

## Low ECD, sag-resistant, non-damaging, barite-free invert emulsion reservoir drill-in fluid comprising novel weighting, emulsifier and filtration control additives

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### Abstract

Reservoir drill-in fluids (RDFs) fall into two major categories: water-based mud reservoir drill-in fluid (WBM RDF), and non-aqueous fluid reservoir drill-in fluid (NAF RDF).

An RDF must produce a robust yet thin filter cake, to support the uncased section of wellbore, often featuring unconsolidated sand or carbonate reservoir. However, as RDFs are used in the production zone of oil wells, they must be non-damaging, and the robust, thin filter cake must be subject to easy removal during clean-up and completion. As operators continue to set records for long horizontal sections within productive reservoirs, classic WBM RDF with acid-soluble calcium carbonate reveals limitations and shortcomings.

The present paper outlines the development of a barite-free NAF RDF comprising acid-soluble, micronized ilmenite, and a novel additive package optimized to deliver low equivalent circulation density (ECD), while producing a thin, robust, acid-soluble, non-damaging filter cake. All of this will be shown to have been optimized in a sag-resistant fluid, at the specified wellbore temperature of interest.

The present work will outline the optimization of the fluid system around parameters of fluid rheology, including the fine viscoelastic properties ( $G'$ ,  $G''$ ). The present optimized fluids were shown to be sag-resistant by virtue of static age study, and determination of sag factors. Further, exceptionally low filtrate loss values at relatively high wellbore temperature and high mud weights were obtained.

### Introduction

Micronized ilmenite is a commercially available weighting agent for drilling fluid applications (Feder 2019). Micronized ilmenite ( $\text{FeTiO}_3$ ) has an average particle size of  $5\mu\text{m}$ . **Table 1** highlights the main physical properties of micronized ilmenite and barite. The new optimized particle size distribution of micronized ilmenite offers significantly better performance and value compared to the typical API barite. The benefits of micronized materials lay in reducing the viscosity and the sag in the resultant formulated fluids. With a density of approximately 4.65 specific gravity (SG), micronized ilmenite

is approximately 15% heavier than 4.1 SG barite, so it offers proportionally fewer solids in the fluid, at comparable density. This leads to reduced rheology and can also improve the rate of penetration when drilling. The high hardness of micronized ilmenite, measured at 5-5.5 Mohs make it less susceptible to degradation, upon mechanical impact. This improves the stability of fluid properties as well allowing for better recycling. It also facilitates the working of the solids control equipment resulting in less dilution to maintain properties and better re-use of the fluid.

Micronized ilmenite is acid soluble (Feder 2019) (Chen 2015), and less damaging to formations than barite, facilitating its use in applications that are sensitive to impairment of productive pores. Higher return permeability results, as demonstrated by formation damage testing, are achievable with micronized ilmenite, which lead to improved productivity (Xiao et al. 2015). Furthermore, micronized ilmenite slurry can be pumped, in contrast to barite slurry. This pneumatic conveyance of micronized ilmenite will benefit operators by reducing logistics costs and providing easier handling.

As discussed above, RDFs may be aqueous or non-aqueous, each fluid having certain technical limitations. Calcium carbonate is the most common weighting agent used in RDFs, as the resultant filter cakes are readily removed with acid. But, relying exclusively on calcium carbonate as a weighting agent dictates a maximum practical fluid density of nearly 12.5 lb/gal (ppg). Furthermore, as applied to use of calcium carbonate in non-aqueous RDF, the high-added, low-gravity solids (calcium carbonate) necessitate emulsification of greater quantities of water to effect suspension. The resultant low oil-water ratio (OWR), combined with the high low-gravity solids (%LGS) content, imparts unacceptably high plastic viscosity (PV) to the fluid.

Akin to completion fluids, higher aqueous RDF density ( $>12.5$  ppg) can be achieved by utilizing various alternative brines, such as calcium bromide, cesium formate and zinc bromide. However, though they provide the requisite density, they suffer drawbacks of cost and handling hazards, e.g. corrosivity.

Aqueous RDFs are contraindicated in formations

comprising swellable clays in their pores, and invert emulsion RDFs are prescribed, though they will also suffer limitations around maximum fluid density, excessive fluid viscosity, excessive cost and/or hazards.

Thus, there exists a need to provide RDFs that afford the advantages of invert emulsions (suspension, swellable clay inhibition), while providing high fluid weights, adequate suspension and proper hole-cleaning.

This paper reports on a solution to the cited limitations, by combining the best aspects of NAF RDF, in a low equivalent circulating density (low ECD) package. Low ECD invert emulsion drilling fluids (IEF) are IEFs with overall low rheological properties and improved suspension properties. The low ECD IEF is expected to deliver improved drilling performance, reduced induced losses, and improved well productivity through reduction of formation damage.

Our recent publication highlighting a novel fluid loss additive, (FLA-R) developed for invert emulsion drilling fluids (Maghrabi et.al 2019) showed that the novel FLA-R as compared to conventional, commercially available FLA delivered:

- Fluid loss performance at lower threshold concentration
- IEF with improved electrical stability (ES)
- IEF with low PV and improved low-shear regime rheological properties

In this study, the novel FLA-R and the micronized ilmenite were combined to formulate a low ECD IEF with

- Overall low fluid viscosity, specifically low PV
- Sag resistance
- Expected non-damaging performance at the reservoir

The micronized ilmenite and FLA-R (1) IEF was compared in a similar formulation with three other fluid systems – barite and FLA-R (2), barite and white polymeric FLA (WP) (3) and micronized ilmenite and WP (4) .

The contents of this paper are arranged as follows:

- Formulation and static age testing of the 15.8 ppg (a) and 18 ppg (b) IEF at 302 F and 325 F respectively for three days for the four fluid systems given above
- Hydraulic calculations and analysis for 15.8 ppg IEF per below:
  - Hole cleaning predictions
  - Frictional pressure loss estimations
- Rheological elucidation of the 15.8 ppg IEF fluid systems (1-4) on parallel plate geometry:
  - Oscillatory amplitude sweep testing of IEF
  - Structure breakdown testing

## Materials and Methods

The fluids were mixed in stainless steel mixing cups on a five-spindle multimixer Model 9B having a rotational speed of 11500 rpm with sine-wave impeller blade No. 9B29X. The fluids were aged in high-temperature, high-pressure (HTHP) stainless steel aging cells placed in a mechanical convection oven. The rheology of the fluids was determined at 150 F on a

standard OFITE oilfield viscometer as per API 13B-2 (API RP 13B-2 2005). The temperature was controlled with an electrically heated thermocup. The ES in V was determined on an Electrical Stability Tester Model 23E from FANN. HPHT fluid loss in mL was determined at 302 F (15.8 ppg) / 325 F (18 ppg) on a 500 ml HPHT filter press assembly for duration of 30 minutes as per API 13B-2 recommendations.

The rheology of the fluid was characterized in terms of the Bingham plastic viscosity (PV) in units cP, Bingham yield point (YP) in units lb/100ft<sup>2</sup> and gels in units lb/100ft<sup>2</sup> which were determined as per API 13B-2.

The fluid was modelled with Herschel Bulkley (HB) equation:

$$\tau = \tau_0 + K\dot{\gamma}^n$$

where  $\tau$ ,  $\tau_0$  are the shear stress and the yield stress respectively in units lb/100ft<sup>2</sup>, K and n are the fluid consistency and fluid flow behavior indices respectively and  $\dot{\gamma}$  is the shear rate in s<sup>-1</sup>. The HB parameters were used to calculate the frictional pressure loss estimations as per 7.4.12.2 of API 13D considering the fluid is in a laminar flow (API RP 13D 2010) . Similarly, pressure to break circulation was made as per 7.4.12.3 of API 13D considering the fluid is in a laminar flow (API RP 13D 2010).

Hole cleaning predictions for the fluids were made with the cuttings carrying index (CCI) equation as per API 13D (API RP 13D 2010):

$$CCI = \frac{\rho \times k_1 \times V_a}{400000}$$

where  $\rho$  is the density of the fluid in ppg,  $k_1$  is the consistency value from the power law model for fluids at a shear rate of 1s<sup>-1</sup> and  $V_a$  is the annular velocity of the fluid in feet per minute (ft/min). A CCI of  $\geq 1$  is considered good for hole cleaning.

Furthermore, rheological elucidation of the fluid was performed on an Anton Paar MCR 302 rheometer at 150 F with a parallel plate geometry – PP50 and a zero gap of 1 mm. The samples were preconditioned as follows for the different tests (Savari et al. 2013).

1. Before running the amplitude sweep and structure breakdown tests, the fluid samples were sheared for five minutes at 1000 s<sup>-1</sup> followed by a rest stage of 10 minutes for microstructure growth

An oscillatory amplitude sweep was performed with a series of oscillations at constant frequency of 10 rad/sec and varying strain amplitude ( $\gamma$ ) from 0.001% - 100%. Under these conditions the following were determined:

1. G', storage modulus which denotes solid character
2. G'', loss modulus which denotes the liquid character
3.  $\delta$ , phase angle, when closer to 0° denotes solid or elastic character, when closer to 90° denotes liquid or viscous character and when 45° it is sol-gel transition when material begins to flow
4. Flow point  $\tau_f$ , is the shear stress at the crossover point of G' and G'' also at the crossover the  $\delta$  is 45°.

These materials properties were compared for the different fluid used in this study. The values in Pa units can be divided

by 0.4788 to convert into units of lb/100ft<sup>2</sup>.

A structure breakdown test was performed at a constant shear rate,  $\dot{\gamma}$  of 2.5 s<sup>-1</sup> with the shear stress,  $\tau$  determined every 0.003 seconds for about six seconds. A  $\dot{\gamma}$  of 2.5 s<sup>-1</sup> roughly corresponds to a 1.5 revolutions per minute (rpm) on a standard oilfield viscometer. This test demonstrates if the gelled fluid exhibits rapid gel-to-flow transition when subjected to a minimum shear rate.

The sagging behavior of the fluid was determined after the static heat age of the fluid for three days at the given temperature as per the below steps:

1. The formulated fluid was mixed on the multimixer for 10 minutes, transferred to the ageing cell and pressurized at 400 psi with nitrogen. The cell was placed in an upright position for static ageing in the oven for desired temperature and duration.
2. After static aging, the top oil separation was determined in volume units with a measuring cylinder and reported as a percentage of the total volume of the fluid.
3. The sag performance was determined with the sag factor. The specific gravity of the bottom ( $SG_{bottom}$ ) portion of the fluid (the last 3<sup>rd</sup> portion of the fluid) in the aging cell was determined by drawing 10 ml volume with a syringe and measuring its weights on an analytical balance. The equation used to calculate the sag factor is (Omland et.al. 2004):

$$Sag\ Factor = \frac{SG_{bottom}}{2 \times SG_{initial}}$$

4. A sag factor greater than 0.53 implies that the fluid has potential to sag (Maxey 2007). After the sag factor determination, the fluid was mixed on the multimixer for five minutes and tested for rheology, ES and HPHT fluid loss.

The additives used to mix the fluids in this study were:

- Base oil: mineral oil
- Weighting agent to adjust the density of the fluid: API barite with a S.G of 4.1 and micronized ilmenite with D<sub>50</sub> of 5 microns and S.G of 4.65
- Alkalinity control agent to activate the emulsifiers: lime
- FLAs to maintain fluid loss control: white polymeric FLA (WP) and novel FLA (FLA-R). The FLA-R is in an aqueous solution and all the concentrations are expressed in an equivalent active solid basis.
- Viscosifiers to maintain viscosity and suspension: polymeric viscosifier and organoclay
- a primary emulsifier (PE) and secondary emulsifier (SE)
- Simulated drill solids
- Wetting agent: to oil wet solids
- CaCl<sub>2</sub> for water phase salinity (WPS)

## Results and Discussions

Relative to all the fluids tested, the formulated NAF RDFs were expected to meet the following specifications

- Controlled HPHT fluid loss < 6 ml,
- ES > 500 V,

- Top oil separation < 10% and sag factor < 0.53 after three days of static ageing.

Two low-fluid viscosity and sag resistant IEFs were successfully formulated with the micronized ilmenite and the FLA-R.

- (1a) A 15.8 ppg IEF with OWR 70/30 and WPS of 25% w/w CaCl<sub>2</sub> static heat aged at 302 F for three days
- (1b) A 18 ppg IEF with OWR 85/15 and WPS of 30% w/w CaCl<sub>2</sub> static heat aged at 325 F for three days.

Three IEF systems with similar formulation were formulated as below.

- (2) Barite and FLA-R
- (3) Micronized ilmenite and WP
- (4) Barite and WP

The optimized formulations with static heat age conditions of these IEFs are given in **Table 2**.

### Static Heat Aging of 15.8 ppg Fluid

The fluid properties of the four, 15.8 ppg IEF systems (1a,2a,3a,4a) are given in **Table 3**. These four fluid systems demonstrated sag resistance with a sag factor of < 0.53 and passed the specifications of HPHT fluid loss, ES and top oil separation.

### Hole Cleaning Predictions

A key consideration when crafting a low-ECD fluid, is that the suspension property and low-shear characteristics facilitate proper hole cleaning.

The hole cleaning performance prediction for the four IEF's were determined with the cuttings carrying index (CCI) for a 3.535 in annulus. The 3.535 in annulus is envisioned for a hole/casing diameter of 8.535 in and a drill string pipe of outer diameter 5.000 in. The CCI was determined at flow rates from 100 – 300 gallons per minute (gpm). These flow rates correspond to annular fluid velocity from 51.2 to 153.7 feet per minute (ft/min). The hole cleaning predictions for the four IEF's is shown as a plot of the CCI against flow rate in gpm in **Figure 1**. The micronized ilmenite and FLA-R (1a) IEF gave the highest CCI of the four IEFs, as the calculations bear this out and the CCI increased in the order, 4a < 3a < 2a < 1a. Thus, 1a exhibited CCI >>1, corresponding to superior hole cleaning. Infact, at the initial low flow rate of 100 gpm, 1a had a CCI ≈ 1, comparatively the other three IEFs had CCI < 0.8.

To further support the conclusion that system 1a comprising micronized ilmenite and FLA-R has superior hole cleaning, Okrajni and Azar have shown that in laminar flow, higher mud yield point and yield-point/plastic viscosity (YP/PV) ratio provide better cuttings transport (Okrajni and Azar 1986), the calculated YP/PV ratios of the four IEFs (**Table 3**) reflect the same trend of hole cleaning cited above. Thus, the micronized ilmenite and FLA-R IEF is expected to provide the best hole cleaning among these four IEFs.

### Friction Pressure Loss Estimations

The friction pressure loss is an important component of the ECD equation and providing fluids with increasingly small

friction pressure loss allows for the drilling of formations with particularly narrow drilling windows (pressure differential between pore pressure, and fracture gradient), i.e. slimhole geometry wells. The ECD is the effective density exerted by the circulating fluid that combines fluid density and friction pressure loss. The ECD estimations help manage the pump flow rate, hole cleaning and rate of penetration (ROP) depending on the well design. The HB parameters used to calculate the friction pressure loss estimations for the four IEFs are given in **Table 4**. The estimations were performed for two scenarios.

1. Laminar flow through a 3.000 in internal diameter (I.D) drill string
2. Laminar flow through a 3.535 in annulus

The friction pressure loss estimation were normalized to psi per foot and reported as ppg. The friction pressure loss estimations of 3.000 in ID and 3.535 in annulus for flow rates from 100 – 300 gpm are shown in **Figure 2** and **Figure 3** respectively.

In both, 3.000 in and 3.535 in annulus, the friction pressure loss estimations for micronized ilmenite and FLA-R (1a) IEF were the lowest. The friction pressure loss estimations increased in the order  $1a < 2a < 3a < 4a$ .

As an example, in the 3.535 in annulus, the friction pressure loss estimations varied from 0.361 to 0.522 ppg for the micronized ilmenite and FLA-R IEF as compared to 0.413 to 0.618 ppg for the barite and WP IEF (**Figure 3**).

In the 3.000 in ID drill string, ECD management becomes more acute, since friction pressure loss estimation varied from 0.677 to 1.194 ppg for the micronized ilmenite and FLA-R IEF as compared to 0.817 to 1.559 ppg for the barite and WP IEF (**Figure 2**).

During drilling, a low friction pressure loss, a high pump flow rate and excellent hole cleaning is desired to maintain a high rate of penetration (ROP). The examples above show that utilizing 1a comprising FLA-R and micronized ilmenite, affords significant friction pressure loss advantage over the other fluids in the comparison.

The analysis demonstrates that micronized ilmenite and FLA-R IEF with its low friction pressure loss estimations and excellent hole cleaning predictions at the given flow rates are expected to deliver better ECD management to maintain high ROP as compared to the other IEFs of this study.

### Rheological Elucidation with Parallel Plate Geometry

Separate from the operational parameters described above, we desired to deepen our understanding of the impact of the various weighting agents and fluid loss additives upon the fine fluid structure. We attempted to characterize the visco-elasticity and, fine gel structure of the formulated NAF RDF.

### Oscillatory Amplitude Sweep Test

In **Figure 4**, the points plotted include the storage modulus in Pa ( $G'$ ), the loss modulus in Pa ( $G''$ ) and the phase angle ( $\delta$ ) as a function of the shear stress in Pa ( $\tau$ ) for micronized ilmenite and FLA-R IEF. The moduli and phase angle trends are described as below:

1. The moduli  $G'$  and  $G''$  are linear in the  $\tau$  range from 0.001 Pa to 0.1 Pa, this is the linear viscoelastic region (LVER) of the fluid, it indicates how large a strain the fluid tolerates before the internal structure of the fluid starts to break. In this region the  $\delta$  is fairly constant and linear between around 25°.
  - The  $G'$  is greater than the  $G''$ , implying that the fluid has solid character and is a gel.
2. In the  $\tau$  range from 0.1 Pa to 1 Pa, the  $G'$  and  $G''$  fall abruptly and the  $\delta$  rises abruptly from around 25°.
  - A  $G'$  and  $G''$  crossover occurs and  $G''$  is now greater than  $G'$ , implying a transition from the gel to a liquid. The crossover of the  $G'$  and  $G''$  occurs at  $\delta$  of 45°. The  $\tau$  at the crossover is the flow point,  $\tau_f$ . The flow point,  $\tau_f$ , better represents flow transition from gel to a liquid. The flow point is also referred as the gel point (Mezger 2018).

Similar trends in the  $G'$ ,  $G''$  and  $\delta$  as a function of  $\tau$  was observed for the other three IEF's.

The 10-minute gel strengths (determined on standard oilfield viscometer) and the flow point/gel point ( $\tau_f$ ) (determined by oscillation amplitude) for the four IEFs are compared in **Figure 5**. A high gel strength needs a high pump initiation pressure to break circulation after mud is in static condition for a period. A high pump pressure increases the probability of formation fracture and thereby induced fluid losses to the formation (Caenn, Gray and Darley 2017). The pressure required to break the gels in the 3.535 in annulus, calculated with the 10-minute gel strength and  $\tau_f$  are compared in **Figure 6**. The pressure to break the gels calculated with the  $\tau_f$  for four IEFs, show a stark difference and increases in the order, 0.02 ppg for 1a < 0.06 ppg for 2a < 0.28 ppg for 3a < 0.46 ppg for 4a. This order also reflects the increasing probability of induced fluid losses when breaking circulation after static condition. As an example, barite and WP (4a) IEF will require 23 times more pump pressure than micronized ilmenite and FLA-R (1a) IEF to break circulation after static period. The analysis shows that the FLA-R imparted a low  $\tau_f$  to the fluids whereas the WP imparted a high  $\tau_f$  to the IEFs. The pressure required to break the gels calculated with the 10-minute gel strengths are similar between 0.20 -0.25 ppg for the four IEFs.

Only the flow points/gel points determined by the oscillatory amplitude sweeps were able to differentiate between the four IEFs.

### Structure Breakdown Test

On initiating circulation after downtime for connections or trips, the pump flow rate is ramped up slowly to prevent significant pressure spikes that can occur due to breaking of the gels formed by the drilling fluid. For fluids that do not exhibit a rapid gel-to-flow transition after a static period, an extra pressure is applied to break the gels which appears as the pressure spikes on a pressure while drilling (PWD) log. These spikes can range from 0.1 – 1.0 ppg. The pressure spike represents a sudden ECD increase for short duration due to breaking of gels and when the ECD exceeds the fracture

gradient, the fluid is lost to the formation. Successive significant pressure spikes during a drilling operation can eventually lead to a catastrophic lost circulation. As the fluid begins to flow, the normal ECD is restored (Moore and Gillikin 2010).

Therefore, a structure breakdown test was performed with the four IEFs to detect the presence of the rapid gel-to-flow transition, depicted in **Figure 7**, where the  $\tau$  in Pa is plotted as a function of time in seconds. On flow initiation with a shear rate of  $2.5 \text{ s}^{-1}$ , the  $\tau$  has a high value of  $\approx 90 \text{ Pa}$  which falls swiftly to a low constant value on application of shear rate. For the three IEFs – micronized ilmenite and FLA-R (1a), barite and FLA-R (2a) and micronized ilmenite and WP (3a), the gel structure disruption is swift within 0.1 seconds or less. However, for the barite and WP IEF (4a), it takes 0.4 seconds for the gel structure disruption and for the  $\tau$  to reach a its constant value. The test demonstrates that on initiating circulation after static conditions, the gel disruption for the three IEFs – 1a, 2a and 3a will be rapid and without the usual pressure spikes during a drilling operation and therefore less prone to lost circulation. However, the 4a IEF demonstrates a comparatively slow gel-to-flow transition and is likely to exhibit pressure spikes and is more prone to lost circulation.

### Static Heat Aging of 18 ppg IEF

The fluid properties of the four, 18 ppg IEF systems (1b, 2b, 3b and 4b) are given in **Table 5**. Also, in **Table 5**, are the fluid properties of similarly formulated 1:1 weight basis mixture of barite-micronized ilmenite and FLA-R (5b) IEF for comparison. Among the five formulations, the micronized ilmenite and FLA-R (1b) and 5b met all the fluid specifications of this study outlined before.

The HPHT fluid loss of the micronized ilmenite and WP (3b) was high at 26 mL whereas the other four 18 ppg IEFs 1b, 2b, 4b and 5b gave controlled fluid loss of less than 6 mL

The YP of the four IEFs 1b, 2b, 4b and 5b were similar in the range of 25 – 26 lb/100ft<sup>2</sup> whereas 3b had a lower YP of 21 lb/100ft<sup>2</sup>. The 600 rpm, dial reading for the micronized ilmenite and FLA-R (1b) IEF was lowest at 99.4 units. The Bingham PV of the four IEFs decreased in the order, 4b > 2b > 3b > 5b > 1b.

The top oil separation of all the IEFs was less than 10%. Only the formulations, 1b and 5b demonstrated sag resistance with a sag factor of < 0.53, whereas formulation 3b had a sag factor of 0.533. The barite only IEFs 2b and 4b did not pass the sag test with a sag factor of 0.542. The 10-minute gel strengths of the barite only IEFs, 2b and 4b were high at 24 and 32 lb/100ft<sup>2</sup> respectively but still failed in the sag test. This probably shows that at 18 ppg, the small particle size of the micronized ilmenite imparted improved suspension character to the IEFs 1b, 2b and 5b as compared to the only barite based IEFs 3b and 4b.

The lowest PV, lowest rheology and sag factor < 0.53 makes 1b – micronized ilmenite and FLA-R the low ECD fluid of choice among the five IEFs. Since the micronized ilmenite is acid-soluble, the 1b qualifies as a low ECD non-damaging IEF.

### Conclusions

1. The 15.8 ppg and 18 ppg low ECD, sag resistant, barite free and non-damaging IEF were successfully formulated with the acid soluble micronized ilmenite weighting agent and the novel FLA-R.
  - The micronized ilmenite and FLA-R IEF systems (15.8 ppg, 18 ppg) exhibited the lowest rheology as determined on standard oilfield viscometer
2. The 15.8 ppg micronized ilmenite and FLA-R IEF demonstrated
  - Best hole cleaning prediction and the lowest friction pressure loss estimation.
  - Lowest pressure required to break circulation (calculated with flow point / gel point), thereby having the least probability to encounter induced fluid losses.
3. The 15.8 ppg micronized ilmenite and FLA-R, micronized ilmenite and WP, and barite and FLA-R IEFs showed rapid gel-to-flow transition and are therefore less prone to lost circulation after static period. In comparison, the barite and WP IEF demonstrated a slower gel-to-flow transition and are more prone to lost circulation after a static period.
4. The flow points /gel points ( $\tau_f$ ) determined by oscillatory amplitude sweep test on parallel plate geometry was able to differentiate between the four IEFs of the study.
  - The pressure required to break the gels calculated with the flow point/gel point showed stark differences between the four IEFs.

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### Nomenclature

API	= American Petroleum Institute
$^{\circ}C$	= Degree Celsius
cP	= Centipoise
CCI	= Cuttings Carrying Index
D.R.	= Dial Reading
ECD	= Equivalent Circulating density in ppg
ES	= Emulsion Stability in V
$^{\circ}F$	= Degree Fahrenheit
FL	= Fluid loss
FLA	= Fluid Loss Additive
g	= grams
G'	= Storage Modulus in Pa
G''	= Loss Modulus in Pa
HB	= Herschel Bulkley model
HPHT	= High Pressure High Temperature
IEF	= Invert Emulsion Fluids
ID	= Internal Diameter in inches
in	= inches
K	= Fluid Consistency Index in Herschel Bulkley model

<i>mL</i>	= milliliter
<i>mins</i>	= Minutes
<i>n</i>	= flow behavior index in Herschel Bulkley model
<i>OWR</i>	= Oil Water Ratio
<i>PE</i>	= Primary Emulsifier
<i>ppb</i>	= lb/bbl
<i>ppg</i>	= lb/gal
<i>PV</i>	= Plastic Viscosity in cP
<i>rpm</i>	= Revolutions per minute
<i>SE</i>	= Secondary Emulsifier
<i>V/V</i>	= Volume/Volume
<i>WPS</i>	= Water Phase Salinity
<i>WP</i>	= Polymeric FLA
<i>w/w</i>	= Weight/Weight
<i>YP</i>	= Bingham Yield Point in lb/100ft <sup>2</sup>
$\tau$	= Shear Stress in Pa or in lb/100ft <sup>2</sup>
$\tau_0$	= Yield Stress in Herschel Bulkley Model
$\tau_f$	= Flow Point in lb/100ft <sup>2</sup>
$\gamma$	= Shear Strain in %
$\dot{\gamma}$	= Shear Rate in s <sup>-1</sup>
$\delta$	= Phase Angle in Degrees °

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## Tables

Property	Barite	Micronized ilmenite
<b>Chemical formula</b>	BaSO <sub>4</sub>	FeTiO <sub>3</sub>
<b>Specific gravity</b>	4.1	4.65
<b>Mean PSD -D<sub>50</sub> (microns)</b>	20	5
<b>Hardness (Moh's scale)</b>	3.0 - 3.5	5.0 – 5.5
<b>Abrasiveness (relative)</b>	1	0.3 – 0.4
<b>Acid solubility</b>	No	Yes

Components	Specific gravity	Mass (g) for 15.8 ppg	Mass (g) for 18 ppg	Mix Time (mins)
<b>Mineral oil</b>	0.79	As required	As required	
<b>Primary emulsifier</b>	0.99	1.0	1.0	1
<b>Secondary emulsifier</b>	0.94	11.0	13.0	1
<b>Lime</b>	2.50	4.0	4.0	1
<b>FLA-R / WP</b>	1.33 for FLA-R / 1.06 for WP	5.0 for FLA-R / 2.0 for WP	5.0 for FLA-R / 2.0 for WP	1
<b>CaCl<sub>2</sub> brine, 30% w/w for 18 ppg and 25% w/w for 15.8 ppg</b>	1.30 for 18 ppg / 1.24 for 15.8 ppg	As required	As required	10
<b>Organoclay</b>	1.60	5.0 when using FLA-R / 4.5 when using WP	5.5	15
<b>Barite / Micronized ilmenite</b>	4.1 for barite / 4.65 for micronized ilmenite	As required	As required	10
<b>Polymeric viscosifier</b>	0.98	2.0	3.5	5
<b>Simulated drill solids</b>	2.30	10.0	10.0	5
<b>Oil wetting agent</b>	0.94	2.0	0.0	5
				54
<b>Mud weight</b>		15.8 ppg	18 ppg	
<b>Oil water ratio</b>		70/30	85/15	
<b>Static age temperature</b>		302°F	325°F	
<b>Static age duration</b>		3 days	3 days	

**Table 3 : Fluid properties of the 15.8 ppg IEFs after static age for 3 days**

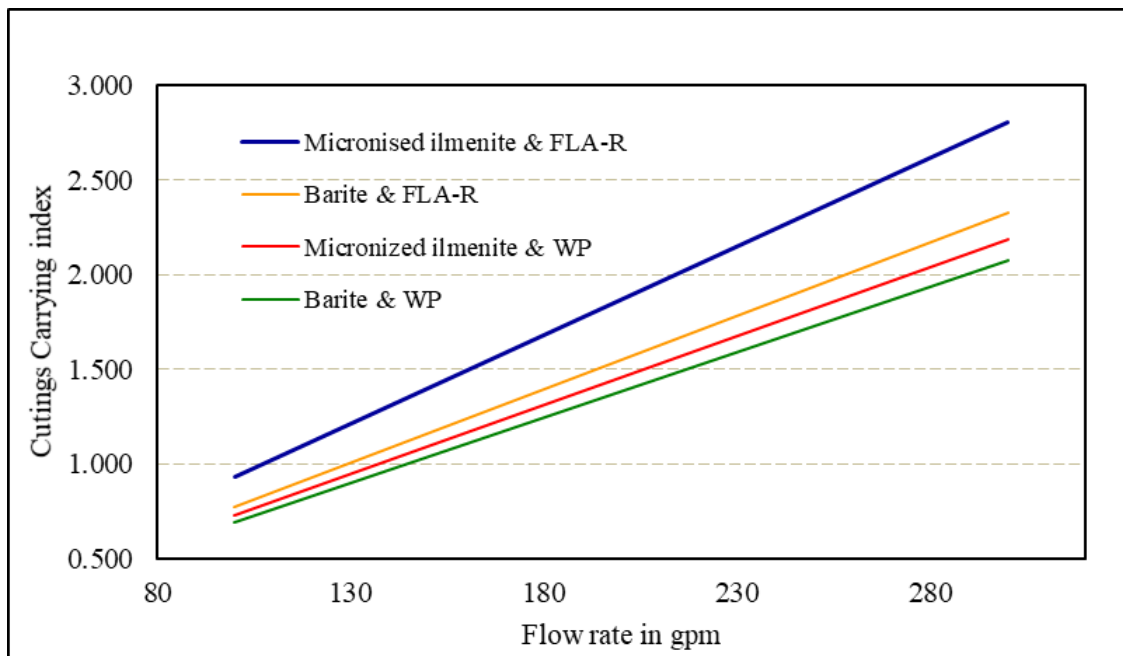
<b>Rheology @ 150°F</b>	<b>Micronized ilmenite and FLA-R (1a)</b>	<b>Barite and FLA-R (2a)</b>	<b>Micronized ilmenite and White Polymer (3a)</b>	<b>Barite and White Polymer (4a)</b>
<b>600 rpm (D.R.)</b>	75.7	88.5	92.0	108.1
<b>300 rpm (D.R.)</b>	48.6	54.9	56.5	65.0
<b>200 rpm (D.R.)</b>	38.7	43.1	44.0	50.4
<b>100 rpm (D.R.)</b>	27.5	29.8	30.3	34.0
<b>6 rpm (D.R.)</b>	10.8	11.1	12.2	11.9
<b>3 rpm (D.R.)</b>	9.5	9.9	11.0	10.4
<b>PV (cP)</b>	27.1	33.6	35.5	43.1
<b>YP (lb/100ft<sup>2</sup>)</b>	21.5	21.3	21.0	21.9
<b>YP/PV ratio</b>	0.79	0.63	0.59	0.51
<b>10" Gel (D.R.)</b>	10.0	10.0	12.0	10.0
<b>10' Gel (D.R.)</b>	11.0	12.0	14.0	12.0
<b>ES (V) @ 150°F</b>	614	582	582	617
<b>HPHT FL (mL) @ 302°F</b>	4.0	1.0	6.0	1.0
<b>Cake of 32nds-inch</b>	8	4	8	4
<b>Top Oil Separation in v/v %</b>	7.4	6.9	6.6	3.7
<b>SAG factor</b>	0.525	0.525	0.524	0.524

**Table 4: Herschel Bulkley (HB) parameters of the 15.8 ppg IEFs after static ageing of 3 days**

<b>HB parameters @ 150°F</b>	<b>Micronized ilmenite and FLA-R</b>	<b>Barite and FLA-R</b>	<b>Micronized ilmenite and White Polymer</b>	<b>Barite and White Polymer</b>
<b><math>\tau_0</math>, lb/100ft<sup>2</sup></b>	8.79	9.30	10.73	9.94
<b>K, lb.s<sup>n</sup>/100ft<sup>2</sup></b>	0.499	0.433	0.347	0.424
<b>n</b>	0.717	0.762	0.798	0.795

**Table 5: Fluid Properties of the 18 ppg IEF's after static age at 325°F for 3 days.**

Rheology @ 150°F	Micronized ilmenite and FLA-R (1b)	Barite and FLA-R (2b)	Micronized ilmenite and White Polymer (3b)	Barite and White Polymer (4b)	Barite-Micronized ilmenite (1:1) and FLA-R (5b)
600 rpm (D.R.)	99.4	125.0	109.7	161.4	106.3
300 rpm (D.R.)	62.2	75.1	65.8	93.7	65.9
200 rpm (D.R.)	48.9	57.2	50.6	70.3	51.2
100 rpm (D.R.)	34.2	37.3	34.3	45.2	35.5
6 rpm (D.R.)	16.1	13.9	15.3	16.3	15.8
3 rpm (D.R.)	15.0	12.6	14.1	14.8	14.2
PV (cP)	37.2	49.9	43.9	67.7	40.4
YP (lb/100ft <sup>2</sup> )	25.0	25.2	21.9	26.0	25.5
10" Gel (D.R.)	18.0	14.0	17.0	19.0	27.0
10' Gel (D.R.)	32.0	24.0	26.0	32.0	39.0
ES (V) @ 150°F	679	1430	726	1070	857
HPHT FL (mL) @ 325°F	5.2	1.0	26	1.0	3.2
Cake of 32nds-inch	8	6	22	6	8
Top Oil Separation in v/v %	9.1	8.0	10	5.1	8.6
SAG factor	0.529	0.542	0.533	0.542	0.529

**Figures****Figure 1: Hole cleaning predictions for 15.8 ppg IEFs with CCI in a 3.535 in annulus**

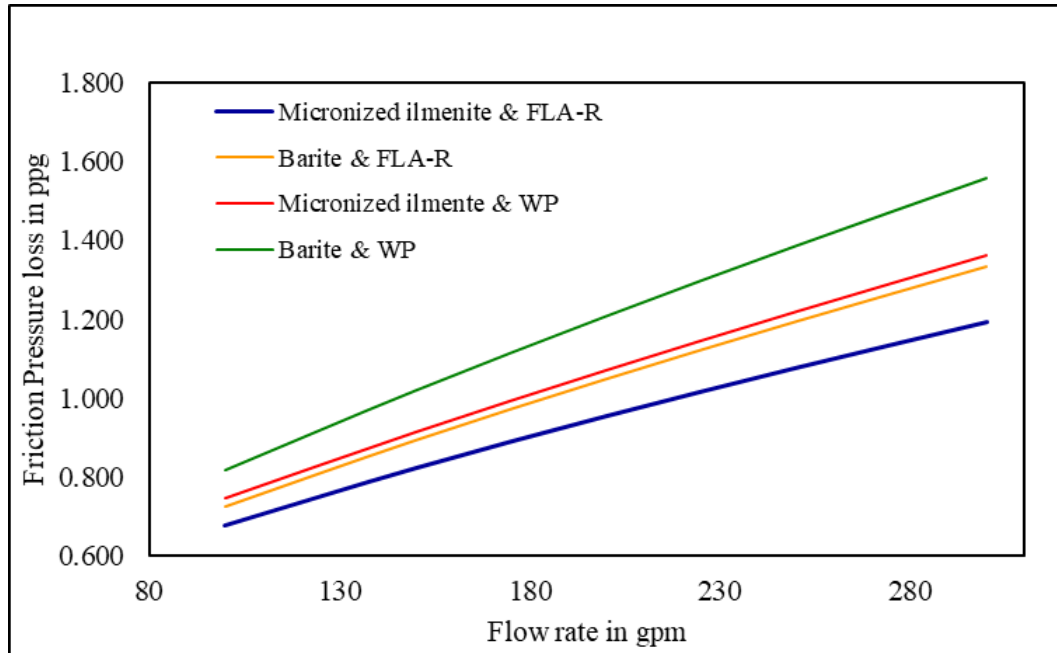


Figure 2: Friction pressure loss estimations for 15.8 ppg IEFs in a 3.000 in ID drill string

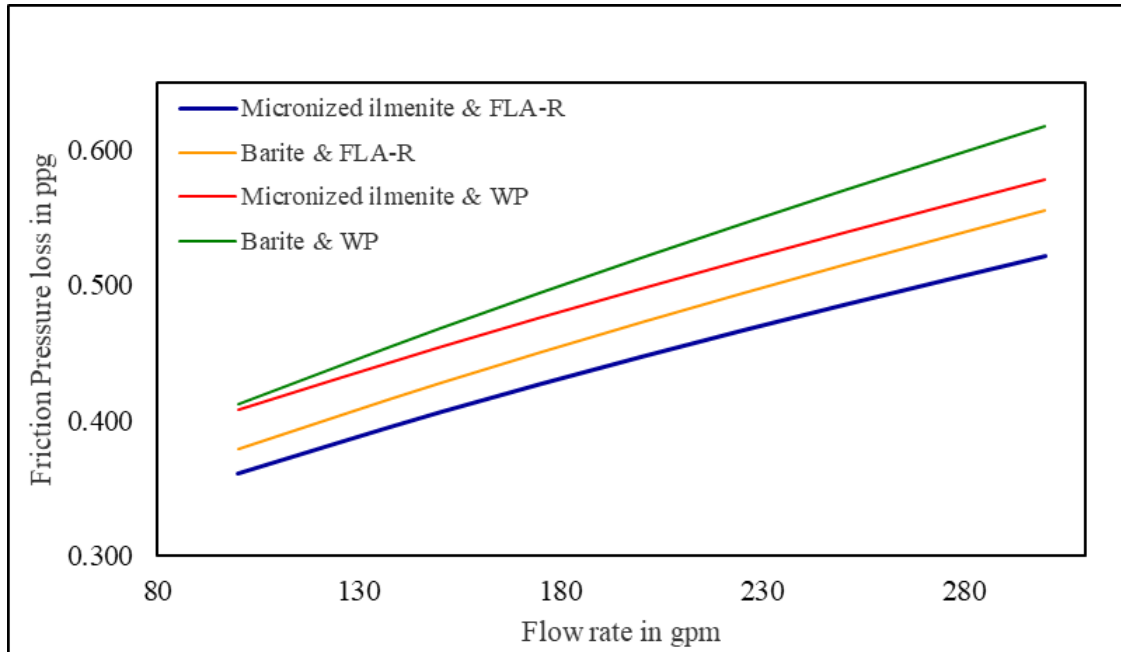


Figure 3: Friction pressure loss estimations for 15.8 ppg IEFs in a 3.535 in annulus

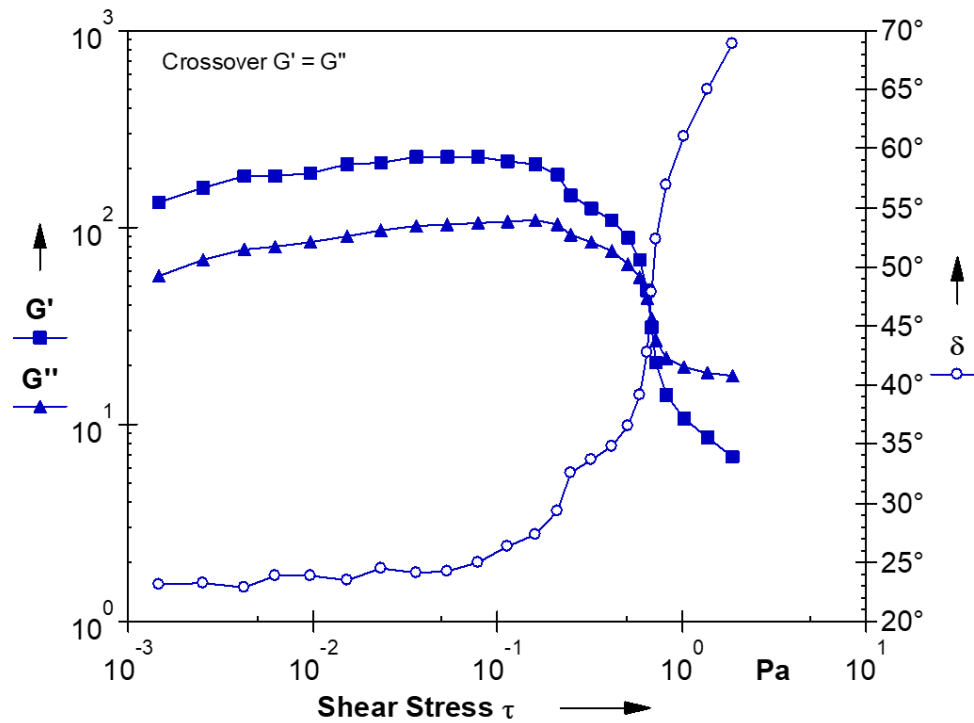


Figure 4: The  $G'$ ,  $G''$  and phase angle ( $\delta$ ) plotted as a function of the shear stress for 1a, 15.8 ppg IEF at 150°F .

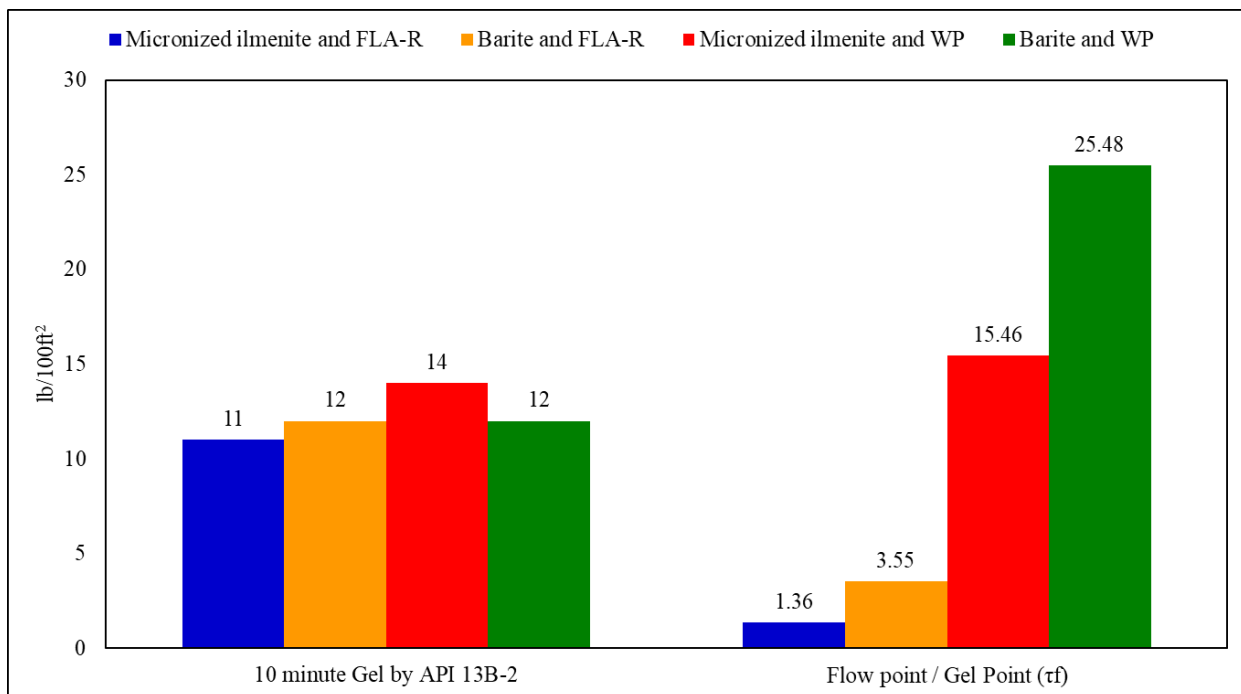


Figure 5: Gel strength and flow point / gel point in  $\text{lb}/100\text{ft}^2$  for 15.8 ppg IEF at 150°F after static hot age at 302°F for 3 days

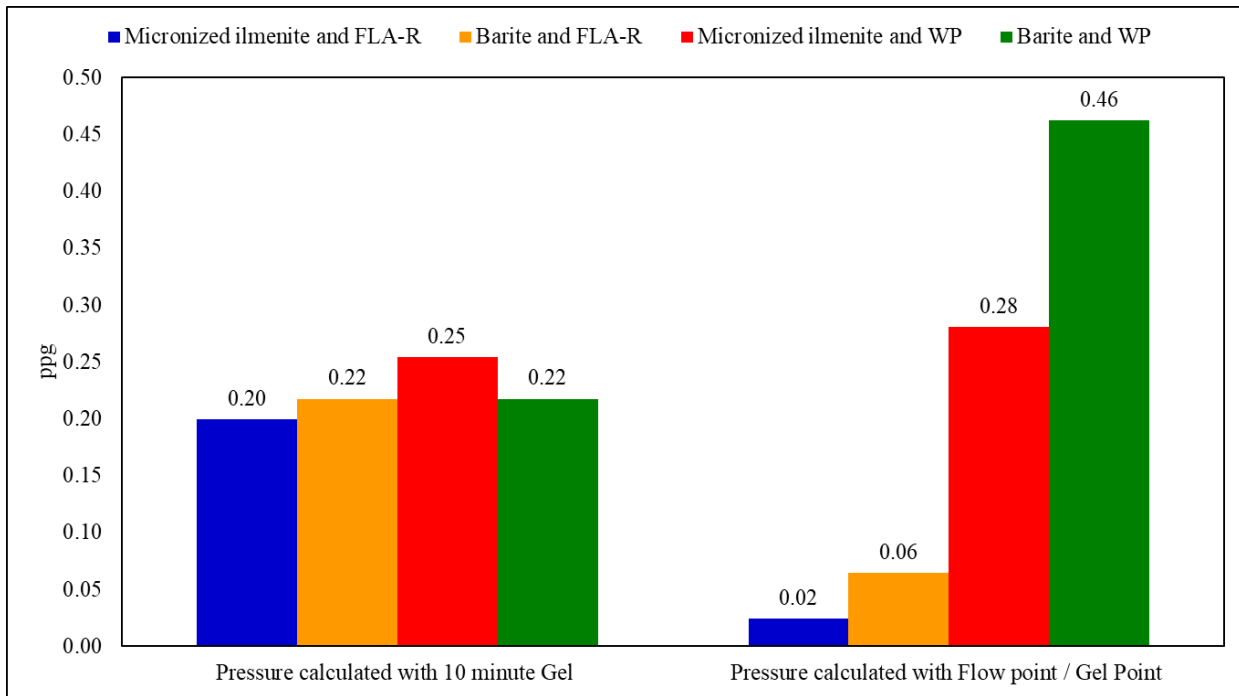


Figure 6: Pressure to break circulation in 3.535 in annulus for 15.8 ppg IEF after static hot age at 302°F for 3 days

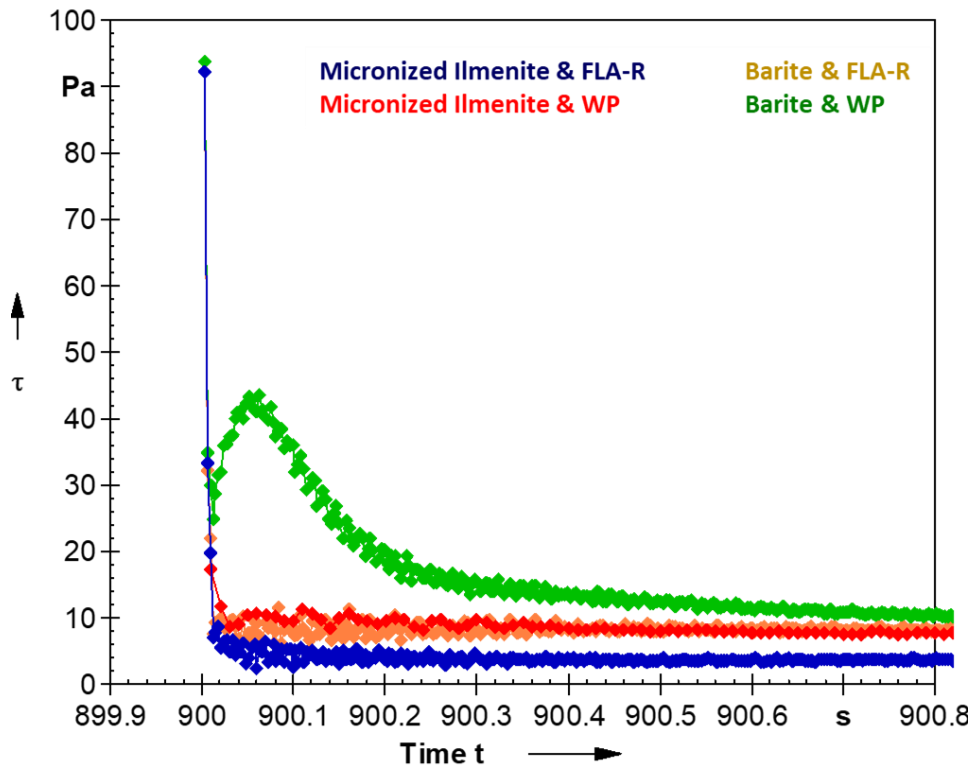


Figure 7 : Structure breakdown of the 15.8 ppg IEFs at 2.5 s<sup>-1</sup> after gel formation at 150°F