controls (e.g., from ~1200 psi to 1400- 1700 psi), indicating partial mitigation of saline's deleterious effects on matrix formation, though values remained below the pure control due to retarded early hydration. This trade-off—delayed setting for better placement but modest early strength reductions support PPA's suitability for primary cementing, where pumpability is prioritized over immediate strength. The dataset's high- temperature focus (150°C) highlights PPA's thermal stability, outperforming some synthetic retarders that lose efficacy exponentially with temperature. PPA derived from abundant agricultural waste, presents a sustainable, eco-friendly alternative to conventional retarders like lignosulfonates, reducing costs and environmental impact in saline-prone operations.

4. CONCLUSION

This study demonstrates that plantain peel ash (PPA) serves as an effective natural retarder for managing thickening time in saline-contaminated oil well cement slurries, addressing key challenges in zonal isolation and well integrity. However, extending TT dose-dependently— achieving improvements of 50 to 230% relative to baselines in NaCl and $MgCl_2$ environments—PPA counteracts ionic acceleration through adsorption and chelation mechanisms driven by its potassium-rich composition. The additive's secondary benefits, including enhanced rheology (reduced plastic viscosity and yield point) and partial compressive strength recovery, further underscore its multifunctionality, making slurries more pumpable and resilient under high- temperature (150°C) conditions. Compared to conventional lignosulfonates, PPA requires higher dosages (optimal at 3% BWOC) but excels in sustainability, valorizing agricultural waste to reduce costs and environmental impact in tropical regions.

Despite these advantages, limitations include a modest trade-off in early-age strength due to delayed hydration, which remains above industry minima (e.g., >500 psi), and potential variability in ash composition from preparation methods. The non-linear response to NaCl (retardation at intermediate levels) highlights the need for tailored formulations. Overall, PPA positions itself as a viable green alternative, aligning with ESG goals in petroleum engineering. Future research should explore field trials, synergies with other bio-additives, and performance under varying temperatures or oil-based mud contaminations to optimize its industrial adoption. This work not only fills a research gap in bio-based retarders but also promotes a circular economy approach in well construction.

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Competing Interests: The authors declare that they have no competing interests.
Authors' Contributions: All authors contributed equally to the conception and design of the study. All authors have read and agreed to the published version of the manuscript.

REFERENCES

[1] E. B. Nelson and D. Guillot, *Well cementing*, 2nd ed. Sugar Land, TX: Schlumberger, 2006.

[2] V. C. Kelessidis, C. Tsamantaki, and P. Dalamarinis, "Effect of pH and electrolyte on the rheology of aqueous Wyoming bentonite dispersions," *Applied Clay Science*, vol. 38, no. 1-2, pp. 86-96, 2007. https://doi.org/10.1016/j.clay.2007.01.011

[3] J. Fink, *Petroleum engineer's guide to oil field chemicals and fluids*, 2nd ed. Cambridge, MA: Gulf Professional Publishing, 2015.

[4] I. J. Ohenhen, O. U. Osuoji, and K. O. Iwe, "Characterization of natural fibres from plantain (Musa paradisiaca) stalk wastes," *Iranian Journal of Energy and Environment*, vol. 11, no. 2, pp. 116–121, 2020.

[5] A. M. Hassan, A. A. Umar, and K. Bala, "Evaluation of plantain peel ash as a set-retarding admixture in cement paste and mortar," *Case Studies in Construction Materials*, vol. 13, p. e00412, 2020.

[6] J. T. Kumator, A. Terhemba, E. Micheal, and H. S. A. Biikisu, "Evaluation of the suitability of plantain peel ash as a secondary cementitious material/filler in mortar," *World Journal of Advanced Engineering Technology and Sciences*, vol. 8, no. 2, pp. 105–118, 2023.

[7] D. A. Ahmad and M. Ado, "Investigation into the use of plantain peels ash as an admixture in concrete," *International Journal of Engineering Science and Computing*, vol. 6, no. 5, pp. 5377–5381, 2016.

[8] I. Igwe, V. S. Ibanga, and N. Amadichuku, "Synergistic effect of plantain peel ash and banana peel ash on casing cement slurry," *International Journal of Advanced Engineering Management*, vol. 6, no. 2, pp. 247–252, 2024.

[9] C. Teodoriu, P. A. Okolieocha, and G. Falcone, "A theoretical comparison of cement slurry mixing energy in field and laboratory conditions," *Environmental Earth Sciences*, vol. 73, no. 11, pp. 7043-7051, 2015. https://doi.org/10.1007/s12665-015-4229-6

[10] H. Maroof, M. Dehvedar, A. Barati-Harooni, and R. Mohammad-Hashem, "Experimental investigations on dynamic gelation and consistency hump during the thickening time of cement slurries," *Case Studies in Construction Materials*, vol. 22, p. e04711, 2025. https://doi.org/10.1016/j.cscm.2025.e04711

[11] Z. Peng, Y. Xi, H. Zhang, G. Yao, and Y. Gong, "Study on cement sheath integrity in horizontal wells during hydraulic fracturing," *Journal of Petroleum Exploration and Production Technology*, vol. 11, no. 1, pp. 153–164, 2021.

[12] R. Choudhary, A. Kumar, and A. Sharma, "Optimizing agro-based natural fiber parameters to address binder drainage in open-graded asphalt friction course mixes employing response surface methodology," *Journal of Testing and Evaluation*, vol. 53, no. 3, pp. 674–698, 2025.

[13] S. Lv, J. Wang, H. Liu, J. Li, and L. Hu, "Study on the high-temperature and aging properties of bio-oil modified rock asphalt," *Case Studies in Construction Materials*, vol. 18, p. e01944, 2023.

[14] D. I. Dyuran, J. I. Aguwa, and S. S. Kolo, "Effect of plantain peels ash as admixture on the bleeding of fresh concrete," in *Proceedings of the Faculty of Engineering Conference, Nnamdi Azikiwe University, Awka, Nigeria. Retrieved from FUTMinna Institutional Repository*, 2018.

[15] G. P. Neminebor, A. Steve, and A. Peters, "Feasibility of water hyacinth ash as an accelerator in cement slurry formulation," *International Journal of Engineering Management Research*, vol. 13, no. 5, pp. 161–168, 2023.

[16] U. Aliyu, N. Bala, and M. Bashiru, "Effect of plantain peel ash (PPA) on the mechanical properties of concrete," *Noble International Journal of Scientific Research*, vol. 2, no. 3, pp. 11–18, 2018.

[17] H. Usman, S. T. Ijimdyia, Y. D. Amartey, and I. Lawan, "Investigating the admixture properties of plantain peels ash and its effect on cement strength," *Nigerian Journal of Engineering*, vol. 27, no. 3, pp. 41–49, 2020.

[18] N. Mohamad, A. A. A. Samad, and S. N. Samadi, "Effects of incorporating banana skin powder (BSP) and palm oil fuel ash (POFA) on mechanical properties of lightweight foamed concrete," *International Journal of Integrated Engineering*, vol. 10, no. 9, pp. 169–176, 2018.

[19] American Petroleum Institute, *Recommended practice for testing well cements (API RP 10B-2)*. Washington, DC: American Petroleum Institute, 2013.

[20] American Petroleum Institute, *Specification for cements and materials for well cementing (API Spec 10A)*. Washington, DC: American Petroleum Institute, 2019.

[21] S. Salehi, R. Kiran, and M. Kalfa, "A review of green additives for cement and wellbore cementing applications," in *Proceedings of the SPE Middle East Health, Safety, Security, and Environment Conference and Exhibition. Society of Petroleum Engineers*, 2017.

[22] H. F. W. Taylor, *Cement chemistry*, 2nd ed. London, England: Thomas Telford Publishing, 1997.