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A Comparative Study of Preparation Methods, Weighting Agents, and Temperature on Quality of E-M Compatible Borehole Imaging Fluid

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ABSTRACT: Imaging fluids plays a crucial role in mitigating the impact of borehole groundwater on borehole E-M imaging results. Such fluid must possess specific characteristics such as low conductivity to minimize electromagnetic wave attenuation, appropriate dielectric permittivity to prevent signal ringing at the fluid-wellbore boundary, higher density than water for settlement at the bottom hole, and long-term stability throughout the imaging process. This study meticulously examines the influence of agitation and temperature on the quality of oil-based imaging fluids, comparing two major preparation methods with distinct grain sizes of the weighting agent. One is the conventional method involving a critical heating step of the emulsifier in 20% of the imaging fluid liquid base, while the second involves dissolving the emulsifier in the liquid base by agitation. Evaluation of the produced fluids encompasses considerations of their stability over time, settlement in various water temperatures, and rheological properties. The results of these experiments reveal the pros and cons of the agitation process compared to the conventional method, weighting agent grain size, and temperature on the overall quality of the produced imaging fluid.

1. INTRODUCTION

High frequency electromagnetic waves are used as the source of Ground Penetrating Radar (GPR) to image and map subsurface geological formations and structures (Jol, 2008). Borehole GPR utilizes high frequency electromagnetic waves for mapping out the downhole subsurface geology. This GPR data quality can be influenced by the presence of borehole water or the media between the antenna and the wellbore Li (2023). Hence, the selection of a proper borehole fluid will help overcome the impact of ground water on imaging data quality. Borehole water should be replaced by an imaging fluid at the bottom hole and cover the E-M antennas while imaging.

The ideal borehole fluid (imaging fluid) should have specific properties such as low conductivity (low EM wave attenuation), appropriate dielectric permittivity close to that of the host rock to avoid signal ringing between the fluid-wellbore boundary, higher density than water to enable it settle at the bottom hole, and stability such that it does not discompose while imaging. Following the above characteristics, the imaging fluid is made up of a liquid base with low dielectric permittivity and conductivity, a weighting agent to increase its density than water to about Specific Gravity (SG) of 1.2 and an emulsifier to ensure its stability by preventing the separation and settlement of suspended solids.

Numerous research has been done to come up with a distinct recipe for the imaging fluid meeting all necessary characteristics and conditions as mentioned above. This study sought to modify the developed standard of preparation of the imaging fluid by eliminating the preheating step of the emulsifier and investigate its impact on the imaging fluid quality and rheological properties.

2. RHEOLOGICAL PROPERTIES OF FLUIDS

Rheology is the study of the deformation and flow of matter. By taking specific fluid measurements, it is possible to predict how a fluid will flow under various variables, such as temperature, pressure, and shear rate. According to Adewale et al. (2017), the capacity of any fluid depends greatly on its rheological properties. Some of the rheological properties studied in this study are as follows Adewale et al. (2017):

- **Plastic viscosity (PV)**, a measurement of the fluid internal resistance to flow because of solids interaction in a fluid, primarily by the mechanical friction between the suspended solid particles, the solid particles, and the liquid phase. Plastic viscosity is expressed in centipoise (cP) and can be estimated as the difference between the 600rpm and the 300rpm viscometer dial readings.

$$\mu_p = \theta_{600} - \theta_{300} \quad (1)$$

The following are the main determinants of fluid plastic viscosity:

- Solids concentration.
- Size and shape of solid particles present in the fluid.
- Viscosity of the fluid phase.
- The presence of some long-chain polymers.
- Oil-to-Water or Synthetic-to-Water ratio in invert-emulsion fluids.
- Type of emulsifiers in invert emulsion fluids.

- **Yield Point (YP)** is a measure of the electrochemical or attractive force in a fluid under flow conditions. It is the measure of the fluid internal resistance to initial flow; it is that part of the resistance to flow that may be controlled by proper chemical treatment Aftab et al. (2017). The yield point will decrease as the attractive forces are weakened by chemical treatment. Mathematically, it is expressed as

$$YP = \theta_{300} - PV \quad (2)$$

The unit is lb. /100ft^2 or Pa.s.

According to Bourgoyne et al. (1991), yield point in the range of 3 to 30 lbm/100ft^2 is considered acceptable for unweighted clay/water-based mud. Yield point can be affected by the following factors Aftab et al. (2017):

- Surface properties of the fluid solids
- Volume concentration of the solids
- Concentration and types of ions in the fluid phase. Afta

- **The ratio of YP/PV** is a significant indicator of a fluid condition. It is a measure of the shear thinning behavior of drilling fluids. A high ratio means the fluid is more shear thinning. Low ratios indicate a greater settling velocity of solids. However, if the gauge hole is not maintained and the diameter of the borehole enlarges, a fluid having a high YP/PV ratio is desirable.
- **Apparent Viscosity** (AP) is the viscosity of a drilling fluid at a specific shear rate and constant temperature. The relationship depends on the fluid's yield point and plastic viscosity, expressed in centipoise (cP). Anawe and Folayan (2018). It is also known as the effective viscosity and expressed as;

$$\mu_a = \frac{\theta_{600}}{2} \quad (3)$$

- **Filtration rate**: This gives an idea on the amount of mud filtrate invasion into porous and permeable formation and the amount of filter cake that will be deposited on the wall of the wellbore whenever filtration happens. As fluid is lost, mud solids build up on the face of the wellbore. This is the filter cake.
- **Flow Behavior Index (n):** This is an indicator of the tendency of a fluid to shear thin and it is dimensionless. When n < 1, the fluid is shear thinning and when n > 1, the fluid is shear thickening. Shear thinning fluids decrease in viscosity as stress increases while shear thickening fluids increase in viscosity with increasing stress.

$$n = 3.32 log(\frac{\theta_{600}}{\theta_{300}}) \quad (4)$$

- **Consistency Index Factor (K):** This is defined as the viscosity index of the fluid system and the unit is lb/100ft2. It is the measure of a fluid change in viscosity with temperature change.

$$k = \frac{\tau}{\gamma^n} = \frac{\theta_{600}}{1022^n} \quad (5)$$

3. MATERIALS AND METHODS

3.1 Basic Ingredients and General Protocol

The three ingredients used to prepare the imaging fluid are described below.

- Fluid base: Biodegradable oil with a dielectric constant of 2.
- Weighting agent: Barite to increase the SG of the mixture to 1.2, allowing for the settlement of the imaging fluid downhole. In this study, two different kinds of barite based on its particle size were used. API barite (d50 of 40μm) and Microbarite (d50 of 2-6μm).
- Emulsifier: Stearic acid which serves as the gelling agent for the imaging fluid to maintain stability with dielectric constant of 2.

The general protocol to prepare the imaging fluid is described below.

- Measure all ingredients (Biodegradable oil, Barite, and Stearic acid).
- Melt the stearic acid by heating it up in 20% of the biodegradable oil to 100°C, until the stearic acid totally melts.
- Put the remaining 80% of the biodegradable oil in a bucket and add the dissolved mixture. Mix the oil until it is clear without any wax.
- Add barite into the dissolved mixture. Barite should be added using a sieve to slow the process and separate the barite powder. Mix the mixture while adding barite.
- Mix for 10 minutes.

3.2 Dissolving Stearic Acid

To investigate an alternative to the heating process of dissolving stearic acid in oil and its effect on the quality of the imaging fluid prepared, 3 different imaging fluid preparation procedures were used for the same quantity of

API barite and Microbarite. A total of 6 imaging fluids were prepared with its breakdown below.

- Dissolving stearic acid by agitation using a mixer with 3000 rpm and adding barite at high temperature.
- Dissolving stearic acid by agitation using a mixer with 3000 rpm and adding barite at low temperature. Note: Before adding API barite in this method, the stearic acid and oil mixture was beginning to solidify and so all of it was oven heated and cooled to a low temperature.
- Dissolving stearic acid by heating in 20% liquid base (general protocol)

Figure 1 below shows the hand drill mixer (3000 rpm) and the experimental setup for the agitation process in dissolving stearic acid in the biodegradable oil and for mixing barite in the dissolved stearic acid and oil mixture. Figure 2 shows the oven used for heating up and dissolving stearic acid in the biodegradable oil.

Fig. 1: Hand drill mixing blade and experimental setup.

Fig. 2: Oven used for heating and dissolving stearic acid.

3.3. Imaging Fluid Quality Check

To evaluate the quality of the imaging fluid produced, its stability over time was observed, settlement in different water temperatures was confirmed, and its rheological properties were measured. It is desired that when the produced imaging fluid is set aside and behavior monitored over time, it remains stable and does not separate. It is also desirable that imaging fluid when poured into water of temperatures 5°C and 24°C, it remains settled in the water.

3.4. Rheological Property Measurement

For this study, two major equipment shown in Figure 3 below was used to determine the rheological properties of the imaging fluid. One is the direct indicating viscometer (an OFITE 8-speed rotational viscometer) used to determine the rheological characteristics of the fluid at atmospheric pressure (14.7 psi), and a Filter Press for fluid loss (filtration) test.

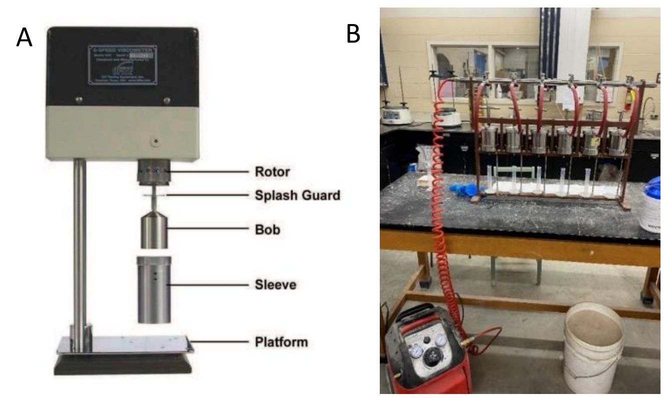

Fig. 3: (A) OFITE 8-speed rotational viscometer (B) API fluid loss test kit.

4. RESULTS AND DISCUSSION

After the imaging fluid was prepared as described above, separation test, settlement test and rheological properties measurement were done on the prepared the results of the test is described below.

4.1 Separation Test

In this study, the imaging fluids prepared via different mixing methods were transferred into separate mason jars, as shown in Figure 4 below, and their behavior was monitored. It was observed that the temperature of the oil and stearic acid mixture before the addition of barite played a significant role in the stability of the fluid as high temperature mixture before adding barite exhibited a more rapid separation of barite in the mixture over time and was also noticed in the imaging fluid produced by heating 20% of the liquid base and stearic acid. This phenomenon is consistent for both types of barites used. However, imaging fluid made with Microbarite was observed to be more stable than API barite produced in the same way. The significance of this test is to determine the need for remixing the imaging fluid when left alone for some time before its use.

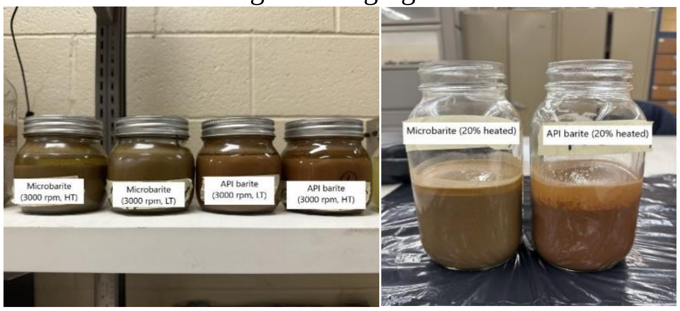

Fig. 4: Separation test of prepared imaging fluids.

4.2. Settlement Test

As the prepared imaging fluid reaches room temperature, 100ml of the prepared imaging fluid (each mixing procedure) is poured into 500ml of water with temperatures 5° and 24°c which falls within the range of ground water temperatures experienced downhole. This test is done to check the stability of the imaging fluid in water, as it is desired for the fluid to settle in water. Figures 5 to 7 shows the fluid settlement in water performance. As shown in Table 1, imaging fluid produced by agitation at high and low temperatures (both Microbarite and API barite) started to separate in water after about an hour to 3 hours with exception to the fluid mixed at 3000rpm and later oven heated that showed good settlement performance alongside that produced with the general protocol method which was seen to show a good settlement performance in water for over 7 days. This can be attributed to the introduction of bubbles because of mixing at high speed for a long period of time resulting to a lower fluid SG of less than 1.2. Bubbles in the mixture decrease the mass of the fluid over the same fluid volume.

Table 1: Settlement in water performance for different mixing procedures and weighting agents.

Weighting agent/ Mixing Procedure	Separation time (Hr)	
	In 5 °c water	In 24 °c water
API Barite (3000 rpm, HT mixed)	1	1
Microbarite (3000 rpm, HT mixed)	3	3
Microbarite (3000 rpm, LT mixed)	3	3
API Barite Imaging fluid (3000 rpm, oven heated, LT mixed)	> 7 days	> 7 days
API Barite (20% heated)	> 7 days	> 7 days
Microbarite (20% heated)	> 7 days	> 7 days

A B C D

Fig. 5: Water settlement test for imaging fluid mixed at 3000 rpm and high temperature in 5 and 24°c A) API barite after 1 hr B) after 24 hrs C) Microbarite after 1 hr D) after 24 hrs.

A B C D

Fig. 6: Water settlement test for imaging fluid mixed at 3000 rpm and low temperature in 5 and 24°c A) API barite (oven-heated) after 1 hr B) after 7 days C) Microbarite after 1 hr D) after 24 hrs.

A B C D

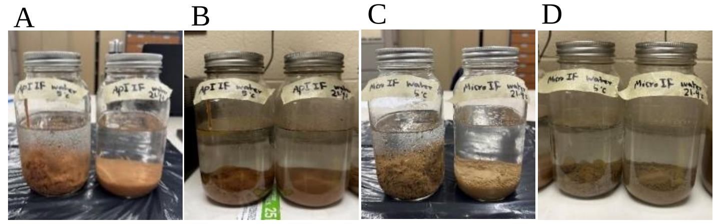

Fig. 7: Water settlement test for imaging fluid mixed using the general protocol in 5 and 24°c A) API barite after 1 hr B) after 7 days C) Microbarite after 1 hr D) after 7 days.

4.3. Fluid Rheology Test

In addition to the separation and settlement test, the imaging fluid rheological properties were measured using the OFITE 8 speed viscometer and the filter press. Table 2 below shows the estimated plastic viscosity, apparent viscosity, yield point and the yield point to plastic viscosity ratio (YP/PV) for all produced imaging fluid.

Table 2: Imaging fluid plastic viscosity, apparent viscosity, yield point, and YP/PV ratio.

Weighting Agent/ Mixing Procedure	PV (cP)	AP (cP)	YP (lb/100ft^2)	YP/PV
API Barite (3000 rpm, HT mixed)	55	60	10	0.18
Microbarite (3000 rpm, HT mixed)	66	75	18	0.27
Microbarite (3000 rpm, LT mixed)	99	121.5	45	0.455
API Barite Imaging fluid (3000 rpm, oven heated, LT mixed)	84	105	41	0.49
API Barite (20% heated)	59.5	66.3	13.5	0.23
Microbarite (20% heated)	64	68	8	0.13

Figures 8 to 11 are bar charts illustrating the variation of plastic viscosity, apparent viscosity, yield point, and YP/PV ratio with the different imaging fluid produced.

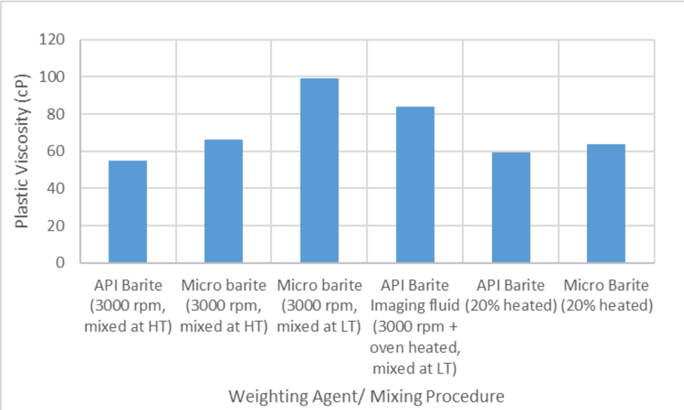

Fig. 8: Bar charts of imaging fluid plastic viscosity (cP) variations.

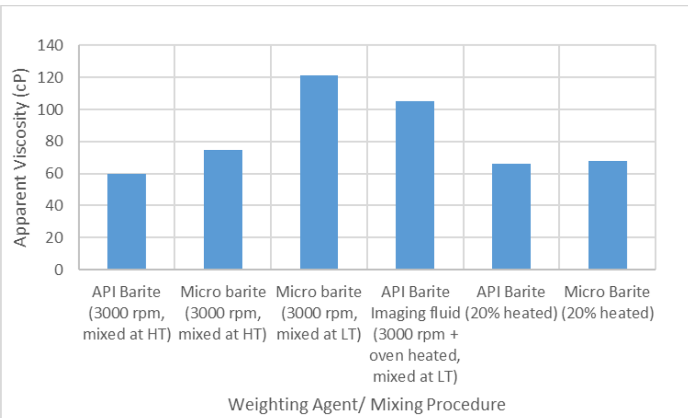

Fig. 9: Bar charts of imaging fluid apparent viscosity (cP) variations.

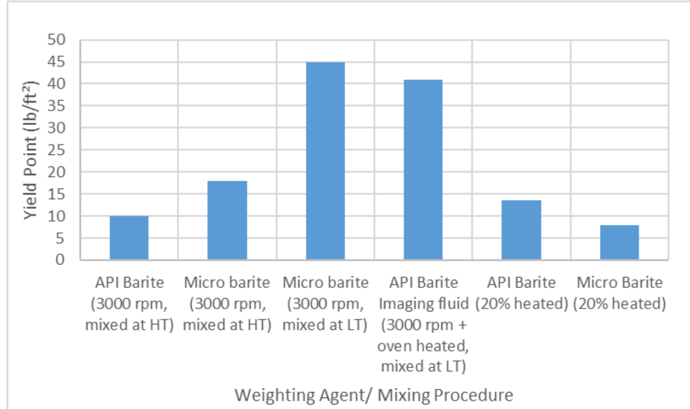

Fig. 10: Bar charts of imaging fluid yield point (lb/100ft^2) variations.

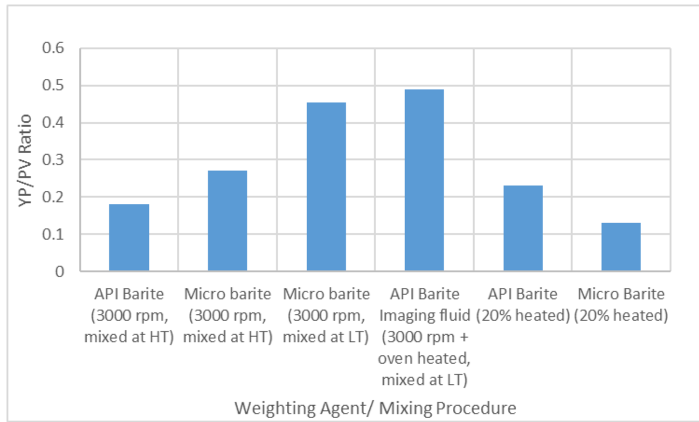

Fig. 11: Bar charts of imaging fluid YP/PV ratio variations.

Table 3 below shows the estimated flow behavior index, viscosity index, measured density, conductivity, filtrate volume, mud cake thickness obtained from filtration test.

Table 3: Flow behavior index, viscosity index, density, conductivity, and filtration test results of prepared imaging fluid.

Weighting agent/ Mixing Procedure	n	K	SG	Filtrate Volume (mL)	Mud Cake Thickness (mm)	Conductivity (μS/m)
API Barite (3000 rpm, HT mixed)	0.884	0.2623	1.19	140	13	0
Microbarite (3000 rpm, HT mixed)	0.836	0.457	1.07	104	8	0
Microbarite (3000 rpm, LT mixed)	0.754	1.304	1.05	83	7	0
API Barite Imaging fluid (3000 rpm, oven heated, LT mixed)	0.741	1.229	1.2	118	10	0
API Barite (20% heated)	0.8595	0.343	1.192	219	21.5	0
Microbarite (20% heated)	0.917	0.2365	1.195	159.5	16.5	0

Figures 12 to 14 show the pictures of the mud cake formed from the filtration rate test for each imaging fluid produced. In all, Microbarite imaging fluid produced in a particular mixing method has a smaller mud cake thickness compared to that produced using API barite.

Fig. 12: Filtration test mud cake for imaging fluid produced using 3000 rpm mixed at high temperature.

Fig. 13: Filtration test mud cake for imaging fluid produced using 3000 rpm (+ oven heated for API barite) mixed at low temperature.

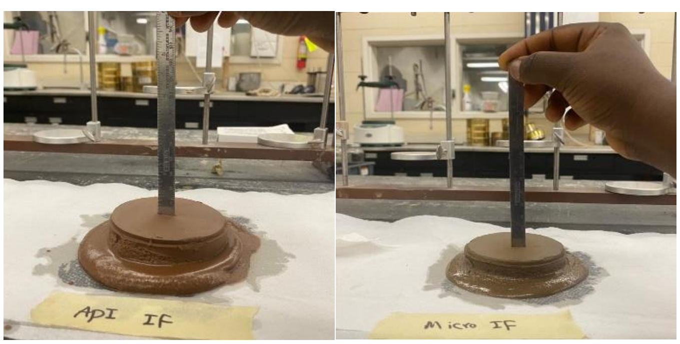

Fig. 14: Filtration test mud cake for imaging fluid produced using the general protocol.

The stability of these imaging fluids (separation test result) can be attributed to their respective yield point values and YP/PV ratios. A high yield point and YP/PV ratio signifies greater internal resistance to initial flow, which is advantageous for maintaining fluid stability over time. Therefore, the imaging fluid produced at 3000 rpm, oven heated, and mixed at LT possesses the highest yield point and is the most stable, followed by the Microbarite imaging fluid at LT. These two imaging fluids had a ratio above 0.4. It could be deduced that an imaging fluid of the same quantity (recipe proportion) with a lower ratio would separate quickly when left with time, which is undesirable.

When comparing imaging fluids made with barite of different particle sizes, it is observed that the fluid containing Microbarite performs better than the one with API barite. Microbarite-based fluid is more desirable due to its lower filtrate volume and thinner mud cake thickness, as the filtration rate test indicates. This difference highlights the influence of weighting agent particle size on the properties of the prepared imaging fluid. The flow behavior index (n) of all the imaging fluids prepared is less than 1, confirming the fluids are shear thinning and the higher the viscosity index (K), the higher the viscosity change rate with temperature change. This temperature-dependent behavior should be considered when selecting or formulating imaging fluids for specific applications.

Based on the measured rheological properties, the most desirable imaging fluid is the Microbarite-based fluid prepared at low temperature, as this imaging fluid has the highest yield point, apparent viscosity, and plastic viscosity. However, from the settlement in water performance tests, this imaging fluid separated after three hours due to introduced bubbles at the mixing step and a lower SG than 1.2, which is the minimum limit for a good performance in water. On the other hand, API barite and Microbarite-based imaging fluids made with the original mixing procedure were stable in water even after more than one week (7 days).

5. CONCLUSION & RECOMMENDATION

This study has investigated the impact of preparation methods, weighting agent particle size and temperature on the quality of imaging fluid. From the study, agitation can dissolve stearic acid only if the temperature of the mixture is raised by effect of mixing to the melting point of the stearic acid, but it introduces bubbles to the imaging fluid which decreases its specific gravity thereby decreasing its settlement in water performance. Imaging fluids made with Microbarite tend to produce a more quality fluid compared to API barite-based imaging fluid.

It is recommended to follow the general protocol in dissolving stearic acid while preparing imaging fluid but mix barite at a low temperature. Future work should focus on developing an imaging fluid recipe that can readily dissolve in a liquid phase without rigorous mixing and heating.

6. NOMENCLATURE

API	American Petroleum Institute
EM	Electromagnetic
GPR	Ground Penetrating Radar
HT	High Temperature
IF	Imaging Fluid

LT	Low Temperature
NBIT	Near Borehole Imaging Technology
PV	Plastic Viscosity
SG	Specific Gravity
YP	Yield Point

7. ACKNOWLEDGEMENT

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