

IMPROVING PERFORMANCE OF OIL-BASED DRILLING FLUIDS WITH ORGANOCLAY

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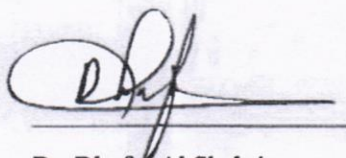
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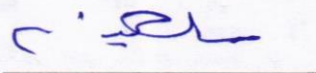
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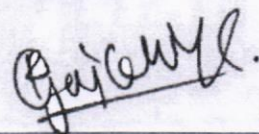


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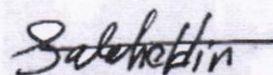


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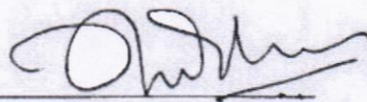
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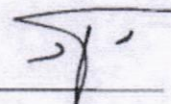
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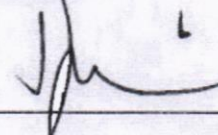
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DEDICATION

*I humbly and wholeheartedly dedicate this dissertation to
my beloved **parents**, for their endless support throughout my entire life,
my **brother** and **sister**, who I hope I will be part of their future success too,
my **friends**, who were the source of joy during this fruitful journey.*

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LIST OF ABBREVIATIONS

OBDF	:	Oil-based drilling fluid
WBDF	:	Water-based drilling fluid
SBDF	:	Synthetic-based drilling fluid
HPHT	:	High-pressure high-temperature
OC	:	Organoclay
MMT	:	Montmorillonite
OMMT	:	Organo-montmorillonite
SEP	:	Sepiolite
OSEP	:	Organo-sepiolite
PAL	:	Palygorskite
OPAL	:	Organo-palygorskite
CO-MMT	:	Cationic-organo-montmorillonite
CN-OMMT	:	Cationic-nonionic-organo-montmorillonite
NO-MMT	:	Nonionic-organo-montmorillonite
MRC	:	Maximum reservoir contact
OWR	:	Oil/water ratio
CTAB	:	Cetyl trimethyl ammonium bromide
CTABr	:	Hexadecyl trimethyl ammonium bromide
CO-SEP	:	Cationic-organo-sepiolite
CO-OSEP	:	Cationic-anionic-organo-sepiolite
DODMAC	:	Diocetadecyl dimethyl ammonium chloride
OREC	:	Organo-rectorite
OBEN	:	Organo-bentonite
OHEC	:	Organo-hectorite
AV	:	Apparent viscosity
PV	:	Plastic viscosity

YP	:	Yield point
GS	:	Gel strength
OTMAC	:	Octadecyl trimethyl ammonium chloride
HDTMAB	:	Hexadecyl trimethyl ammonium bromide
XRD	:	X-ray diffraction
XRF	:	X-ray fluorescence
SEM	:	Scanning electron microscopy
PSD	:	Particle size distribution
LCM	:	Lost circulation material
EAS	:	Emulsified acid system
DRA	:	Drag reducing agent
SDD	:	Silicon drift detector
VSST	:	Viscometer sag shoe test
G'	:	Storage modulus
G''	:	Loss modulus
LVR	:	Linear viscoelastic region
PPB	:	Pounds per barrel
RPM	:	Revolutions per minute

ABSTRACT

Full Name : [Ali Adel Ali Mahmoud]

Thesis Title : [Improving Performance of Oil-Based Drilling Fluids with Organoclay]

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The demand for energy resources from the oil and gas industry is increasing to a level where it is difficult for conventional hydrocarbon reservoirs to fulfill. Oil and gas companies are in search of novel ways to exploit the potential of unconventional reservoirs. Using the proper drilling fluid is a critical part of any successful drilling operation. There is a need to use high-performance drilling fluids while drilling unconventional hydrocarbon reservoirs due to the high-pressure high-temperature (HPHT) conditions encountered and the requirement of long horizontal/multilateral for the maximum reservoir contact (MRC). The cost, environmental impact, and shale inhibition need to be accounted for in selecting the optimal drilling fluid.

Oil-based drilling fluids (OBDFs) are used to minimize drilling problems related to shale hydration, drag and torque, pipe sticking, and wellbore instability. OBDFs are preferred to water-based drilling fluids (WBDFs) for wellbore stability in HPHT wells and shale-bearing formations. Despite the cost and environmental impact of OBDFs, the industry is using them due to their superiority to withstand HPHT conditions and shale inhibition. However, it does have a pitfall when it comes to cutting transport and dealing with sagging. Inherently poor cutting transport leads to a slow rate of penetration (ROP), and the building

of cutting beds, especially in the horizontal and inclined section of the wellbore causes problems such as stuck pipe, high torque, high friction, and poor cementing quality. There are different studies on the effect of OCs on the rheological properties of oil-based systems but finding new OCs or developing new OCs as rheology control agents is attractive for the oil and gas industry.

The objective of this study was to investigate the different OCs alone and in combinations for their efficacy as a rheology modifier for the OBDFs at HPHT conditions. In this study, six OCs were evaluated for rheology modifiers for the OBDFs. The characteristics of OCs were studied using X-ray Diffraction (XRD), X-ray fluorescence (XRF), Scanning electron microscopy (SEM), and particle size analysis (PSD). The performance of OCs as a rheology modifier for the OBDFs was evaluated by testing drilling fluid prepared using OCs at HPHT conditions. The tests included sag tests, electrical stability tests, rheology tests after hot rolling (AHR), oscillatory measurements (amplitude sweep, frequency sweep tests, time sweep tests), and HPHT filtration tests.

The results showed that the OCs remarkably enhanced emulsion stability. It effectively mitigated sagging issues under both static and dynamic conditions, leading to improvements in plastic viscosity (PV), yield point (YP), apparent viscosity (AV), and the YP/PV ratio. The addition of OCs resulted in heightened gel strength (GS) and improved filtration properties of the drilling fluid. These findings highlight OCs as a valuable additive for enhancing OBDF performance, particularly in challenging HPHT conditions. Its ability to provide emulsion stability, reduce static and dynamic sag, improve rheological properties, and filtration control holds the potential to enhance drilling operations, minimize downtime, and bolster wellbore stability.

ملخص الرسالة

الاسم الكامل: علي عادل علي محمود

عنوان الرسالة: تحسين أداء سوائل الحفر المعتمدة على النفط باستخدام الطين العضوي

التخصص: هندسة بترول

تاريخ الدرجة العلمية: ديسمبر 2024

يزداد الطلب على موارد الطاقة من صناعة النفط والغاز إلى مستوى يصعب على مكامن الهيدروكربونات التقليدية تلبيته. تبحث شركات النفط والغاز عن طرق جديدة لاستغلال إمكانات المكامن غير التقليدية. وبعد استخدام سائل الحفر المناسب جزءاً أساسياً من أي عملية حفر ناجحة. هناك حاجة إلى استخدام سوائل حفر عالية الأداء أثناء حفر مكامن الهيدروكربونات غير التقليدية بسبب ظروف الضغط العالي ودرجة الحرارة العالية (HPHT) التي تتم مواجهتها ومتطلبات الحفر الأفقي/متعدد الأفرع الطويل لتحقيق أقصى اتصال بالمكامن. (MRC) يجب مراعاة التكلفة والتأثير البيئي وتنشيط الصخر الزيتي عند اختيار سائل الحفر الأمثل.

تُستخدم سوائل الحفر الزيتية (OBDFs) لتقليل مشاكل الحفر المتعلقة بترطيب الصخر الزيتي، ومقاومة السحب وعزم الدوران، والتصاق الأنابيب، وعدم استقرار جدار البئر. تُفضل سوائل الحفر الزيتية على سوائل الحفر المائية (WBDFs) لتحقيق استقرار جدار البئر في الآبار ذات الضغط العالي ودرجة الحرارة العالية وفي التكوينات الحاملة للصخر الزيتي. على الرغم من التكلفة والتأثير البيئي لسوائل الحفر الزيتية، إلا أن الصناعة تستخدمها بسبب تفوقها في تحمل ظروف الضغط العالي ودرجة الحرارة العالية وتنشيط الصخر الزيتي. ومع ذلك، فهي تعاني من قصور عندما يتعلق الأمر بنقل القطع والتعامل مع الترهل. يؤدي نقل القطع الضعيف بطبيعته إلى معدل اختراق بطيء (ROP)، وتراكم طبقات القطع، خاصة في الأجزاء الأفقية والمائلة من جدار البئر، مما يسبب مشاكل مثل التصاق الأنابيب، وعزم الدوران العالي، والاحتكاك العالي، وسوء جودة التدعيم بالإسمنت. هناك دراسات مختلفة حول تأثير المواد العضوية المركبة (OCs) على الخواص الريولوجية للأنظمة الزيتية، ولكن إيجاد مواد عضوية مركبة جديدة أو تطويرها كعوامل للتحكم في الريولوجيا يعد أمراً جذاباً لصناعة النفط والغاز.

كان الهدف من هذه الدراسة هو دراسة المواد العضوية المركبة المختلفة بمفردها وفي مجموعات لمعرفة فعاليتها كمعدل للريولوجيا لسوائل الحفر الزيتية في ظروف الضغط العالي ودرجة الحرارة العالية. في هذه الدراسة، تم تقييم ستة مواد عضوية مركبة كمعدلات للريولوجيا لسوائل الحفر الزيتية. تمت دراسة خصائص المواد العضوية المركبة باستخدام حيود الأشعة السينية (XRD) ومطيافية الأشعة السينية الفلورية (XRF) والمجهر الإلكتروني الماسح (SEM) وتحليل حجم الجسيمات (PSD). تم تقييم أداء المواد العضوية المركبة كمعدل للريولوجيا لسوائل الحفر الزيتية عن طريق اختبار سائل الحفر المحضر باستخدام المواد العضوية المركبة في ظروف الضغط العالي ودرجة الحرارة العالية. وشملت الاختبارات اختبارات الترهل واختبارات الاستقرار الكهربائي واختبارات الريولوجيا بعد الدرجة الساخنة (AHR) و القياسات التذبذبية (اختبارات مسح السعة ومسح التردد ومسح الوقت) واختبارات الترشيح في ظروف الضغط العالي ودرجة الحرارة العالية.

أظهرت النتائج أن المواد العضوية المركبة عززت بشكل ملحوظ استقرار المستحلب. لقد خففت بشكل فعال مشاكل الترهل في كل من الظروف الثابتة والديناميكية، مما أدى إلى تحسينات في اللزوجة اللدنة (PV) ونقطة الخضوع (YP) واللزوجة الظاهرية (AV) ونسبة YP/PV. أدى إضافة المواد العضوية المركبة إلى زيادة قوة الهلام (GS) وتحسين خصائص الترشيح لسائل الحفر. تسلط هذه النتائج الضوء على المواد العضوية المركبة كمادة مضافة قيمة لتعزيز أداء سوائل الحفر الزيتية، خاصة في ظروف الضغط العالي ودرجة الحرارة العالية الصعبة. إن قدرتها على توفير استقرار المستحلب، وتقليل الترهل الثابت والديناميكي، وتحسين الخواص الريولوجية، والتحكم في الترشيح تحمل إمكانية تعزيز عمليات الحفر، وتقليل وقت التوقف، وتعزيز استقرار جدار البئر.

CHAPTER 1

INTRODUCTION

Drilling fluids are used to drill oil and gas wells. These complex fluids correspond to 15–18% of a well's total cost (Khodja et al., 2010). The drilling fluids have several purposes which must be adjusted to ensure safety and minimize hole problems. Some of these functions include the removal of the cutting downhole, providing wellbore stability, cooling and lubricating the drill string and bit, controlling the downhole formation pressures, and preventing formation damage by creating a filter cake that seals the rock pores (Caenn et al., 2011; Caenn & Chillingar, 1996). Any failure of the drilling mud to meet its required functions can prove extremely costly and jeopardize the success of the drilling operation. When selecting the optimum drilling fluid, the cost of the drilling fluid, environmental regulations, and shale inhibition characteristics are important factors to consider (M. Ali et al., 2020a).

Drilling fluids are categorized into WBDFs and OBDFs. Depending on whether the continuous phase is water or oil. The oil base can be diesel, crude oil, or mineral oil (Amani et al., 2012a). In most cases, WBDFs is used due to the low cost and minimal environmental impact (Zhuang et al., 2016). On the other hand, WBDF has significant disadvantages, including interfering with oil flow through the porous rocks and dissolving salts (Zhuang et al., 2015). In addition, WBDFs have limitations in HPHT conditions. OBDFs are complex fluids composed of water, oil, different additives, and organophilic clays

(Herzhaft et al., 2003). For HPHT wells, OBDF is utilized due to its superior performance. In addition, OBDF provides a higher lubricity, high thermal stability, shale inhibition, better wellbore stability, and higher rates of penetration, and achieves a lower filter loss and thin filter cake (Caenn et al., 2011; Caenn & Chillingar, 1996; Karakosta et al., 2021; Khodja et al., 2010). Hydraulic fracturing is the most common technique to extract hydrocarbons in shale formations (Mahmoud et al., 2021). For shale formations, OBDF is utilized to eliminate the water-sensitive shale's problems of hydration and swelling (J. R. Zhang et al., 2020).

Drilling fluids are non-Newtonian thixotropic shear-thinning fluids (Karakosta et al., 2021; Werner et al., 2017). Their behavior varies depending on the temperature and pressure. The drilling fluid exhibits low viscosity when sheared and it thickens to hold the cuttings in place when the shearing is stopped. Different models are used to describe the rheology of drilling fluids, such as the Bingham Plastic model, Herschel-Bulkley model, and Casson model (Andaverde et al., 2019; Saasen & Ytrehus, 2020). Several rheological studies showed that the Herschel-Bulkley and Casson models fit the flow behavior of OBDFs at elevated temperature and pressure (Bergane & Hammadi, 2020; Growcock & Frederick, 1996; Hermoso, Martinez-Boza, et al., 2014; Hermoso, Martínez-Boza, et al., 2014; Houwen & Geehan, 1986; Politte, 1985). Various additives are added to the drilling fluids to adjust the density or chemical properties (Zhuang, Gao, et al., 2019a; Zhuang, Zhang, et al., 2019; Zhuang, Zhang, Peng, et al., 2018a).

1.1 Organoclays (OCs)

An OCs are formed by modifying clay materials with organic ammonium salts naturally and are widely used in industrial applications as rheology modifiers, such as grease, and cosmetics, as well as for the preparation of OBDFs (de Paiva et al., 2008). OCs are a crucial additive for drilling fluids preparation. The interlayer cations of clay are replaced by organic molecules such as alkyl ammonium cation. Due to the favorable dispersing properties in the oil phase and filtration characteristics, organophilic bentonites have been used extensively (Jordan, 1961). OCs have several advantages when added to OBDFs, such as the swelling ability in an organic medium, high thermal stability, and favorable rheological properties (Akkal et al., 2013; Hermoso, Martinez-Boza, et al., 2014a; Msadok et al., 2020; Weng et al., 2018; Zhou et al., 2016; Zhuang, Zhang, Peng, et al., 2018; Zhuang, Zhang, Wu, et al., 2017; Zhuang, Zhang, Yang, et al., 2018).

1.2 Common organoclays (OCs) used in oil-based drilling fluids (OBDFs)

Montmorillonite (MMT) (Abdo & Haneef, 2013; Abu-Jdayil, 2011; Caenn et al., 2011; Zhuang et al., 2015, 2016), palygorskite (PAL) (Baltar et al., 2009; Galan, 1996; Murray, 2000; Neaman & Singer, 2004; Zhuang, Wu, et al., 2017; Zhuang, Zhang, Gao, et al., 2017), and sepiolite (SEP) (Abdo et al., 2016; Altun & Serpen, 2005; Galan, 1996; Zhuang, Zhang, & Chen, 2018; Zhuang, Zhang, Yang, et al., 2018) are the most widely used clay minerals in WBDFs due to the formation of network structures in water. In OBDFs, OCs

are used as rheological additives. OCs have been shown to thicken organic compositions. In addition, appropriate colloidal and rheological properties of OBDF systems are obtained by adding OC (Mahmoud et al., 2023; Zhuang, Zhang, et al., 2019). Moreover, adding OC to the continuous phase of the drilling fluid enhances the fluid properties (Hermoso, Martinez-Boza, et al., 2014). Recently, scientists have studied the application of OC in OBDFs. The search for new OCs with favorable properties to be used in OBDFs is an area of active research. Also, the recent development in nanotechnology has opened a route for the development of OC for OBDFs applications. The work of this study will be presented with details in the following chapters:

Chapter 2- Application of Organoclays in Oil-Based Drilling Fluids: A Review: This paper was published in ACS Omega Journal.

Chapter 3- Investigating the efficacy of novel organoclay as a rheological additive for enhancing the performance of oil-based drilling fluids: This paper was published in Scientific Reports Journal.

Chapter 4- Evaluating the effect of Claytone-EM on the performance of oil-based drilling fluids: This paper was published in ACS Omega Journal.

CHAPTER 2

APPLICATION OF ORGANOCCLAYS IN OIL-BASED DRILLING FLUIDS: A REVIEW

This paper was published in ACS Omega:

Mahmoud, A., Gajbhiye, R., & Elkatatny, S. (2023). Application of organoclay in oil-based drilling fluids: a review. *ACS omega*, 8(33), 29847-29858.

2.1 Abstract

Organoclay (OC), formed by surface modification of clay minerals using organic compounds are typical additives for providing rheology for oil-based drilling fluids (OBDFs). There are different studies on the effect of OCs on the rheological properties of oil-based systems under high-pressure, high-temperature (HPHT) conditions but finding new OCs as rheology control agents is attractive for drilling fluid engineers.

This work reviews different OCs used in OBDFs namely organo-montmorillonite (OMMT), organo-sepiolite (OSEP), and organo-palygorskite (OPAL). Furthermore, the structure of OCs in OBDFs, their rheological properties, and the thermal stability of OCs were investigated. Besides, the role of fibrous and layered OCs in enhancing the rheological properties of OBDFs is illustrated. Finally, the synergistic use of different OCs to enhance the thermal stability and rheological properties of OBDFs is presented. The

study highlights research gaps and recommendations for research approaches and potential areas that need further investigation.

The application of OCs in OBDFs is a wide field and has a huge potential to be developed.

The use of OCs in OBDFs will promote the development of the oil and gas industry.

Keywords: Organoclay, Oil-Based Drilling Fluid, Rheological Properties, Montmorillonite, Sepiolite, Palygorskite.

2.2 Introduction

The demand for energy resources from the oil and gas industry is increasing to a level that is difficult for conventional hydrocarbon reservoirs to fulfill. Oil and gas companies are in search of novel ways to exploit the potential of unconventional reservoirs. Using a proper drilling fluid is critical to any successful drilling operation. High-performance drilling fluids must be used while drilling unconventional hydrocarbon reservoirs due to the high-pressure, high-temperature (HPHT) conditions encountered and the requirement of long horizontal/multilateral drilling for the maximum reservoir contact (MRC).

Drilling fluids are used to drill oil and gas wells and are considered a crucial part of any drilling operation. These complex fluids correspond to 15–18% of a well's total cost (Khodja et al., 2010). Figure 1 shows a schematic of the drilling operation including main constituents, main function, and classification of drilling fluid. They have several purposes which must be adjusted to ensure safety and minimize hole problems. Some of these functions include the removal of the cutting downhole, providing wellbore stability, cooling and lubricating the drill string and bit, controlling the downhole formation

pressures, and preventing formation damage by creating a filter cake that seals the rock pores.(Caenn et al., 2011; Caenn & Chillingar, 1996; Werner et al., 2017) Any failure of the drilling mud to meet its required functions can prove extremely costly and jeopardize the success of the drilling operation. When selecting the optimal drilling fluid, the cost of the drilling fluid, environmental regulations, and shale inhibition characteristics are key factors to consider.

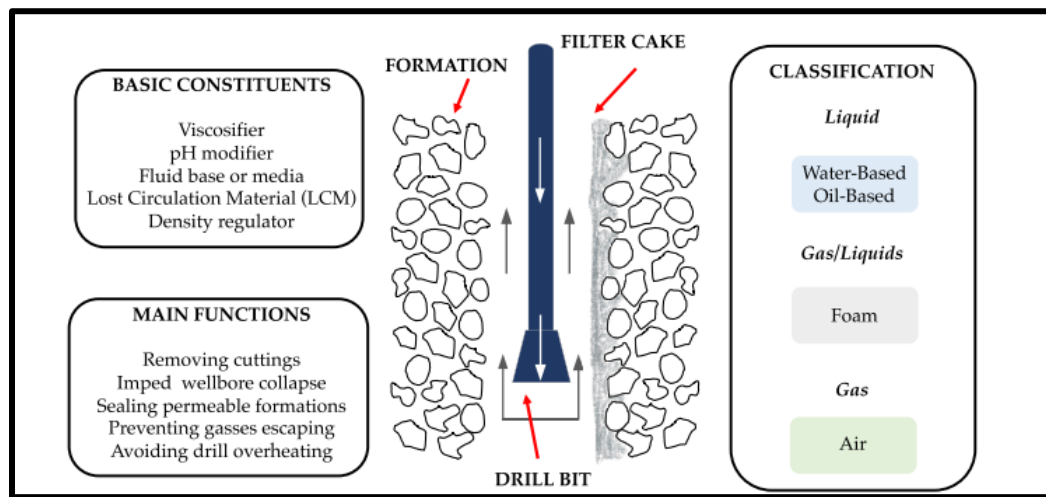


Figure 1 Schematic of drilling operation including main constituents, main function, and classification of drilling fluid (Zamora-Ledezma et al., 2022)

Drilling fluids are categorized into water-based drilling fluids (WBDFs) and oil-based drilling fluids (OBDFs) depending on whether the continuous phase is water or oil. The oil base can be diesel, crude oil, or mineral oil (Amani et al., 2012b). In most cases, WBDFs are used because of their low cost and minimal environmental impact (Zhuang et al., 2016). On the other hand, WBDFs have significant disadvantages, including interfering with oil flow through porous rocks and dissolving salts (Zhuang et al., 2015). In addition, WBDFs have limitations in HPHT conditions. OBDFs are complex fluids composed of water, oil, different additives, and organophilic clays (Herzhaft et al., 2003). For HPHT wells, OBDFs

are used due to their superior performance. Also, OBDFs provide higher lubricity, thermal stability, and shale inhibition; better wellbore stability; and higher rates of penetration, and achieve lower filter loss and thin filter cake (Caenn et al., 2011; Caenn & Chillingar, 1996; Karakosta et al., 2021; Khodja et al., 2010). Hydraulic fracturing is the most common technique to extract hydrocarbons in shale formations (Mahmoud et al., 2021). For shale formations, OBDF is used to eliminate the water-sensitive shale's problems of hydration and swelling (J. R. Zhang et al., 2020).

The complex drilling fluids are non-Newtonian thixotropic shear-thinning fluids (Karakosta et al., 2021; Werner et al., 2017). Their behavior varies depending on the temperature and pressure. Drilling fluid exhibits low viscosity when sheared, and it thickens to hold the cuttings in place when the shearing is halted. Different models are used to describe the rheology of drilling fluids, such as the Bingham plastic model, the Herschel–Bulkley model, and the Casson model (Zhuang, Zhang, et al., 2019). Various additives are added to drilling fluids to adjust their density or chemical properties (Zhuang, Gao, et al., 2019b; Zhuang, Zhang, et al., 2019; Zhuang, Zhang, Yang, et al., 2018).

2.3 Organoclays (OCs)

OCs are formed naturally by modifying clay materials with organic ammonium salts and are widely used in industrial applications as rheology modifiers, such as grease, and cosmetics, as well as in the preparation of OBDFs (de Paiva et al., 2008). OCs are a crucial additive in drilling fluids' preparation. The interlayer cations of clay are replaced by organic molecules such as alkyl ammonium cations. Due to its favorable dispersing properties in the oil phase and filtration characteristics, organophilic bentonite has been

used extensively (Jordan, 1961). OCs have several advantages when added to OBDFs, such as the ability to swell in an organic medium, high thermal stability, and favorable rheological properties (Akkal et al., 2013; Hermoso, Martinez-Boza, et al., 2014; Msadok et al., 2020; Weng et al., 2018; D. Zhou et al., 2016; Zhuang, Zhang, Peng, et al., 2018b; Zhuang, Zhang, Wu, et al., 2017; Zhuang, Zhang, Yang, et al., 2018). (Ogawa & Kuroda, 1997a) discussed the preparation of inorganic–organic nanocomposites through the intercalation of organoammonium ions into layered silicates. The authors developed a method to create tiny particles that are made up of both inorganic and organic materials. This process creates a new material that has unique properties and can be used in a variety of applications, such as in the production of plastics, coatings, and other materials.

2.4 Common organoclays (OCs) used in oil-based drilling fluids (OBDFs)

Montmorillonite (MMT) (Abdo & Haneef, 2013; Abu-Jdayil, 2011; Caenn et al., 2011; Caenn & Chillingar, 1996), palygorskite (PAL) (Baltar et al., 2009; Dahab, 1991; Dahab & Jarjarah, 1989; Galan, 1996; Murray, 2000; Neaman & Singer, 2004), and sepiolite (SEP) (Abdo et al., 2016; Al-Malki et al., 2016; Altun & Serpen, 2005; Galan, 1996) are the most widely used clay minerals in WBDFs due to the formation of network structures in water. In OBDFs, OCs are used as rheological additives. OCs thicken the organic compositions (Zhuang, Zhang, et al., 2019). In addition, appropriate colloidal and rheological properties for OBDF systems are obtained by adding OCs (Zhuang, Zhang, et al., 2019). Moreover, adding OCs to the continuous phase of the drilling fluid enhances the fluid properties (Hermoso et al., 2015; Hermoso, Martinez-Boza, et al., 2014). Recently,

scientists have studied the application of OCs in OBDFs. The search for new OCs with favorable properties for use in OBDFs is an area of active research. This review presents the application of OMMT, OSEP, and OPAL. Furthermore, the structure, colloidal and rheological properties, and thermal stability of OCs in OBDFs are summarized. Also, the recent development in nanotechnology has opened a route for developing OCs for OBDF applications.

2.5 Montmorillonite (MMT)

MMT is the main component of bentonite. It belongs to the general family of clay minerals. The structure of MMT is made of two continuous (SiO₄) tetrahedral sheets and an (AlO₆) octahedral sheet (Bergaya et al., 2012; Brigatti et al., 2013). MMT is negatively charged due to isomorphism. Due to the substitution of Mg²⁺ and other lower-charge cations for Al³⁺ in octahedral sites, a negative charge layer is formed (Brigatti et al., 2013; Jaber et al., 2014). Thus, some exchangeable cations present in the interlayer space, such as Na⁺ and Ca²⁺ counterbalance the deficit of positive charges (Bergaya & Lagaly, 2013; Brigatti et al., 2013; Murray, 1991). The fluid has a very high viscosity due to MMT's high charge and fine particle size. MMT is mainly used in WBDFs, while OMMT is used in OBDFs.

2.5.1 Organo-montmorillonite (OMMT)

Organic cations can intercalate into the interlayer space due to the exchangeable cations (de Paiva et al., 2008). This results in the expansion of the interlayer space. Besides, organic cations also coat the surface of MMT, which results in increased hydrophobicity (Zhuang et al., 2015, 2016). Several organic compounds can be used to prepare OMMT, e.g., cationic surfactants (Bardziński, 2014; Z. Li et al., 2003; Vazquez et al., 2008; Xi et al.,

2007; L. Zhou et al., 2009; Zhu et al., 2009), anionic surfactants (Sarier et al., 2010; K. Yang et al., 2007; Yılmaz & Alemdar, 2005; Z. Zhang et al., 2010), and nonionic surfactants (Guégan et al., 2015; Nourmoradi et al., 2012; Ouellet-Plamondon et al., 2014; Platikanov et al., 1977; Shen, 2001; Silva et al., 2014; Yin et al., 2015). OMMT modified using cationic surfactants is widely used because of its low cost, easy reaction, and controllable hydrophobicity (Zhuang, Gao, et al., 2019b). Additionally, mixtures of these organic compounds can be used, such as cationic and anionic surfactants (D. Chen et al., 2008, 2011; Fu et al., 2016; Regev & Khan, 1996; Sanqin et al., 2014; Z. Zhang et al., 2013), cationic and nonionic surfactants (Yin et al., 2015; Y. Zhang et al., 2012; Zhuang et al., 2015), and nonionic and anionic surfactants (K. Yang et al., 2005; Y. Zhang et al., 2012; Zhuang et al., 2015). Some properties of OMMT can be modified using two or more types of surfactants by changing the type and concentration of surfactants (Zhuang, Zhang, et al., 2019).

2.5.2 Application of organo-montmorillonite (OMMT) in oil-based drilling fluids (OBDFs)

(Jordan, 1961) used OMMT as a thicker organic solvent. The author investigated the conversion of clay from a highly hydrophilic condition to an organophilic condition. The organocation used in the study is octadecylammonium. OMMT is the most popular commercial rheological additive used in OBDF. Due to its hydrophobicity and large basal spacing, OMMT controls the rheological behavior of an OBDF by dispersing, swelling, and exfoliation in a base oil. (Zhuang, Zhang, et al., 2019) This study provides insights into the factors involved in the conversion process and the extent of the conversion.

(Silva et al., 2014) used OMMT with nonionic surfactants as dispersants in organic-based drilling fluids. The paper discusses the use of nonionic surfactants, specifically Ultramina 20 (TA20) and Ultramina 50 (TA50), as OC modifiers for use in organic-based drilling fluids. The study shows that the nonionic surfactants effectively intercalate in the OCs, and the content of incorporated surfactants was quantified. The swelling results demonstrate chemical compatibility between diesel and kerosene organic media and the OCs produced. The authors highlighted that nonionic surfactants are superior to ionic surfactants as they enhance the thermal stability and chemical properties of OCs and are eco-friendly. Furthermore, the results indicate efficient intercalation of nonionic surfactants in OCs. In addition, OCs considered poor in WBDFs showed great potential with organic-based drilling fluids. However, there was no direct correlation between apparent viscosity and swell indices, and the swell index should be used only for a qualitative analysis of the solvent–OC interaction and not as an indication of the viscosity of the dispersion to be used as a drilling fluid.

Recently, (Hermoso, Martinez-Boza, et al., 2014) studied the influence of the viscosity modifier and concentration on the rheological properties of OBDFs with two commercial OMMT samples (B34 and B128) as additives at different pressures. The authors used a controlled-stress rheometer to measure the fluids' viscous flow behavior as a function of OC concentration, OC nature, and pressure. They concluded that the nature and concentration of the OC strongly influenced the viscous flow behavior of OBDFs (Figure 2). Also, a Sisko–Barus model can be used to calculate pressure losses in different sections of the bore. In addition, higher concentrations of OMMT increased the viscosity. Moreover, the experimental pressure-viscosity data were fitted in to a Sisko–Barus model,

which considers shear and pressure effects. The study also found that the microstructure of the OC dispersions is related to the cohesion energy between microgel domains, and the pressure–viscosity behavior of these dispersions is mainly influenced by the piezo-viscous properties of the oil and the properties of the continuous phase.

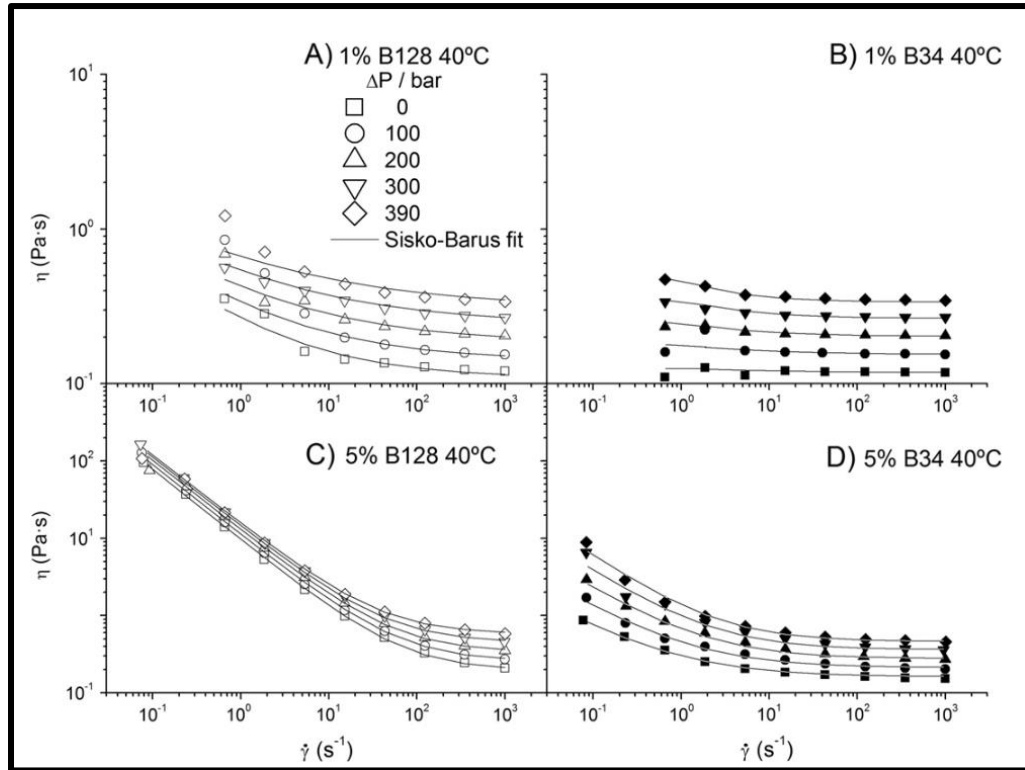


Figure 2 Experimental viscous flow curves and Sisko–Barus model fitting for the different OMMT/oil fluids studied as a function of pressure at 40 °C A) viscous flow curve for the lowest B128 concentration B) viscous flow curve for the lowest B34 concentration C) viscous flow curve for the highest B128 concentration D) viscous flow curve for the highest B34 concentration (Hermoso, Martinez-Boza, et al., 2014)

(Hermoso et al., 2015) studied the effect of OC concentration (1 and 3 wt.%) and aqueous phase volume fraction on the rheology of OMMT in invert-emulsion OBDs. The OC used in this study was Bentone 128, which was modified by a cationic exchange reaction between bentonite clay and dimethyl-benzyl-hydrogenated tallow. The authors concluded that at low concentrations of OC, the yield stress varied linearly; on the other hand, at high OC concentrations, the yield stress varied according to a power law model. The study found

that increasing the aqueous phase volume fraction led to a decrease in the viscosity, while increasing the OC concentration led to an increase in viscosity, confirming previous research results (Bhatt et al., 2013; Hyun et al., 2001). Moreover, the emulsion's stability increased due to a decrease in mean droplet diameter due to the increase in the concentration of OC, as has been reported earlier (Binks et al., 2005).

(Zhuang et al., 2015) compared cationic-organo-montmorillonite (CO-MMT), cationic-nonionic-organo-montmorillonite (CN-OMMT), and nonionic-organo-montmorillonite (N-OMMT) intended to be used in OBDFs. The study involved the preparation and characterization of the organo-montmorillonites using various techniques such as X-ray diffraction, differential thermal analysis, thermogravimetric analysis, the contact angle test, and the swell index. The results of the study indicated that both cationic and nonionic surfactants can intercalate into the interlayer spaces of MMT, and the order of their thermal stability was CN-OMMT > CO-MMT > NO-MMT. The order of surface lipophilicity and swelling indices in oils was CN-OMMT > CO-MMT > NO-MMT. Moreover, CN-OMMT presented a novel potential rheological control additive for OBDF, especially for high-oil/water ratio (OWR) fluids.

(D. Zhou et al., 2016) studied the rheological and filtration properties of OBDFs using OMMT modified by cationic and anionic surfactants. The authors first modified the MMT through mechanochemistry and studied the fluids' structures and properties using various techniques such as X-ray diffraction, thermal analysis, contact angles, and dispersion. They found that the cationic and anionic surfactants had intercalated into the interlayer spaces of MMT, resulting in higher surface polarity, better thermal stability, and better dispersion in highly polar solvents than cationic OMMT alone. The authors studied the thixotropic

behavior, viscosity properties, gel properties, and filtration loss at ambient and elevated temperatures (200–220°C). It was concluded that cationic and anionic OMMT have better thixotropy, enhanced rheological properties, and less filtration loss compared to commercial cationic OMMT in OBDFs with different OWRs.

(Hermoso et al., 2017) investigated the influence of two types of OCs and their concentration on the density of OC suspensions at a wide range of pressures and temperatures. The study found that the addition of OC to the liquid matrix resulted in a significant increase in density values across the range of temperatures and pressures evaluated (Figure 3). The volumetric behavior of these suspensions was found to be influenced by the nature of the OC and dampened by increasing pressure. The Tait equation was used to model the pressure–temperature dependence of the volumetric properties.

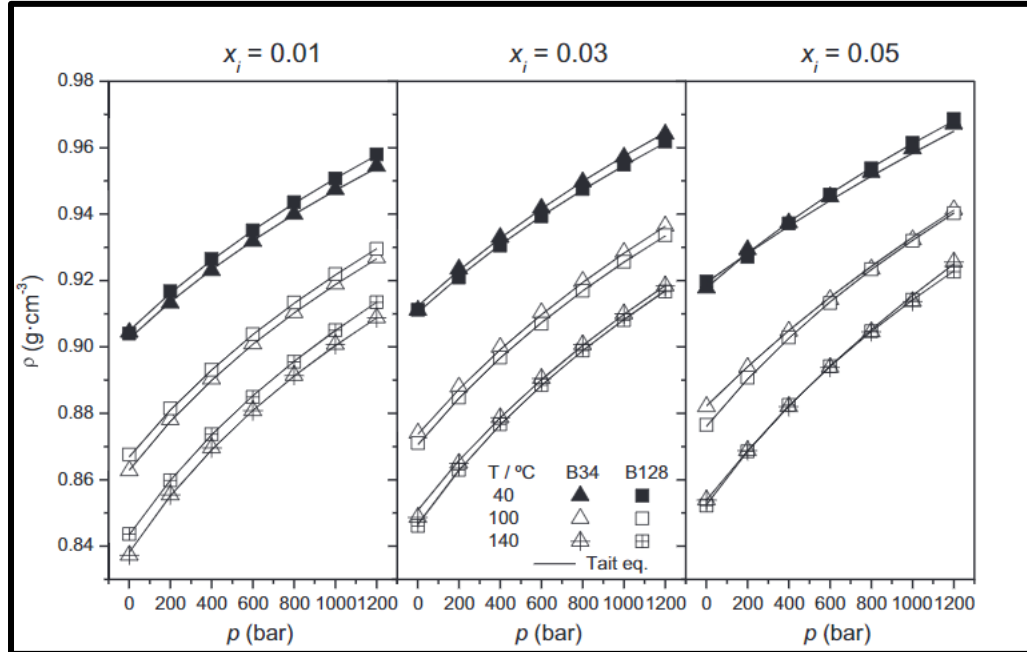


Figure 3 Evolution of the experimental density with pressure at different temperatures for the OMMT/oil fluids (Hermoso et al., 2017)

(Zhuang et al., 2016) studied the structure of OMMT, OMMT/oil gels, and the rheology of OMMT/oil fluids aged at different temperatures. The results demonstrated that surfactant loading influenced the structure and surface properties of the OMMT. Furthermore, the authors discovered that the structure of OMMT in oil went through four stages with increasing temperature: swelling, continuous swelling, exfoliation, and shrinking, respectively. The enwrapping, absorption, and other attraction among absorbed surfactants bridged individual OMMT sheets, particles, and aggregates, forming the gel structure. The swelling and gel formation of OMMT/oil was influenced by the surface properties, basal spacing, surfactant loadings, and temperature. Moreover, the rheological studies indicated that the fluid followed the Bingham plastic model at a high shear rate ($\geq 20 \text{ s}^{-1}$), while deviation emerged at a low shear rate range (Figure 4). The viscosity, gel strength, and thixotropy of OMMT/oil were relevant to the structure which was influenced by multiple elements, such as surface properties, basal spacing, surfactants loadings, temperature, etc. The best performance of individual elements did not automatically lead to the greatest rheological properties. For oil-based drilling fluids containing OMMT prepared with cetyl trimethyl ammonium bromide (CTAB), the recommended operating temperature was below 150 °C.

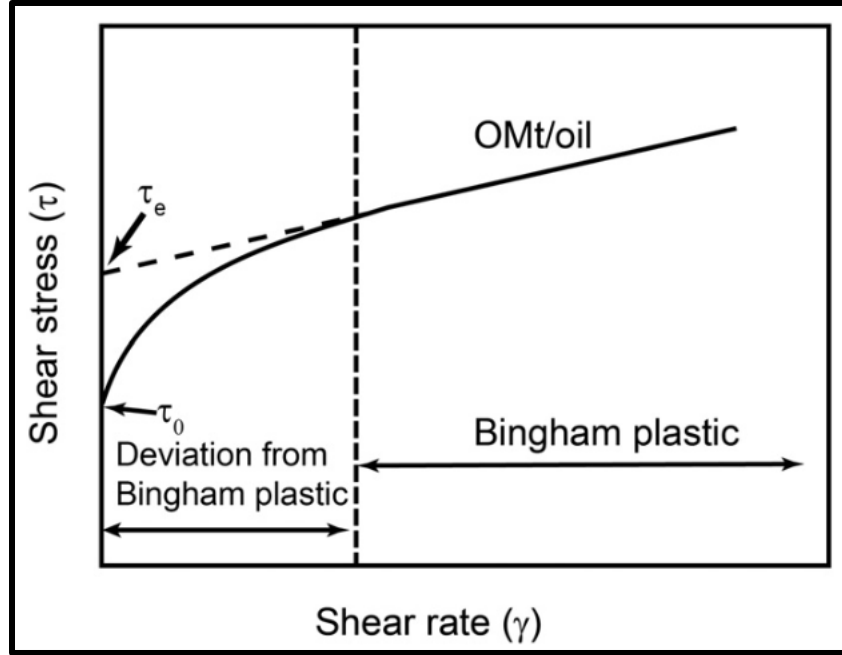


Figure 4 Interpretative diagram of the rheological model of OMMT/oil fluid (Zhuang et al., 2016)

Several rheological studies conducted show that at elevated temperature and pressure, the Herschel–Bulkley and Casson models fit the flow behavior of OBDFs fairly well (Bergane & Hammadi, 2020; Growcock & Frederick, 1996; Hermoso, Martinez-Boza, et al., 2014; Houwen & Geehan, 1986; Politte, 1985). The Casson rheological model accurately predicts the drilling fluid behavior across the low and high shear rates. In addition, it is preferred to the Herschel–Bulkley rheological model due to the correction factor that is introduced to the yield stress and PV.

2.6 Sepiolite (SEP) and palygorskite (PAL)

SEP and PAL are used in many technological applications due to their unique adsorptive, colloidal, and rheological properties (Zhuang, Zhang, et al., 2019). These clay minerals contain a continuous two-dimensional tetrahedral sheet, but they lack continuous octahedral sheets. The structure of SEP and PAL clay minerals is shown in Figure 5. Also,

a variable amount of zeolitic water is contained in the channels of SEP and PAL (Guggenheim & Krekeler, 2011; Krekeler & Guggenheim, 2008; Suárez & García-Romero, 2011). SEP and PAL clay minerals exhibit extra negative charges that are balanced by cations in the channels due to isomorphism substitution. These clay minerals are used in paints, adhesives, sealants, fertilizer dispersions, and cosmetics (Galan, 1996; Murray, 2000). They are also used in OBDFs (Abdo & Haneef, 2013; Al-Malki et al., 2016; Altun & Serpen, 2005; Baltar et al., 2009; Dahab, 1991; Dahab & Jarjarah, 1989; Neaman & Singer, 2004).

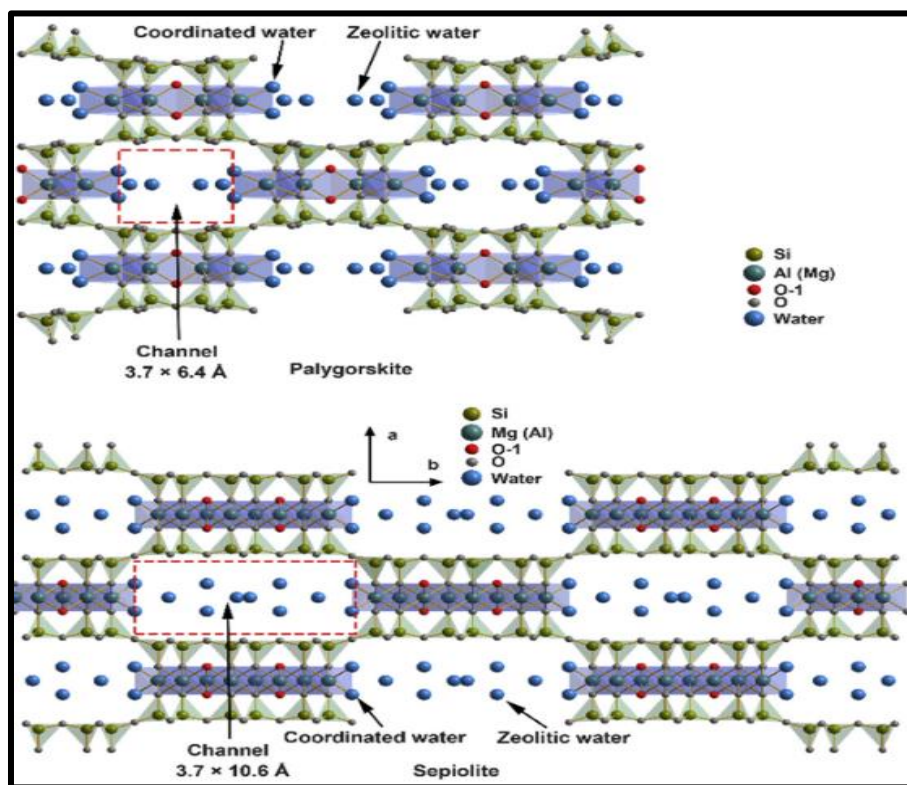


Figure 5 Crystal structures of PAL and SEP (Zhuang, Zhang, et al., 2019)

2.6.1 Organo-sepiolite (OSEP) and organo-palygorskite (OPAL)

In some applications, the organic modification of SEP and PAL is due to the poor compatibility between these clay minerals and organic compounds. The modifiers include

cationic surfactants, amines, polymers, and organosilanes. Table 1 summarizes the synthesis of OSEP and OPAL.

Table 1 Synthesis of OPAL and OSEP (Zhuang, Zhang, et al., 2019)

Clay mineral	Modifiers	Method	Reference
PAL	Series of quaternary ammonium salts	Reacting in water	(Zhuang, Wu, et al., 2017; Zhuang, Zhang, Gao, et al., 2017)
PAL	Chitosan	Stirring in toluene at 60 °C	(Peng et al., 2013)
PAL	Octadecyl trimethyl ammonium chloride (OTMAC)	Reacting in water with ultrasonication	(Huang et al., 2007)
PAL	Hexadecyl trimethyl ammonium bromide (HDTMAB)	Reacting in water with ultrasonication	(Lei et al., 2009)
SEP	Series of quaternary ammonium salts, amines, and organosilanes	Adsorption and grafting	(Tartaglione et al., 2008)
SEP	Series of quaternary ammonium salts	Reacting in water	(Zhuang, Gao, et al., 2018; Zhuang, Zhang, Yang, et al., 2018)
SEP	Series of quaternary ammonium salts and sodium dodecyl sulfate (SDS)	Reacting in water	(Weng et al., 2018)
SEP	Alkoxysilane	Reacting in water	(García et al., 2011)

2.6.2 Application of organo-sepiolite (OSEP) and organo-palygorskite (OPAL) in oil-based drilling fluids (OBDFs)

In the presence of dissolved salts, PAL and SEP remain a viscous dispersion, unlike MMT (Abdo & Haneef, 2013; Baltar et al., 2009; Galan, 1996). PAL and SEP develop a haystack structure by organizing the nanofibers. PAL and SEP are organically modified due to the poor compatibility between the clay surface and base oil.

(Zhuang, Zhang, Gao, et al., 2017) investigated the effects of different surfactants on the properties of OPAL in OBDFs. In this study, three different quaternary ammonium salts with different lipophilicity were used to organically modify PAL. The study found that the surfactants' lipophilicity affects the dispersity of OPAL in oil, with better lipophilicity leading to better dispersity. However, excellent dispersity does not necessarily contribute to high viscosity and gel strength. A little polarity is beneficial for promoting the rheological properties of OBDFs. The authors concluded that rising temperatures facilitate the disaggregation of OPAL in oil, but high temperatures may result in the thermal decomposition of surfactants on the surface of PAL (Figure 6). The content of sequestered oil in the interspace of OPAL units affects the network structure of OPAL in oil, with more sequestered oil resulting in a stronger network structure.

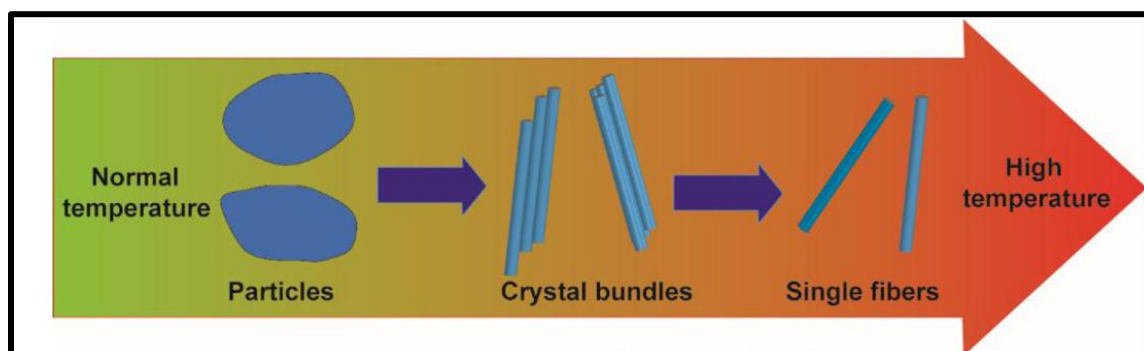


Figure 6 Organization change of OPAL in oil with the temperature rising (Zhuang, Zhang, Gao, et al., 2017)

(Zhuang, Wu, et al., 2017) characterized the structure of OSEP and evaluated its rheological properties in OBDFs. SEP was modified with benzyl dimethyl octadecyl ammonium chloride to create OSEP samples. The authors used different techniques such as X-ray diffraction, scanning electron microscopy, specific surface area, and thermal analysis to characterize the structure of OSEP. The surfactants coat the surface of SEP and are inserted into the channels and tunnels, resulting in lipophilicity and a decline in the

surface area of OSEP. The rheological properties of OSEP/oil fluids were evaluated using viscosity, yield point, dynamic rheological behavior, and thixotropy. The authors concluded that the addition of surfactants to OSEP promoted its rheological properties, but extremely high surfactant loading levels resulted in a decrease in rheological properties. OSEP modified with 35% surfactant showed the best rheological properties. Furthermore, rising temperatures promoted the rheological properties of OSEP/oil fluids by changing the organization of OSEP. However, extremely high temperatures resulted in a deterioration of rheological properties. The authors concluded that OSEP is a potential rheological additive in OBDFs with excellent rheological properties. However, an alternative organic modifier with high thermal stability is recommended to improve the thermal stability of OSEP/oil fluids.

(Zhuang, Zhang, & Chen, 2018) characterized the structure and properties of OPAL with three different cationic surfactants and evaluated its effectiveness in OBDFs. The three different cationic surfactants used were octadecyl trimethyl ammonium chloride (C18-A), benzyl dimethyl octadecyl ammonium chloride (C18-B), and dimethyl dioctadecyl ammonium chloride (DC18) (Figure 7). The authors found that the surfactant modification did not change the crystal structure of PAL, but it did change the aggregation of the fibers. Also, the surfactants mainly coated the surface of the PAL, but the details of the coating were influenced by the molecular scale of the surfactants and the coating level. Furthermore, OPAL was effective at increasing the viscosity of OBDFs and showed excellent thixotropy at temperatures above 150°C. Moreover, the rheological properties of the OPAL/oil fluids were influenced by the nature of the surfactants, coating level, and

temperature. The researchers found that OPAL was a promising rheological additive for OBDFs, with potential applications in the oil and gas industry.

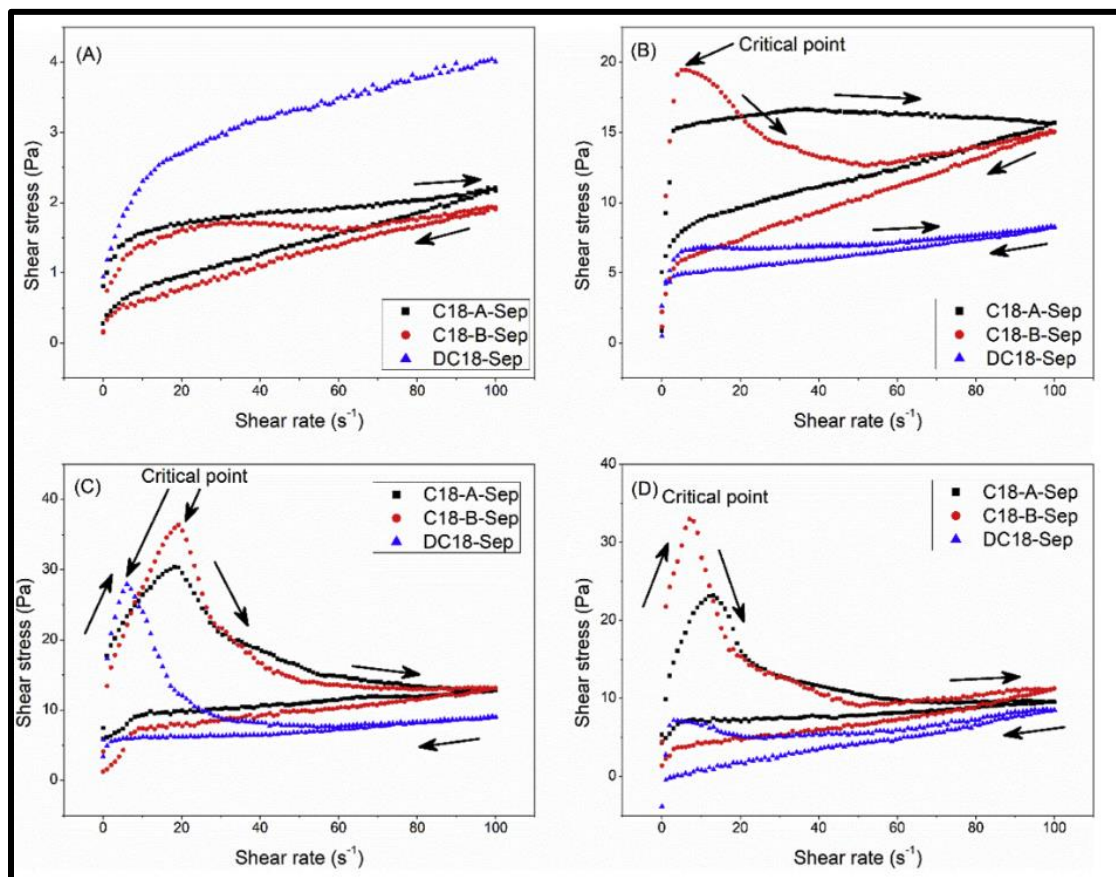


Figure 7 Dynamic rheological curves of OSEP/oil fluids aged at (A) 66 °C, (B) 150 °C, (C) 180 °C, and (D) 200 °C for 16 hours (Zhuang, Zhang, & Chen, 2018)

(Weng et al., 2018) studied the rheological properties and structure of cationic organo-sepiolite (CO-SEP) and cationic-anionic organo-sepiolite (CA-OSEP) to be used in OBDFs. The authors discussed the preparation and characterization of CO-SEP and CA-OSEP. The researchers used surfactants to modify the SEP and studied the effect of the dosage and chain length of surfactants, as well as the ratio of cationic to anionic surfactants, on the properties of the modified SEP. They found that CA-OSEP had higher surface polarity and better thermal stability than CO-SEP. The authors concluded that long-chain

cationic surfactants had superior adhesion to the surface of the SEP compared to short-chain surfactants. Furthermore, the thermal stability of the CA-OSEP was better than that of CO-SEP. Moreover, CA-OSEP had a higher surface polarity and improved rheological properties compared to CO-SEP. CA-OSEP presented a new kind of potential rheological control additive for oil-based drilling fluids that would exhibit excellent thermal stability.

According to (Zhuang, Zhang, et al., 2019) OPAL forms a network structure in oil easily due to its fibrous morphology. In addition, compared to the house of cards structure of OMMT, OPAL exhibits excellent thermal stability due to the haystack structure in OBDFs (Zhuang, Zhang, Gao, et al., 2017; Zhuang, Zhang, Jaber, et al., 2017).

(de Brito Buriti et al., 2022) discussed the synthesis and characterization of OPAL using cationic and nonionic surfactants for use as an additive in OBDFs. The objective of the study was to determine the rheological properties and thermal stability of the resulting dispersions. The authors used Praepagen WB as the cationic surfactant and Ultramina TA50 and Ultramina TA20 as the nonionic surfactant. The OPAL was obtained using a proportion of 15% surfactants. The results showed that the surfactants coated the clay surface without changing its crystal structure and morphology. The incorporation of surfactants was found to be in the order of Praepagen WB > Ultramina TA20 > Ultramina TA50. The authors concluded that OPAL when mixed with oil, can be used as an additive to OBDF due to its enhanced thermal stability and better rheological properties when compared with dispersions prepared with olefin at a high temperature (150 °C). This study shows that the nonionic surfactant can also be used to obtain OCs, which could have important implications for the development of more efficient and cost-effective drilling fluids.

2.7 Application of other organoclays (OCs) in oil-based drilling fluids (OBDFs)

(J. Li et al., 2014) developed and evaluated an OBDF for ultra-deep well drilling and shale gas well drilling. The authors describe the synthesis and evaluation of an OC and an oil-based filtrate reducer, as well as the optimization of the OBDF formulation. Long-carbon-chain quaternary ammonium salt was used as a modifying agent when synthesizing organo-bentonites. The laboratory tests showed that the OC and oil-based filtrate reducer had great compatibility and performance with other additives in the OBDF. The OBDF formula was determined based on optimal additive addition amount tests, and the test results showed that the OBDFs with various densities had great performance. The laboratory tests also showed that the oil-based drilling fluid developed was high temperature resistant, and had good inhibition, and reservoir protection performance. The field test showed that the developed OBDF had stable performance with a great ability to maintain wellbore stability and lower density than WBDF. The drill bits could be used for a longer time, and the average penetration rate was increased. The OBDF was able to satisfy the drilling requirements.

(Ratkievicius et al., 2017) studied the effect of dispersing organo-bentonite (OBEN) as a viscosity enhancer. The authors performed a surface modification procedure to disperse the clay in the organic phase of a vegetable OBDF. They used soybean oil, lauryl alcohol tri-ethoxylate, brine, bentonite modified by hexadecyl trimethylammonium bromide (CTABr), and barite to prepare the fluids. The study evaluated the influence of the concentration of CTABr in clay modification, viscosity enhancer concentration in the

composition of the drilling fluid, and temperature on the rheological properties of the fluid. The results showed that temperature was the most influential factor on the rheological properties of the prepared fluid. The study also found that as higher amounts of quaternary ammonium cations were adsorbed on clay surfaces, there was a decrease in the contact angle, suggesting an increasing affinity for oil.

(W. Li et al., 2018) introduced a modified rectorite clay that can be used as an additive in biodiesel-based drilling fluid to improve its rheological and filtration properties. The modified rectorite was created through a suspension production technique that involved modifying the clay with non-ionic surfactants. The authors presented laboratory results that demonstrate the effectiveness of the modified rectorite in improving the yield point, low-end rheology, and suspendability of the fluids. Organo-rectorite (OREC) has better swell performance in biodiesel emulsion compared to traditional organophilic bentonite. Furthermore, the modified rectorite can be combined with appropriate rheological modifiers to provide formulated fluid with great suspendability, as evidenced by the static barite-sag test. Moreover, the electrical stability of biodiesel emulsion is enhanced by the addition of the modified rectorite due to the formation of a Pickering emulsion. Therefore, this novel modified rectorite clay can be used as a cost-effective viscosifier for biodiesel-based fluids and other non-aqueous drilling fluids.

(Fakoya & Ahmed, 2018) studied the rheological properties of OBDFs and their continuous phase by adding different concentrations (2.9, 8.6, and 17.1 g/L) of organophilic clay (amine-treated bentonite) at different oil/water ratios (OWRs) (65/35, 75/25, and 85/15) within a temperature range of 24–87 °C. The study focuses on the apparent viscosity of OBFs and how it is affected by various factors such as organophilic clay concentration and

OWR. The authors concluded that the apparent viscosity (AV) of the OBDF increased with the OC concentration and OWR, and the influence of the OWR was major (Figure 8). Furthermore, the thermal thinning of the OBDF was reduced by increasing the OWR. The Herschel-Bulkley model was found to be the best fit to describe the rheological behavior of OBDFs. In addition, the rheological parameters of OBDFs showed a higher decrease with temperature than WBDFs; this clarifies the sensitivity of OBDFs to barite sag challenges. Moreover, a comprehensive rheological model was created to combine the OBDFs' viscosity with the temperature, continuous phase viscosity, and dispersed phase volume fraction. The authors developed empirical models that link the AV of the continuous phase to that of the OBDF, which can be used to predict an OBDF rheological parameters based on its formulation and the borehole's condition.

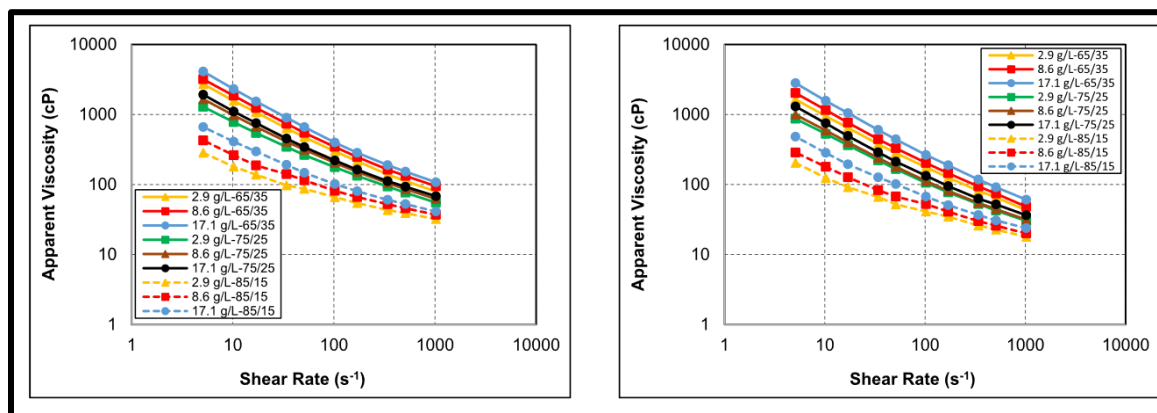


Figure 8 Effects of OC concentration and OWR on the apparent viscosity of OBM at 52 °C (right) and 79 °C (left) (Fakoya & Ahmed, 2018)

(Geng et al., 2019) investigated the effects of three different OCs, namely OSEP, organohectorite (OHEC), and OMMT, on the rheological properties of OBDFs at high temperatures. The organoclays were prepared through chemical modification of unmodified clays using dioctadecyldimethylammonium chloride (DODMAC), which is a

quaternary ammonium salt. The results of X-ray diffraction (XRD) and scanning electron microscopy (SEM) show that DODMAC is adsorbed on the surface of particles and inserted into the layers of OMMT and OHEC, while it can only be adsorbed on the surface of OSEP particles. The study found that the OHEC particle-stabilized invert emulsion fluid provides better rheological properties than the other two organoclays at high temperatures. This is attributed to the weak flocculation of OHEC particles, which is maintained by their nonreactive Mg–OH surface groups. On the other hand, on the particle surface of OMMT and OSEP, Al–OH may react with OH[−] under alkaline conditions, which destroys the weak flocculation due to increased repulsion interaction.

(Msadok et al., 2020) investigated the effect of using modified Tunisian clay with different cationic surfactant concentrations on the rheological properties of diesel OBDFs. The modified clay samples were characterized using various techniques such as X-ray diffraction, infrared spectroscopy, scanning electron microscopy, and specific surface area analysis. The oil–clay suspensions were investigated using polarized light optical microscopy and a double cone rheometer. The results showed that the rheological properties of the suspensions were influenced by the concentration of the surfactant used. As the surfactant concentration increased, the yield stress and consistency coefficient also increased. The best behavior was observed for the 3.0 CEC concentration. The organoclay sample at 10 wt.% showed the highest Herschel–Bulkley parameters, indicating that it could be used as a viscosity enhancer for OBDFs.

(Jiang, Shi, et al., 2022) formulated a low-cost, environmentally friendly biodiesel of soybean oil ethyl ester with low temperature and low viscosity properties as a base oil for OBDFs. The authors optimized the raw materials and selected cheap and environment-

friendly biodiesel of soybean oil ethyl ester as the base oil. They also developed key treatment agents compatible with biodiesel to establish and evaluate the drilling fluid system. The authors selected Span80 with a hydrophile-lipophile balance (HLB) value of 4.3 as the only emulsifier and prepared biodiesel-based emulsions with different OWRs. They optimized the oil/water ratio and formulated a biodiesel-based flat-rheology drilling fluid system with a density of 1.2 g/cm³. The authors used OC prepared with a cationic modifier of hexadecyl trimethyl ammonium chloride to improve the rheologic properties, stability, and fluid loss of the drilling fluid while preventing low-temperature thickening. They also synthesized a flat-rheology modifier with dimer fatty acid and coconut fatty acid diethanolamine, which could form a strong network structure in the biodiesel-based drilling fluid to effectively adjust the rheological properties of the drilling fluid.

2.8 Integration of different organoclays (OCs) in oil-based drilling fluids (OBDFs)

The synergistic use of two clay minerals to enhance the rheological properties of WBDFs has been studied by some researchers. (Neaman & Singer, 2000) studied the rheological properties of MMT and PAL as additives in WBFDs. The authors concluded that the addition of a low concentration of MMT (≤ 10 wt.%) increased the rheological properties in terms of PV and yield value. Later, (İşçi & Turutoğlu, 2011) investigated the effect of a mixture of MMT and SEP as additives in WBDFs. The authors concluded that the mixture is not suitable for WBDFs and recommended the use of stabilizers. (Au & Leong, 2013) used a mixture of MMT and kaolinite in WBFDs. They concluded that by changing the concentration of these two clay minerals, the optimized pH value can be adjusted. (Al-

Malki et al., 2016) used a mixture of bentonite-based drilling fluids with SEP nanoparticles. The authors revealed enhanced stability in the yield point (YP) and PV over a wide range of temperatures and pressures, particularly in HPHT conditions.

The previous work showed that the combined use of OMMT and OSEP can also improve the rheological properties and thermal stability of OBDFs. (Mainye & Teutsch, 2016) investigated the use of a mixture of OMMT and OPAL (or OSEP) as a rheological additive to enhance the ultra-low shear rate viscosity and to improve the carrying capacity of OBDFs. Compared to using the OCs separately, the mixture of OCs yielded stable gels that were non-progressive. (Zhuang, Zhang, Peng, et al., 2018b) evaluated the rheological properties and thermal stability of OBDFs by using a mixture of OMMT and OSEP as the rheological additive. The authors prepared OMMT and OSEP in water and characterized their structures using X-ray diffraction, scanning electron microscopy, and transmission electron microscopy. The authors found that OMMT swelled in oil at low temperatures and then exfoliated above 150 °C, while OSEP always maintained its crystal structure. Mixing these two OCs did not significantly influence their structures, but it did promote gel formation ability, resulting in improved rheological properties and thermal stability of OBDFs. The nanolayers of OMMT and nanofibers of OSEP interwove with each other, reinforcing the network structure, and protecting them from collapse at high temperatures. The mixture of OMMT and OSEP with a mass proportion of 50% for each displayed the optimal rheological properties and thermal ability.

2.9 Lessons Learned

For several years, the oil and gas industry has searched for novel ways to enhance the rheological properties of OBDF systems. The recent advancement in nanotechnology has

promoted the development of OCs for application in OBDFs. To solve the current problems, new OCs with suitable rheological additives for OBDFs must be developed and evaluated. Clay mineralogy, colloidal chemistry, and rheological properties are important when studying OCs developed for OBDFs. OCs control the rheological behavior of OBDFs by dispersal, swelling and exfoliation, eventually increasing the fluids' viscosity and thixotropy. OCs exhibit unique characteristics in improving the formulation of OBDFs. This work has reviewed three different OCs, namely OMMT, OSEP, and OPAL, in terms of the structure, rheological properties, and thermal stability of OBDFs. In general, the following are the key lessons learned from this study.

1. The viscous flow behavior of OBDFs at different pressure is greatly influenced by the OC's nature and concentration.
2. At low OC concentrations, the yield stress varies linearly; on the other hand, at high OC concentrations, the yield stress varies according to a power law model.
3. CN-OMMT presents a novel potential rheological control additive for OBDFs, especially for high-oil/water ratio fluids.
4. OPAL forms a network structure in oil easily due to its fibrous morphology. Compared to the house of cards structure of OMMT, OPAL exhibits excellent thermal stability due to the haystack structure in OBDFs.
5. OPAL when mixed with oil, can be used as an additive to OBDF due to its enhanced thermal stability and better rheological properties compared with dispersions prepared with olefin at a high temperature (150 °C).

6. The rheological properties of OSEP/oil fluids are improved with temperature. However, at extremely high temperatures ($>180\text{ }^{\circ}\text{C}$) the rheological properties decline due to the desorption of surfactants.
7. The combination of high temperatures and high concentrations of OBEN significantly affects the yield strength and thixotropy of OBDFs.
8. When compared to OBEN, OREC has better-swelling behavior, an improved yield point, and improved rheological properties in a biodiesel emulsion. In addition, OREC enhanced the thermal stability of the inverted biodiesel emulsion.
9. OCs prepared using cationic surfactants enhance the rheological properties, stability, and fluid loss of OBDFs.
10. Synergistic use of OMMT and fibrous OC enhances the rheological properties and thermal stability of OBDFs.

2.10 Recommendations

For further studies of the application of OCs in OBDFs, the following recommendations should be investigated in extensive research.

1. Aiming to provide greater viscosity, thixotropy, and thermal stability for OBDFs, it is recommended to use surfactants with longer alkyl chains to prepare OMMT.
2. OMMT is the most common rheological additive used in OBDFs. More research is needed on the application of OPAL and OSEP in OBDFs.

3. OBDFs are complex mixtures that contain several agents, such as emulsifiers and weighting agents; the compatibility between OCs and these agents must be evaluated to develop adequate physicochemical characteristics.
4. The Casson rheological model accurately predicts drilling fluid behavior across low and high shear rates. In addition, it is preferred to the Herschel–Bulkley rheological model due to the correction factor that is introduced to the yield stress and PV.
5. The effects of temperature and pressure must be studied extensively, as they have a significant effect on the rheological properties of OBDFs.
6. The interactions between OCs and organic surfactants and their effect on the structure of OCs in oil need to be deeply investigated.

CHAPTER 3

INVESTIGATING THE EFFICACY OF NOVEL ORGANOCLAY AS A RHEOLOGICAL ADDITIVE FOR ENHANCING THE PERFORMANCE OF OIL-BASED DRILLING FLUIDS

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3.1 Abstract

Oil-based drilling fluids (OBDFs) are extensively used in the drilling industry due to their superior performance in challenging drilling conditions. These fluids control wellbore stability, lubricate the drill bit, and transport drill cuttings to the surface. One important

component of oil-based drilling fluids is the viscosifier, which provides rheological properties to enhance drilling operations.

This study evaluates the effectiveness of Claytone-IMG 400, a novel rheological agent, in enhancing the performance of OBDFs under high-pressure and high-temperature (HPHT) conditions. A comparative analysis was conducted with a pre-existing organoclay (OC) to assess the improvements achieved by Claytone-IMG 400. The OCs were analyzed using X-ray diffraction (XRD), X-ray fluorescence (XRF), scanning electron microscopy (SEM), and particle size distribution (PSD) to identify their mineral and chemical compositions, morphologies, and particle sizes. The drilling fluid density, electrical stability, sagging tendency, rheological properties, viscoelastic properties, and filtration properties were studied to formulate a stable and high-performance drilling fluid. The results confirmed that the novel OC does not affect the drilling fluid density but enhances the emulsion stability with a 9% increment compared with the drilling fluid formulated with MC-TONE. The sagging experiments showed that Claytone-IMG 400 prevented the sagging issues in both static and dynamic conditions. Also, Claytone-IMG 400 improved the plastic viscosity (PV), yield point (YP), and apparent viscosity (AV). The PV, YP, and AV were improved by 30%, 38%, and 33% increments respectively compared with the drilling fluid formulated with MC-TONE. The YP/PV ratio increased with a 6% increment from 1.12 to 1.19. Moreover, the gel strength (GS) was significantly increased, and the filtration properties were enhanced. The filtration volume was reduced by 10% from 5.0 cm³ to 4.5 cm³, and the filter cake thickness had a 37.5% reduction from 2.60 mm to 1.89 mm.

The novelty of this study is highlighted by the introduction and evaluation of Claytone-IMG 400 as a new rheological additive for safe, efficient, and cost-effective drilling

operations. The results indicate that Claytone-IMG 400 significantly improves the stability and performance of OBDFs, thereby reducing wellbore instability and drilling-related problems.

3.2 Introduction

Drilling fluids are special fluids that are used in the process of drilling oil and gas wells. They serve a variety of purposes during the drilling process including lubricating and cooling the drill bit, carrying drilled cuttings to the surface, maintaining wellbore stability, and preventing formation damage or blowouts by controlling pressure imbalances between subsurface formations and the wellbore (Caenn et al., 2011; Caenn & Chillingar, 1996; Khodja et al., 2010; Mahmoud et al., 2023; Zamora-Ledezma et al., 2022). There are various types of drilling fluids, which can be broadly classified into two main categories namely water-based drilling fluids (WBDFs) and oil-based drilling fluids (OBDFs) (Amani et al., 2012a). Each type of drilling fluid has its unique properties and advantages, and the selection of the appropriate drilling fluid for a particular drilling operation depends on several factors, including the type of formation being drilled, the drilling depth, and the environmental regulations (Karakosta et al., 2021). OBDFs are preferred for deeper and more challenging drilling operations.

OBDFs offer several advantages over WBDFs in certain drilling applications. OBDFs have better thermal stability compared to WBDFs, making them suitable for high-temperature drilling operations. This stability means that OBDFs can maintain their rheological and filtration properties under extreme temperature conditions, ensuring efficient drilling and

wellbore stability (Zhuang, Zhang, et al., 2019; Zhuang, Zhang, Peng, et al., 2018b). Furthermore, OBDFs provide superior lubrication to the drill string, drill bit, and other downhole components, compared to WBDFs. This improved lubrication reduces friction, which can lead to lower rates of equipment wear, reduced torque and drag, and ultimately, extended equipment life and reduced costs (Fakoya & Ahmed, 2018). Moreover, OBDFs are less reactive with shale formations than WBDFs due to their lower water content and wettability properties (Mahmoud et al., 2021). This reduced reactivity helps to prevent shale swelling, dispersion, or sloughing, which can lead to wellbore instability and other drilling-related issues (M. Ali et al., 2020b).

One of the major disadvantages of OBDFs is their potential environmental impact. The use of OBDFs can lead to the release of hydrocarbons into the environment, posing a risk to aquatic life and ecosystems (Pereira et al., 2022). Also, OBDFs are generally more expensive than WBDFs due to the higher cost of the base oil and the need for additional additives to achieve the desired performance (Davoodi, Al-Shargabi, et al., 2023a; W. Li et al., 2016; Razali et al., 2018). Moreover, if circulation losses occur during drilling, it can be challenging to stop the losses with OBDFs. Severe loss situations can be time-consuming to cure, as the drilling fluid viscosity may not increase, and the OBDF may continue opening fractures (J. Yang et al., 2022; Zhong et al., 2018). Furthermore, OBDFs may not be suitable for drilling certain formations, such as highly permeable formations. These formations can cause excessive fluid invasion, resulting in wellbore instability and potential formation damage (Rafati et al., 2018; Zhong et al., 2018). In addition, handling and working with OBDFs may present health and safety risks to drilling personnel. The potential exposure to toxic additives and the flammability of the base oil requires strict

adherence to safety protocols and the use of personal protective equipment (PPE) (Fadairo et al., 2012; Martin et al., 2023).

Clay swelling in drilling operations can lead to significant challenges and potential issues. Clay swelling can lead to wellbore instability, formation damage, and potential problems such as stuck pipes, lost circulation, and well control issues (Anderson et al., 2010). When exposed to WBDFs, clays can absorb water and swell, leading to wellbore instability, decreased drilling efficiency, and potential formation damage (Khodja et al., 2010). Controlling clay swelling is crucial to ensure safe and efficient drilling operations (Khezerloo-ye Aghdam et al., 2023). OBDFs have proven effective in mitigating clay swelling due to their ability to prevent water penetration into the formation, thereby maintaining wellbore stability. By controlling clay swelling, OBDFs contribute to improved wellbore stability, reduced formation damage, and enhanced drilling efficiency, making them a valuable choice for challenging drilling operations (Aghdam et al., 2021; Khezerloo-ye Aghdam et al., 2019).

Drilling fluid properties play a crucial role in the efficiency, safety, and success of drilling operations. These properties can be broadly categorized into rheological properties, physical properties, and chemical properties (Karakosta et al., 2021; J. R. Zhang et al., 2020). Regular testing and analysis of drilling fluid properties, along with appropriate adjustments to the fluid's composition or treatment, are essential components of drilling fluid management. The selection and use of drilling fluid additives depend on several factors, including the type of formation being drilled, the drilling depth, and the environmental regulations. These additives include viscosifiers, fluid loss control agents, weighting agents, thinners, and lost circulation materials (LCMs) (Herzhaft et al., 2003).

Proper selection and use of additives can help optimize drilling fluid performance and minimize the risk of formation damage and other problems during drilling operations.

Organoclays (OCs) are a type of clay mineral that has been modified with organic compounds to improve their performance. The modification process involves exchanging the cationic particles on the surface of the clay with an organic compound, typically quaternary ammonium compounds (de Paiva et al., 2008; Ogawa & Kuroda, 1997b). The resulting OC has unique properties that make it ideal for use in OBDFs (Jordan, 1961). One major advantage is its ability to increase viscosity and suspension properties while maintaining low shear rates which helps prevent cuttings from settling within the wellbore thereby improving hole stability. Other benefits include improved filtration control & rheological stability which helps enhance overall efficiency during the drilling operation (Weng et al., 2018; Zhuang, Zhang, Yang, et al., 2018). OCs are used as additives to help control rheological properties and improve the drilling fluid performance. They are particularly useful in OBDFs and synthetic-based drilling fluids (SBDFs) due to their ability to adsorb and stabilize oil droplets and other non-polar substances within the fluid (Akkal et al., 2013; Hermoso et al., 2015, 2017; Hermoso, Martinez-Boza, et al., 2014; Msadok et al., 2020; Weng et al., 2018).

Claytone-IMG 400 is a type of OC specifically designed for use as a rheological additive in OBDFs and SBDFs. It is a chemically modified smectite clay, typically derived from bentonite, treated with a quaternary ammonium compound through ion exchange. This modification enhances the clay's affinity for nonpolar organic compounds and improves its rheological properties. The specific gravity of Claytone-IMG 400 is 1.6 g/cm³, the bulk density is 30 lb/ft³ and is supplied by BYK company.

In this study, Claytone-IMG 400 is introduced as a new rheological additive to formulate drilling fluids that meet the desired performance criteria and address specific drilling challenges. It is also aimed at improving the performance of OBDs. Important drilling fluid characteristics, represented by the drilling fluid density, emulsion stability, rheological properties, viscoelastic properties, filtration behavior, and static and dynamic sag tests were addressed and compared with an existing OC (MC-TONE) used in a drilling fluid service company. Claytone-IMG 400 exhibits enhanced affinity for nonpolar organic compounds and improved rheological properties. It offers various benefits in drilling fluid applications, including rheological control, emulsion stabilization, filtration control, and shale stabilization.

3.3 Materials

A Hamilton Beach mixer was used to prepare two invert emulsion samples in ambient conditions. The applied field formulation is shown in Table 2 listing the practical additives with the quantities in pounds per barrel, the mixing time, and the function of each component. The mixing was done at ambient conditions and the rotational speed was 10000 RPM. The additives were mixed sequentially to control the viscosity, alkalinity fluid loss, and filter cake formation. Diesel was obtained from a local gas station while the additives were provided by a drilling fluid service provider. The experimental methodology for performing this study is summarized in Figure 9.

Table 2 Drilling fluid formulation used in this study

Additive	Quantity (ppb)	Mixing time (mins)	Function
Diesel	154.46	-	Continuous phase

Primary emulsifier	8	10	Emulsion stabilization
Secondary emulsifier	6	5	Enhance emulsion stability
Lime	6	5	Alkalinity control
CaCl ₂ brine (25% weight)	65.53	15	Dispersed phase/ shale stabilization
Organoclay	7	10	Viscosifier
Organophilic lignite	8	10	Fluid loss control
Barite	377	10	Weighting material

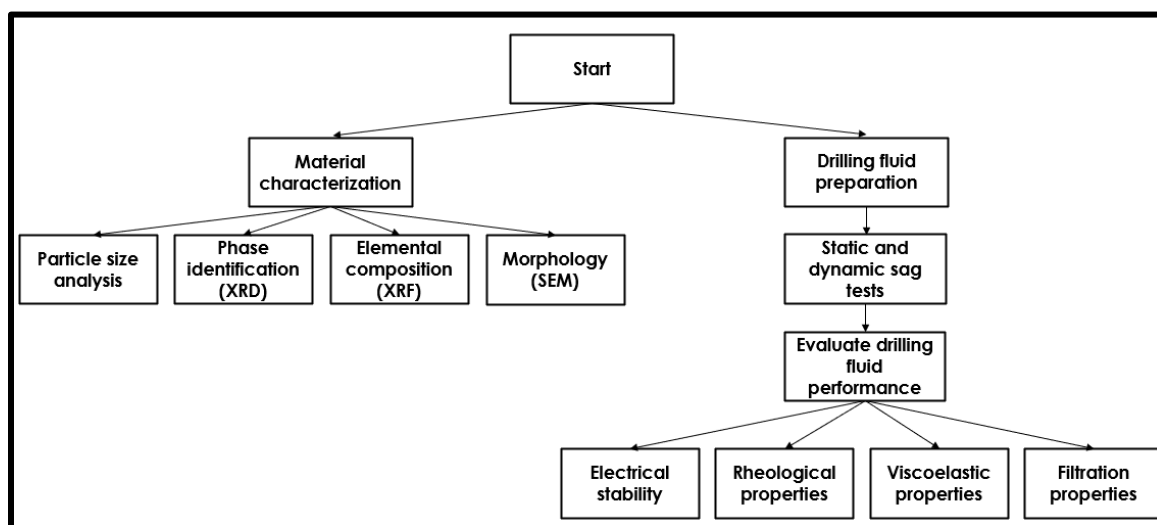


Figure 9 Experimental methodology

3.4 Experimental Work

The following procedure was performed in order to evaluate the effect of using Claytone-IMG 400 on the drilling fluid properties:

1. Prepare the drilling fluid mixture at ambient temperature.

2. Measure the density and electrical stability at ambient temperature.
3. Perform the static sag test at 275 °F and 500 psi differential pressure under vertical and inclined (45°) conditions.
4. Perform the dynamic sag test using the sag shoe and the rheometer at 150 °F and 100 revolutions per minute (rpm).
5. Perform the amplitude sweep test at 275 °F and 500 psi differential pressure to determine the linear elastic region of the fluid.
6. Perform the angular frequency test at 275 °F and 500 psi differential pressure to determine the storage modulus of the invert emulsion drilling fluid.
7. Perform the time sweep test at 275 °F and 500 psi differential pressure to determine the fluid's viscosity changes over time and assesses its thixotropic behavior.
8. Measure the rheological properties at 275 °F and 500 psi differential pressure.
9. Measure the filtration properties at 275 °F and 500 psi differential pressure.

3.4.1 Material Characterization

Both OCs used in this study were characterized to understand the mineral compositions, elemental compositions, and morphologies by particle size distribution (PSD), X-ray diffraction (XRD), X-ray fluorescence (XRF), and scanning electron microscopy (SEM).

3.4.2 Density and Electrical Stability

The drilling fluid weight and electrical stability under ambient conditions were measured for the two prepared drilling fluid samples using a mud balance and an electrical stability

tester, respectively. The recommended electrical stability value is >400 Volt (Zanten et al., 2012a). Monitoring and controlling the density of drilling fluids is essential for maintaining safe and efficient drilling operations. The stability of the emulsion is crucial for maintaining appropriate rheological properties, minimizing fluid loss, and ensuring overall drilling fluid performance.

3.4.3 Sagging Tests

Sagging tests are conducted on OBDs to determine the stability and suspension properties of the fluid. Sagging is settling denser solids within the drilling fluid, which can lead to potential issues such as stuck pipes, lost circulation, and well control problems (Ofei et al., 2022; Saasen, 2002a). By addressing sagging issues in OBDs, operators can minimize the associated risks and maintain efficient drilling operations.

Static sagging test measures the settling of solids in a fluid sample after a certain period of static conditions. The static test was conducted at vertical and vertical and inclined 45° positions since the solid sagging problems occur in both vertical and deviated wells (Amighi & Shahbazi, 2010a). The static sagging test was performed by subjecting the drilling fluid in an aging cell to 275 °F temperature and 500 psi pressure for a period of 24 h. The weights of 10 cm³ of the fluids from the upper and bottom parts of the aging cell were measured to calculate the sag factor using the following equation. The recommended sag factor is 0.50–0.53 (Maxey, 2007).

$$SF = \frac{\rho_{\text{bottom}}}{\rho_{\text{bottom}} + \rho_{\text{top}}} \quad (1)$$

Dynamic sagging tests are used to simulate the dynamic conditions experienced in a wellbore, the dynamic sag test was conducted at 150°F and atmospheric pressure using a viscometer rotated at 100 rpm for 30 min. The recommended viscometer sag shoe test (VSST) value is 0–1 (Aldea et al., 2001).

The following procedure was performed for the dynamic sag test (Zamora & Bell, 2004):

1. Insert the sag shoe into the thermocup and put it together on the viscometer plate.
2. Pour the drilling fluid inside the thermocup and raise it until the upper surface touches the lower part of the viscometer sleeve. Then lower the cup around 7 mm.
3. Heat the 140 mL drilling fluid with the sag shoe to 150 °F.
4. Set the viscometer at 100 rpm and start a 30 min timer.
5. Using the syringe with the cannula, extract a 10 mL sample and record the weight of the drilling fluid-filled syringe (W_1).
6. Stop the viscometer after 30 min and take another sample of 10 mL.
7. Record the weight of the drilling fluid-filled syringe (W_2).
8. Calculate the VSST using the following equation.

$$VSST = 0.833 \times (W_2 - W_1) \quad (2)$$

3.4.4 Amplitude, Frequency, and Time sweep tests

Amplitude, frequency, and time sweep tests are rheological tests performed on drilling fluids to understand their flow behavior and stability under different conditions. These tests

are crucial for predicting the performance of the drilling fluid under the varying conditions of a drilling operation. Anton-Paar rheometer was used to conduct oscillatory amplitude, frequency, and time sweep tests. Conducting amplitude, frequency, and time sweep tests on OBDs helps operators better understand the fluid's rheological behavior and make necessary adjustments to the fluid formulation to optimize suspension properties, hole cleaning, and wellbore stability.

Amplitude sweep test evaluates the linear viscoelastic region (LVE) of the drilling fluid by varying the applied shear strain while maintaining a constant frequency. The LVE is the range where the fluid exhibits a linear relationship between the applied stress and the resulting strain. The point at which the fluid's response deviates from linearity is considered its yield point, which is a measure of the fluid's ability to carry cuttings. The test helps to identify the optimal range of shear stress or strain for subsequent frequency and time sweep tests. Oscillatory amplitude tests were conducted to study the effect of using the novel OC on the storage modulus G' and loss modulus G'' . The amplitude test was conducted at a fixed frequency of 10 rad/s and the range of shear strains from 0.01 to 100% to determine the region of linear viscoelastic and stability.

In a frequency sweep test, the frequency of the applied oscillatory shear stress is varied while keeping the shear strain constant, usually within the LVE. The test provides information about the fluid's viscoelastic behavior over a range of frequencies, which represent different shear rates that the fluid may experience during drilling operations. The frequency test was carried out at different frequencies (0.1–100 rad/s) and constant shear strain was selected from the linear range to study the elasticity behavior of the inner structure.

The time sweep test monitors the changes in the fluid's rheological properties over time under constant amplitude and frequency conditions. This test is particularly useful for evaluating the stability of the fluid's viscoelastic properties during aging or as a function of time under specific shear conditions. This test can provide information about the fluid's thixotropic behavior (time-dependent shear thinning property) and its ability to maintain its properties over time. The time sweep test applies an oscillatory shear stress or strain to the fluid sample at a constant amplitude and frequency. The rheometer will record the fluid's viscoelastic properties, such as storage modulus G' and G'' , at regular time intervals during the test for 60 min.

3.4.5 Rheology Tests

Rheology tests are used to evaluate the flow properties of drilling fluids. These tests are important for assessing the ability of the fluid to carry cuttings to the surface, prevent formation damage, and maintain wellbore stability. The rheological properties of OBDFs were measured at 275 °F and 500 psi differential pressure using a rheometer. The plastic viscosity (PV), yield point (YP), and apparent viscosity (AV) using a Grace viscometer (model M3600) to investigate the effect of novel OC on the drilling fluid rheology compared with the drilling fluid formulated using the pre-existing OC. The Grace viscometer is designed to measure the rheological properties of drilling fluids, specifically their viscosity and gel strength (GS). It is commonly used in the oil and gas industry for quality control and performance evaluation of drilling fluid formulations. The Model M3600 Grace viscometer operates based on the principle of rotational viscometry. The instrument consists of a cylindrical cup containing the drilling fluid sample and a spindle that rotates at a constant speed within the fluid. As the spindle rotates, it experiences

resistance from the fluid, which is measured as torque by the viscometer. The Grace M3600 viscometer offers several features and capabilities including multiple speed settings, temperature control, data display and storage, and a user-friendly interface. The GS was estimated directly from dial reading at 3 RPM after different periods (i.e., 10 s, 10 min, and 30 min). The following formulas were implemented to estimate the PV, YP, and AV:

$$PV = \phi_{600} - \phi_{300} \quad (3)$$

$$YP = \phi_{300} - PV \quad (4)$$

$$AV = \frac{\phi_{600}}{2} \quad (5)$$

3.4.6 Filtration Tests

The HPHT filtration loss test is a crucial laboratory test performed on OBDs to evaluate their fluid loss performance under simulated downhole conditions. Fluid loss control is important to maintain wellbore stability, minimize formation damage, and ensure efficient drilling operations. The HPHT filtration loss test is conducted using a specialized HPHT filter press, which subjects the drilling fluid sample to elevated pressure and temperature conditions. A specialized HPHT filter press is a type of filtration equipment specifically designed to evaluate the filtration properties of drilling fluids under HPHT conditions. It is commonly used in the oil and gas industry to simulate downhole conditions and assess the performance of drilling fluid formulations in preventing fluid loss and maintaining wellbore stability. The HPHT filter press consists of a cylindrical cell or chamber with a filter medium that allows fluid to pass through while retaining solid particles. The drilling fluid is placed in the cell, and pressure is applied to simulate the downhole pressure

experienced during drilling operations. Additionally, the system is heated to replicate the high temperatures encountered in deep wells. The test measures the volume of filtrate that passes through a filter medium under specified temperature and pressure conditions. The filtration test was performed at 275 °F and 500 psi differential pressure using filter paper as the filtration medium. The filtration volume was monitored with respect to time for 30 min, and the filter cake thickness was measured.

3.5 Results and Discussions

3.5.1 Material Characterization

Figure 10 shows the XRD pattern and the plot of identified phases of Claytone-IMG 400. The main components of Claytone-IMG 400 are montmorillonite (71.1%) and clinocllore (28.7%) with a small percentage of quartz (0.2%). Figure 11 shows the XRD pattern and the plot of identified phases of MC-TONE. The main components of MC-TONE consist of feldspar (35.9%), orientite (29.4%), cristobalite (25.1%), and calcite (9.6%). Table 3 shows the chemical compositions of the two OCs used in this study. Claytone-IMG 400 is composed of silicon (47.41%), aluminum (34.86%), magnesium (10.41%), sodium (6.15%), and iron (1.11%), while MC-TONE is composed of silicon (53.67%), aluminum (14.67%), chlorine (11.84%), iron (11.09%), and calcium (7.08%).

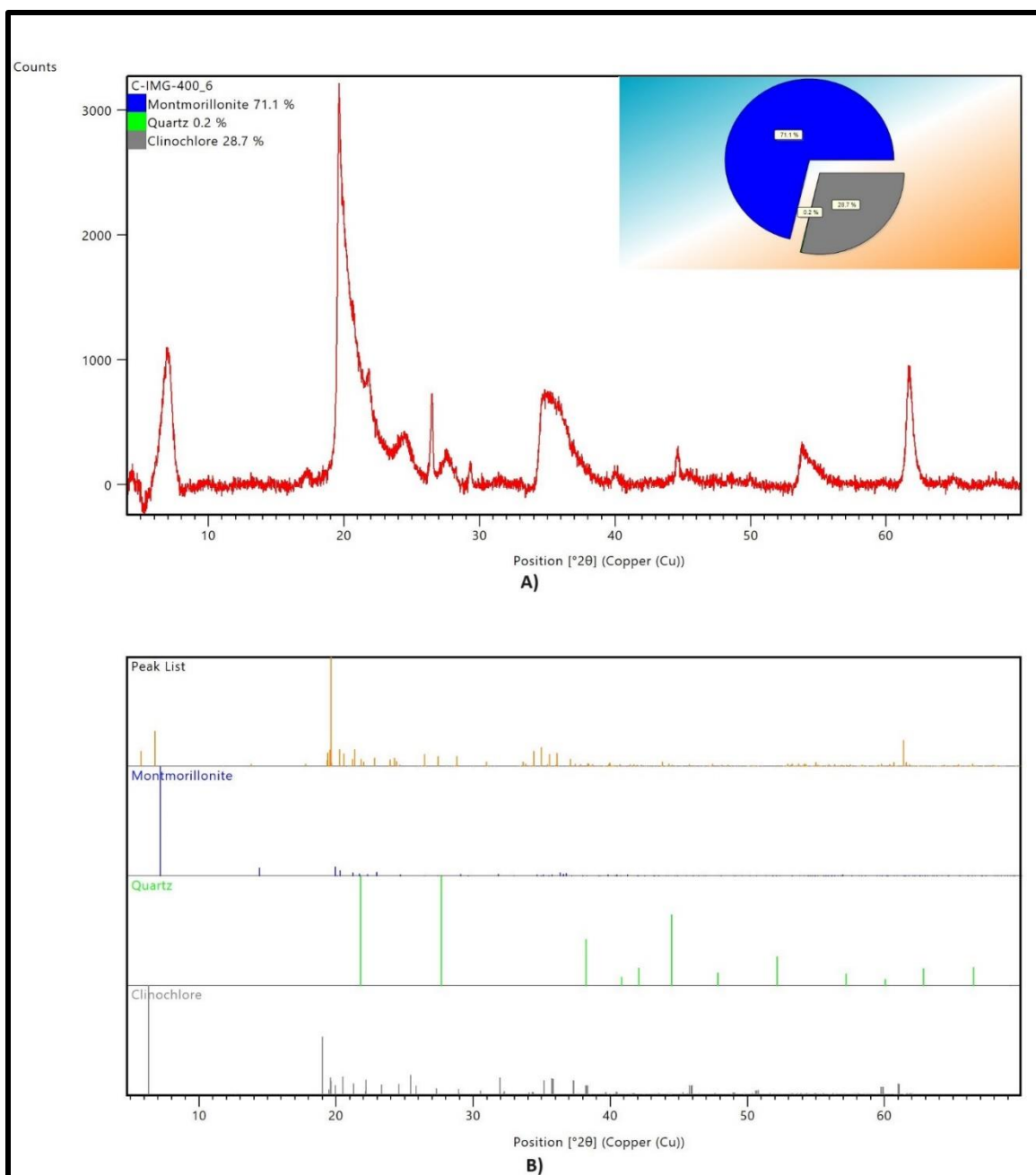


Figure 10 The A) XRD pattern and B) plot of identified phases of Claytone-IMG 400

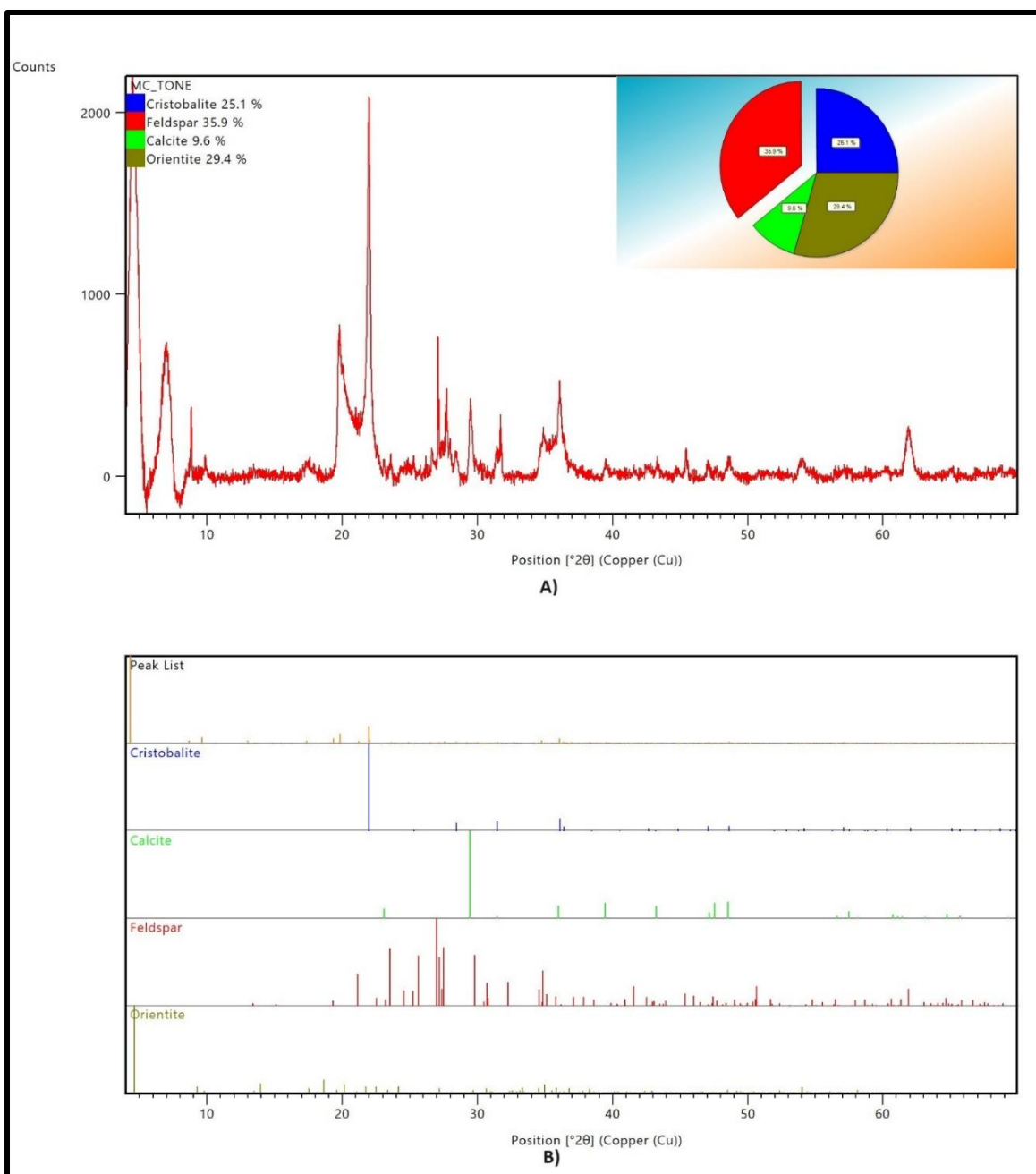


Figure 11 The A) XRD pattern and B) plot of identified phases of MC-TONE

Table 3 XRF analysis for the OCs used in this study

Sample ID/ Chemical composition (%)	Na	Mg	Al	Si	Fe	Cl	K	Ca
Claytone-IMG 400	6.15	10.47	34.86	47.41	1.11	-	-	-
MC-TONE	-	-	14.67	53.67	11.09	11.84	1.65	7.08

The results of the PSD shown in Figure 12 show that the average particle size (D_{50}) of Claytone-IMG 400 is 14.74 μm and that of MC-TONE is 40.01 μm . The fine particle size of Claytone-IMG 400 is desirable in many applications because it can lead to improved dispersion and stability within non-polar liquids like OBDFs. Claytone-IMG 400 has a small average particle size distribution, which contributes to its desirable properties such as high surface area, good dispersion, and high brightness. It is also characterized by its low abrasiveness, low moisture content, and high purity.

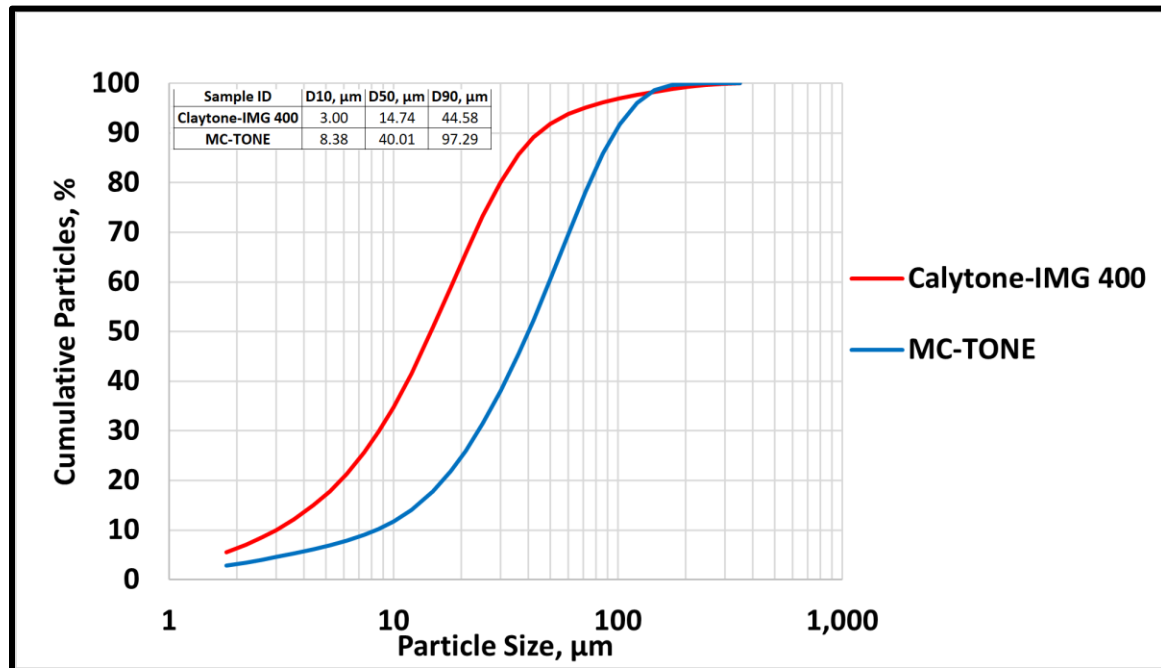


Figure 12 PSD for Claytone-IMG 400 and MC-TONE

The SEM images for both OCs used in this study are shown in Figure 13. In SEM images of Claytone-IMG 400, the quaternary ammonium compounds used in surface modification treatment create distinct morphological features on the surfaces of these particles which helps them disperse better within non-polar fluids. Furthermore, it is common to observe a collection of small, irregularly shaped particles with a relatively smooth surface texture. The particles appear to be loosely packed together, forming a porous structure with many small voids and channels. This porous structure is due to the irregular shape of the particles and the way they pack together. Moreover, the particles appear as individual platelets or stacks that are held together by interactional mechanisms such as ion-dipole interaction, hydrogen bonds, acid-base reactions, charge transfer, electrostatic interaction, and van der Waals forces (de Paiva et al., 2008; Guégan, 2019; Zhuang, Zhang, Jaber, et al., 2017). Also, the uniformity and small size distribution seen in SEM images suggest that Claytone-IMG 400 is well dispersed within non-polar fluids like OBDs. Compared to Claytone-IMG 400, MC-TONE has higher irregularity and sharper particle edges which increases the sagging tendency.

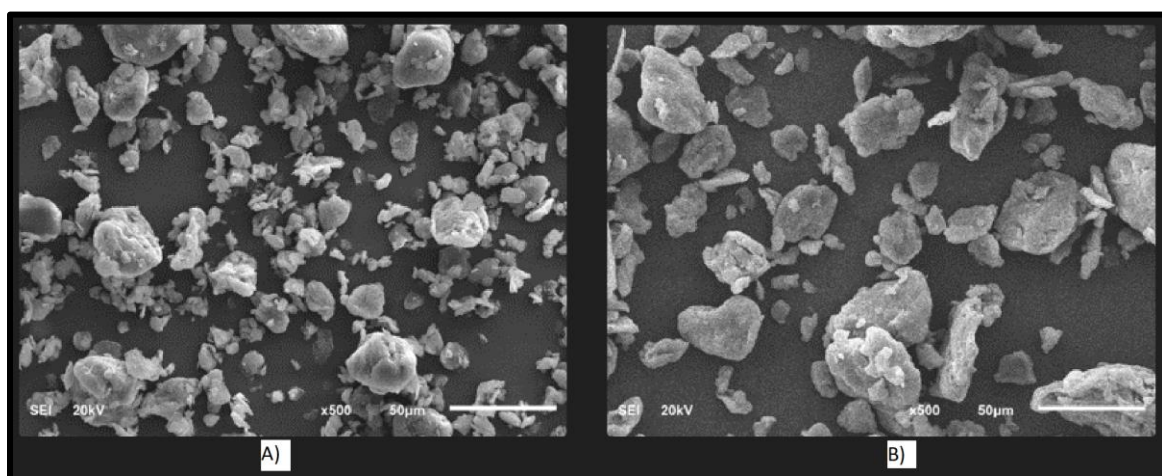


Figure 13 SEM images of A) Claytone-IMG 400 and MC-TONE

3.5.2 Density and Electrical Stability

No change in the density of the drilling fluid was observed when adding Claytone-IMG 400 OC instead of MC-TONE OC as it remains unchanged at 15 ppg. Figure 14 shows that Claytone-IMG 400 enhanced the electrical stability of the invert emulsion with a 9% increment to 942 Volt compared to 863 Volt for the drilling fluid prepared with MC-TONE. This is due to its relatively small particle size and high surface area (Sinha Ray & Bousmina, 2005). The quaternary ammonium compounds used in surface modification treatments make the clay particles more hydrophobic, which can reduce their tendency to flocculate under certain conditions (Ansari et al., 2021; Y. Chen et al., 2022; Meng et al., 2020). Additionally, the small average particle size distribution of Claytone-IMG 400 contributes towards improved electrical stability by reducing sedimentation rates in suspensions when subjected to an electric field. Smaller particles tend to have less settling velocity than larger ones due to their smaller mass thus allowing them to remain suspended for longer periods (Fakoya & Ahmed, 2018; Ofei et al., 2022). Furthermore, Claytone-IMG 400 can reduce the affinity of water droplets for the solid surfaces present in the fluid system. This reduction in water wetting can help to minimize the contact between water and conductive solids, thereby reducing the potential for electrical conductivity and stability issues (Borges et al., 2022; Growcock et al., 1994; Magalhães et al., 2016).

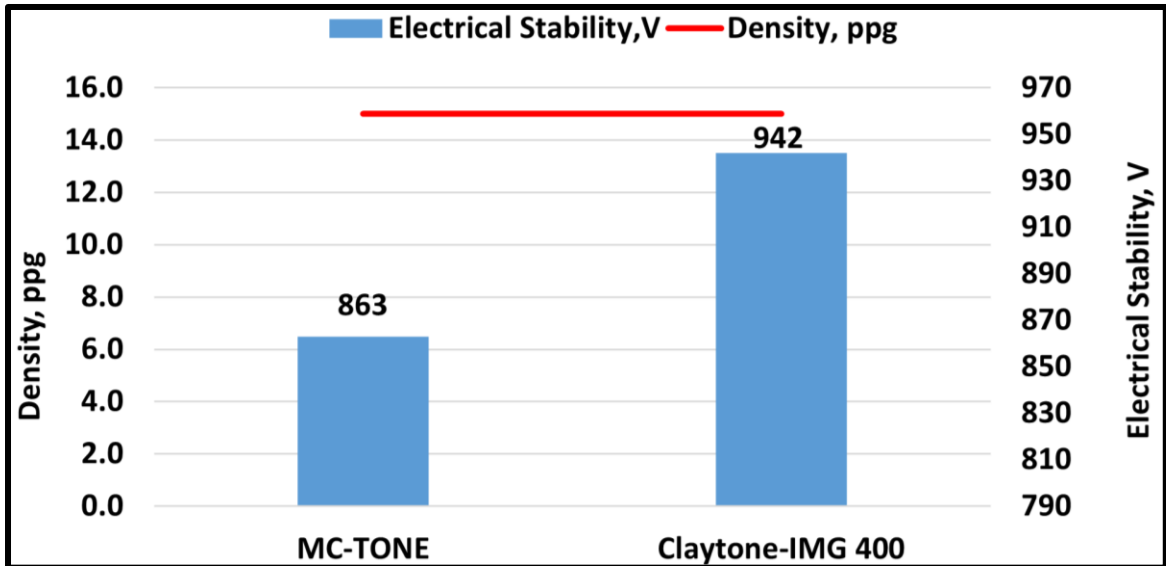


Figure 14 Effect of Claytone-IMG 400 on drilling fluid density and electrical stability

3.5.3 Sagging Tests

The vertical and inclined conditions sag factors for the MC-TONE/oil and Calytone-IMG 400/oil fluids are shown in Figure 15. It is clear that Claytone-IMG 400 increased the vertical sag to 0.529 compared to the drilling fluid formulated using MC-TONE 0.515 but this increase is within the acceptable range. Furthermore, Claytone-IMG 400 decreased the sag factor from 0.531 which is higher than the recommended safe range of 0.50–0.53 to 0.527. The mechanism by which Claytone-IMG 400 helps prevent static sag involves its ability to function as a rheological modifier and its impact on the suspension stability of the fluid system. Claytone-IMG 400 can impart thixotropic behavior to a fluid system, which means that the system's viscosity decreases when subjected to shear and quickly recovers when the shear is removed. Thixotropic behavior can help prevent static sag by allowing the fluid to flow more easily under shear and then rapidly increase in viscosity when at rest, preventing the settling of particles (Maxey, 2007). Furthermore, Claytone-IMG 400 also contributes to the yield stress of a fluid system, which is the minimum stress

required to initiate flow. A higher yield stress means that the fluid system can resist the gravitational force acting on the suspended particles more effectively, helping to prevent static sag and maintain a stable suspension (Maxey, 2007; Saasen, 2002a). Moreover, the interaction between Claytone-IMG 400 particles and the other components in the fluid system can influence the overall suspension stability. OCs can form a network structure within the fluid, which helps to support and stabilize the suspended particles, preventing them from settling or separating (Agarwal et al., 2013). Also, Claytone-IMG 400 can adsorb onto the surfaces of suspended particles, altering their surface properties and improving the overall stability of the suspension. The adsorption of OCs can help to prevent aggregation and settling of particles, which contributes to the prevention of static sag (Ghavami et al., 2018a).

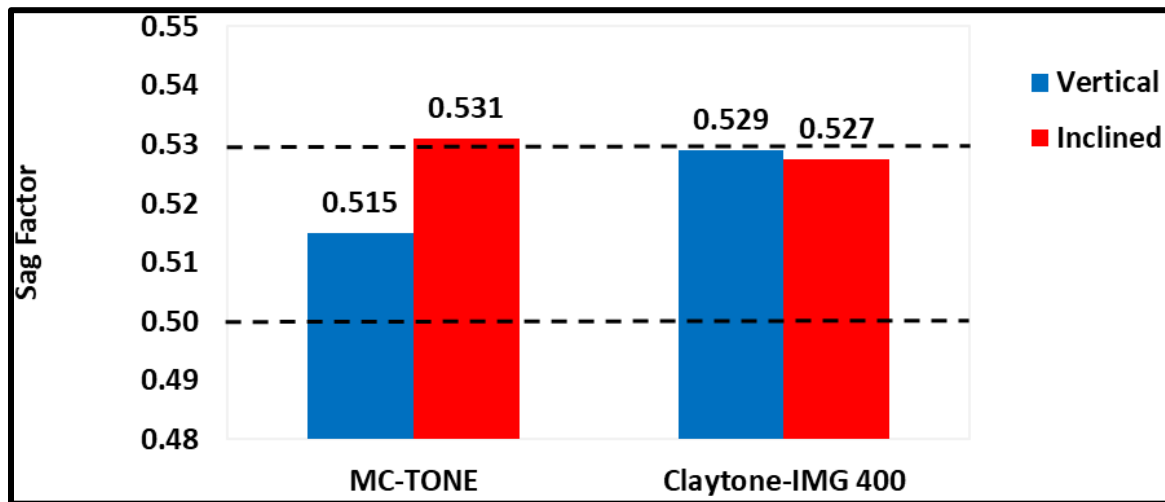


Figure 15 Effect of Claytone-IMG 400 on the static sag factors

The VSST sag factors for both OCs are shown in Figure 16. The results show a reduction in the VSST value from 0.869 ppg to 0.515 ppg. Claytone-IMG 400 can contribute to the yield stress of the fluid system, which is the minimum stress required to initiate flow. A higher yield stress helps the fluid system resist the component of gravitational

force acting during dynamic motion more effectively, preventing dynamic sag and maintaining a stable suspension (Maxey, 2007; Saasen, 2002a). In dynamic applications, Claytone-IMG 400 can form a network structure within the fluid that supports and stabilizes the suspended particles, preventing them from settling downward under gravity during motion which influences the overall suspension stability. Moreover, adsorption can help prevent aggregation and settling of particles in dynamic applications, contributing to the prevention of dynamic sag (Ghavami et al., 2018a). Furthermore, it allows the fluid to flow and level out easily during application and then rapidly increase in viscosity when subjected to dynamic forces, preventing the sagging, or settling of particles due to its positive effect on the thixotropic behavior of the fluid.

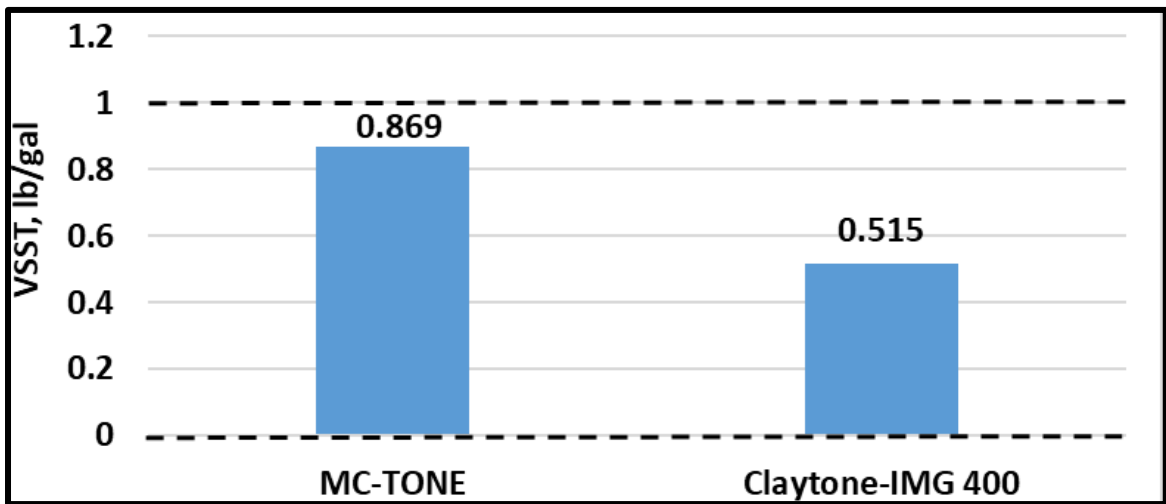


Figure 16 Effect of Claytone-IMG 400 on the dynamic sag factor

3.5.4 Amplitude, Frequency, and Time Sweep Tests

The oscillatory amplitude test showed that Claytone-IMG 400 results in a small increase for both G' and G'' in the LVE region that is limited to 0.1% shear strain compared to the fluid formulated using MC-TONE as shown in Figure 17. This results in better elasticity, sag resistance, and a solid-like behavior. Claytone-IMG 400 can increase the yield stress,

indicating better resistance to deformation and improved stability under applied stress. Claytone-IMG 400 can increase the elastic or solid-like behavior of a formulation, which is reflected in a higher G' value. This can be beneficial in applications where good sag resistance, thixotropic behavior, or suspension properties are desired (Bui et al., 2012; Werner et al., 2017). Furthermore, the presence of Claytone-IMG 400 can also affect the viscous or liquid-like behavior of a formulation, as shown by changes in the G'' value. An increased G'' value can lead to better leveling or flow control in specific applications. Moreover, the addition of Claytone-IMG 400 can enhance the overall viscoelastic properties of a formulation. This can lead to improved performance in terms of flow control, stability, and resistance to deformation. Also, incorporating Claytone-IMG 400 into a formulation can result in increased complex viscosity, indicating a higher resistance to flow under oscillatory shear. This can be beneficial for applications that require shear-thinning behavior or improved sag resistance (Bui et al., 2012; Werner et al., 2017).

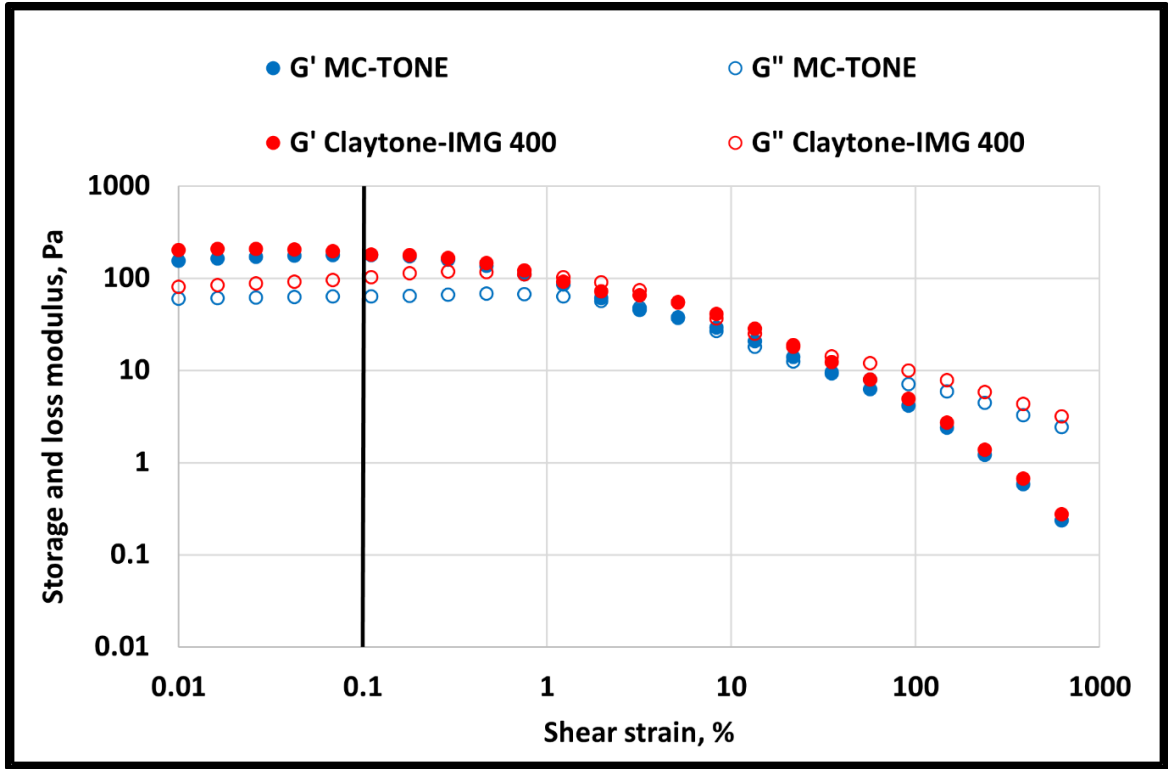


Figure 17 Effect of Claytone-IMG 400 on oscillatory amplitude sweep test

Figure 18 shows the results of the oscillatory frequency sweep tests for the MC-TONE/oil fluid and Claytone-IMG 400/oil fluid. When Claytone-IMG 400 is added to a drilling fluid, it has been shown to enhance both G' and G'' , indicating improved elasticity and viscous behavior. This means that at varying frequencies, the fluid will maintain its desirable flow properties without experiencing sagging or settling. Furthermore, Claytone-IMG 400 improves suspension properties within drilling fluids by preventing solids from settling out and causing issues such as blockages or pump wear. Also, Claytone-IMG 400 increases the material's storage modulus and improves its mechanical strength, which could be beneficial for applications that require high stiffness or resistance to deformation (Ettehad et al., 2022). Moreover, Claytone-IMG 400 also increases the material's viscosity and reduces its flowability, which could be beneficial for applications that require high thixotropy or sag resistance (Werner et al., 2017). The addition of Claytone-IMG 400 can

improve the stability of a formulation by increasing its yield stress and resistance to deformation. In a frequency sweep test, this can be observed as an increase in G' at low frequencies, indicating enhanced elastic or solid-like behavior (Bui et al., 2012).

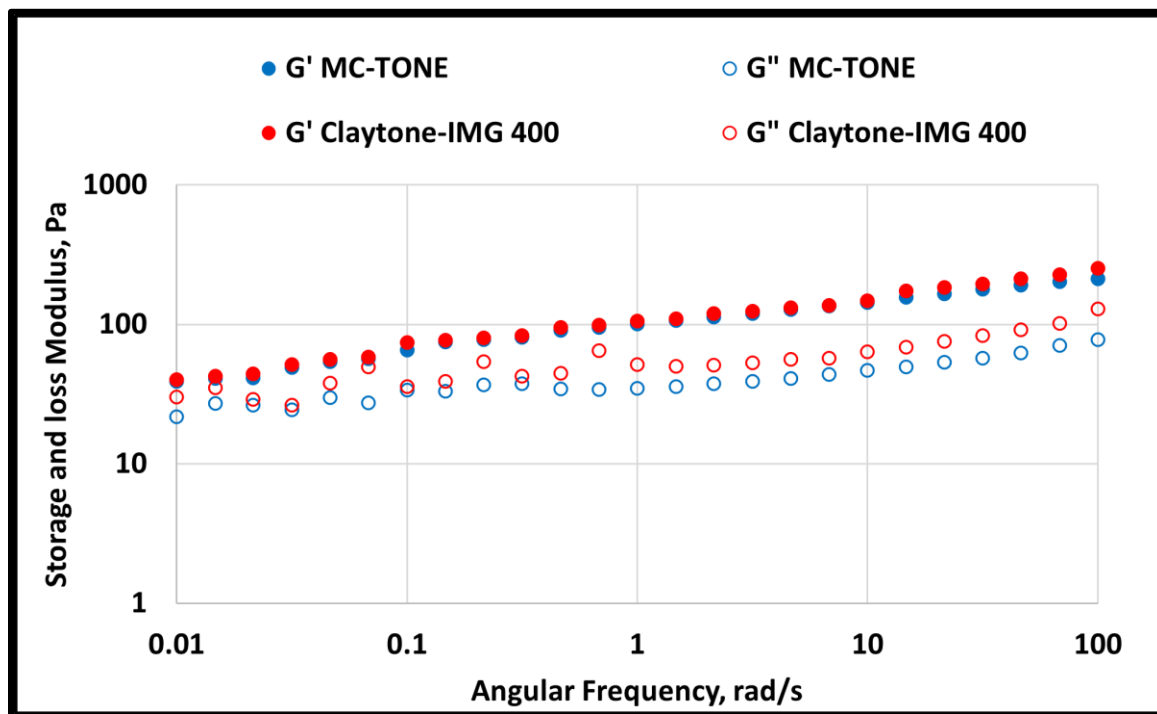


Figure 18 Effect of Claytone-IMG 400 on oscillatory frequency sweep test

The results of the time sweep tests are shown in Figure 19. Claytone-IMG 400 increases the G' of the material, indicating improved solid-like behavior and resistance to deformation. The change in G'' over time may provide insights into the material's viscosity and liquid-like behavior. Furthermore, the addition of Claytone-IMG 400 also affects the G'' of the material. Moreover, Claytone-IMG 400 enhances the thixotropic behavior of a formulation, allowing it to thin under shear stress and recover its initial viscosity once the stress is removed (Bui et al., 2012). This property can be observed through the recovery of G' and G'' after a change in applied stress, demonstrating the material's ability to regain its structure over time (Ofei et al., 2019).

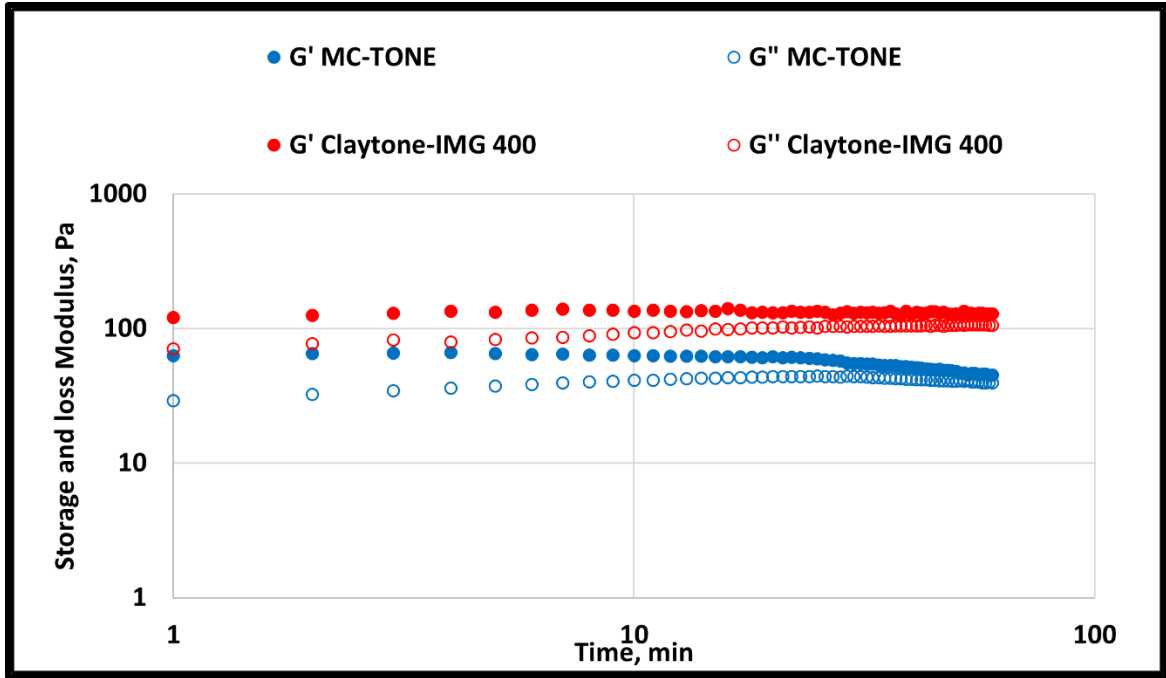


Figure 19 Effect of Claytone-IMG 400 on time sweep test

3.5.5 Rheology Tests

The effect of Claytone-IMG 400 on the drilling fluid rheology was examined and compared with the drilling fluid formulated using MC-TONE. Figure 20 confirms that Claytone-IMG 400 produces higher shear stress and viscosity in the low shear range. This results in better suspension performance, gelling, and sag. The Bingham plastic model is used to describe the rheological behavior of the two drilling fluid samples with R^2 values of 0.9773 (Claytone-IMG 400) and 0.9803 (MC-TONE). Several studies have provided support for the applicability of the Bingham plastic model in characterizing the flow properties of OBDFs (Fakoya & Ahmed, 2018; Nooripoor & Hashemi, 2020; Razali et al., 2018; Werner et al., 2017). (Werner et al., 2017) demonstrated the effectiveness of the Bingham plastic model in capturing the viscoelastic properties and flow behavior of OBDFs, particularly under HPHT conditions. In addition, (Fakoya & Ahmed, 2018) highlighted the suitability of the Bingham plastic model for predicting the apparent viscosity of OBDFs, further

emphasizing its relevance in understanding the rheological characteristics of OBDFs. These findings collectively underscore the validity and applicability of the Bingham plastic model in characterizing the flow properties and rheological behavior of OBDFs, thereby establishing its significance in the analysis and optimization of drilling fluid performance. The effect of Claytone-IMG 400 on the drilling fluid rheology is shown in Figure 21 at 275°F. The plastic viscosity (PV) was increased by a 30% increment from 22.45 cP for the drilling fluid formulated using MC-TONE to 29.14 cP with Claytone-IMG 400 OC. Claytone-IMG 400 can increase the plastic viscosity of drilling fluid by forming a network structure within the fluid. This network helps to improve the fluid's flow resistance, which can be beneficial for suspending and transporting drill cuttings and maintaining proper hole cleaning. Drilling fluids are typically non-Newtonian and exhibit shear-thinning behavior, meaning their viscosity decreases with increasing shear rate (Werner et al., 2017). Claytone-IMG 400 can enhance this shear-thinning behavior, providing a higher plastic viscosity at low shear rates and a lower plastic viscosity at high shear rates. This property can be advantageous for drilling operations, as it allows for better suspension of cuttings and reduced frictional pressure losses in the circulation system. The addition of Claytone-IMG 400 can also improve the thixotropic behavior of drilling fluid, allowing it to thin under shear stress and recover its initial viscosity once the stress is removed. This property can help maintain the fluid's stability and carrying capacity during drilling operations while ensuring that it flows easily through the system when necessary. Furthermore, the yield point increased by a 38% increment from 25.06 lb/100ft² to 34.67 lb/100ft² due to the high dispersion of Claytone-IMG 400. This increase in yield point improves the fluid's ability to suspend and transport drill cuttings, which is essential for maintaining proper hole

cleaning and preventing sag or settlement of cuttings during drilling operations. Furthermore, a higher yield point can help maintain borehole stability by providing better support to the borehole walls. The addition of Claytone-IMG 400 can improve the drilling fluid's capacity to resist deformation and flow under low-stress conditions, preventing the walls of the borehole from collapsing or sloughing during drilling operations (J. Yang et al., 2022). Also, the yield point plays a role in the formation of an effective filter cake on the borehole walls. A drilling fluid with a higher yield point can create a more stable and uniform filter cake that helps minimize fluid loss and stabilize the borehole. Moreover, Claytone-IMG 400 can enhance the thixotropic behavior of drilling fluid, allowing it to thin under shear stress and quickly recover its initial viscosity once the stress is removed. This property can contribute to the fluid's ability to maintain its yield point and carrying capacity during drilling operations, while also ensuring that it flows easily through the system when necessary (Vryzas & Kelessidis, 2017). The apparent viscosity (AV) increased by a 33% increment from 34.98 lb/100ft² to 46.47 lb/100ft². The YP/PV ratio increased with a 6% increment from 1.12 to 1.19. A higher YP/PV ratio indicates better suspension and carrying capacity for drill cuttings, which is crucial for maintaining hole cleaning and preventing sag or settling of cuttings during drilling operations (Caenn et al., 2011; Caenn & Chillingar, 1996). Figure 22 shows that the high viscosity at a low shear rate of Claytone-IMG 400 enhanced the suspension ability and gelling strengths (GS). The gelling strengths at 10 s, 10 min, and 30 min were increased from 10.76, 10.56, and 11.15 lb/100ft² for the drilling fluid formulated using MC-TONE to 16.24, 16.04, and 16.63 lb/100ft² respectively when using Claytone-IMG 400. A high gelling strength increases the

fluid's resistance to flow, particularly when static or under low shear rates, helping to suspend and transport drill cuttings and maintain borehole stability.

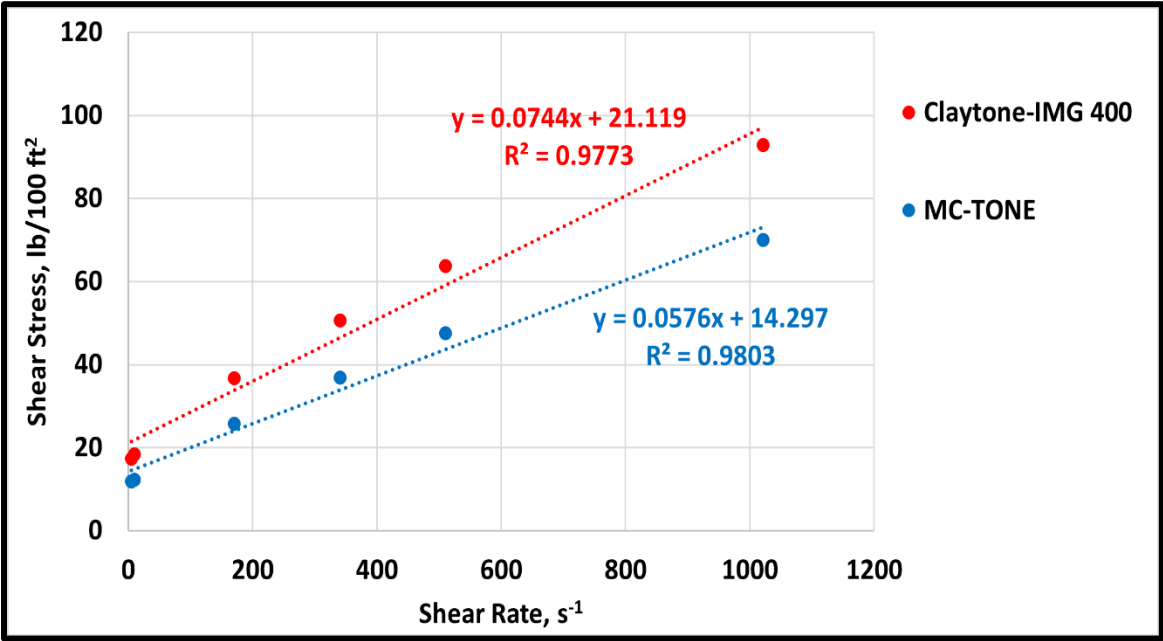


Figure 20 Effect of Claytone-IMG 400 on the stress-strain relationship at 275°F

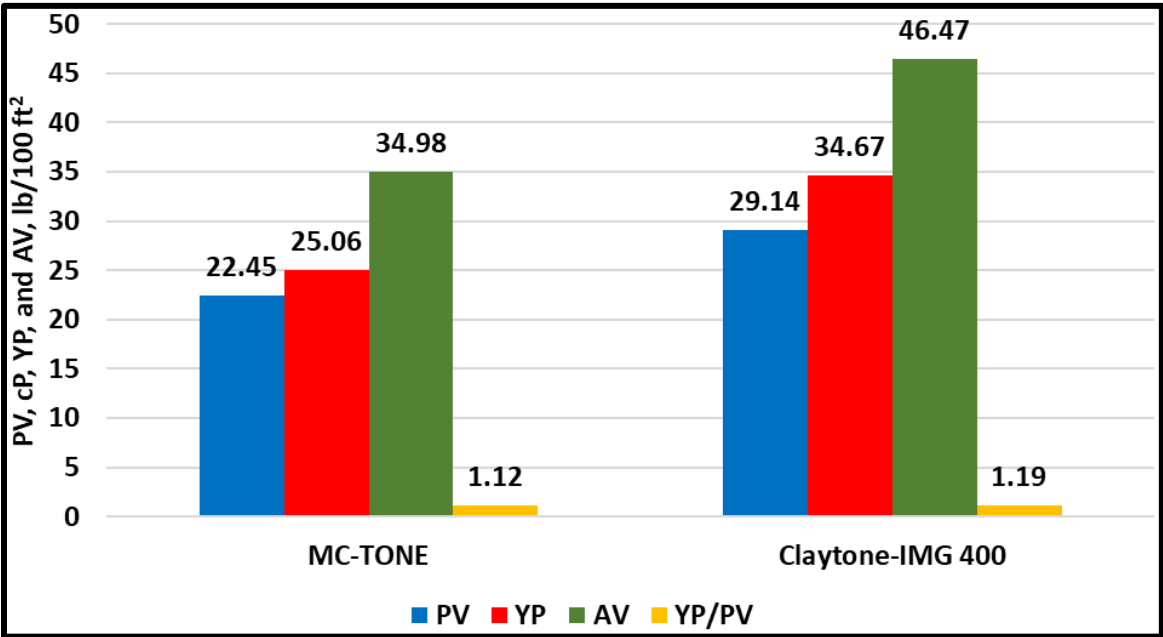


Figure 21 Effect of Claytone-IMG 400 on drilling fluid rheology at 275 °F

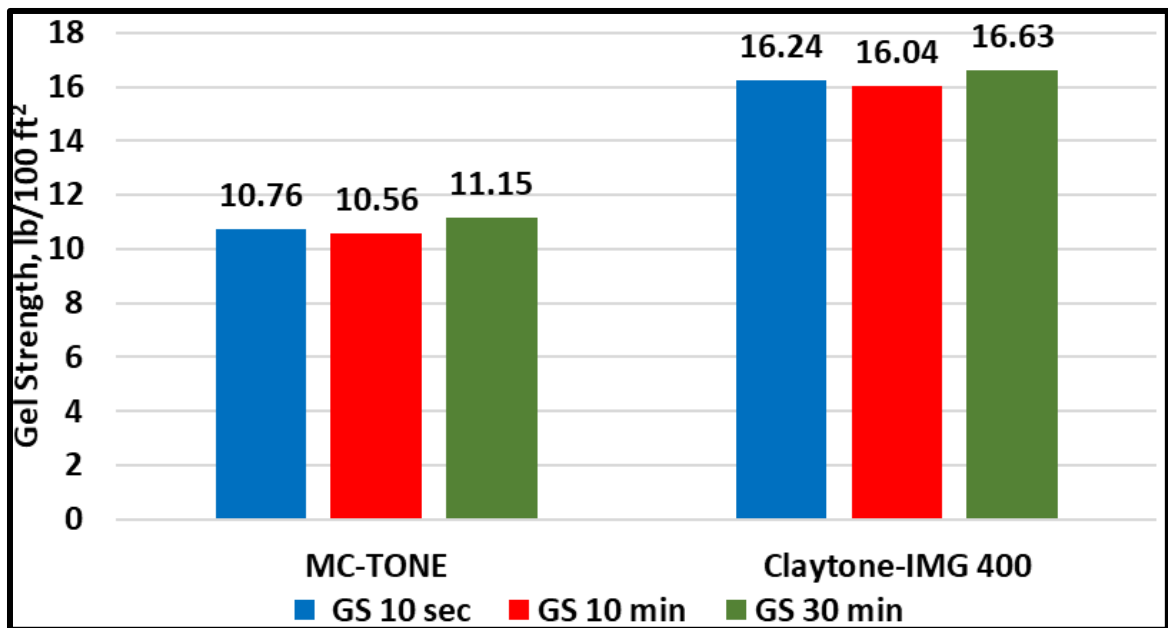


Figure 22 Effect of Claytone-IMG 400 on gel strength at 275 °F

3.5.6 Filtration Tests

The filtration test results showed that Claytone-IMG 400 enhanced the filtration properties. Figure 23 shows a 10% reduction in the filtration volume from 5 to 4.5 cm³, while Figure 24 shows a significant decrease of 37.5% from 2.60 to 1.89 mm in the filter cake thickness. The addition of Claytone-IMG 400 reduced the fluid loss of drilling fluid by increasing its AV and GS. These rheological properties can help create a more effective filter cake, which can better prevent the loss of fluid to the formation during drilling operations. Reduced fluid loss is crucial for maintaining wellbore stability and minimizing formation damage. Also, Claytone-IMG 400 improved the formation of a stable and uniform filter cake on the borehole walls. This enhancement is due to the ability to form a network structure within the fluid, which can help minimize fluid loss and stabilize the borehole. A well-formed filter cake is essential to maintain drilling efficiency and prevent

excessive fluid invasion into the formation, which can cause formation damage or reduced productivity.

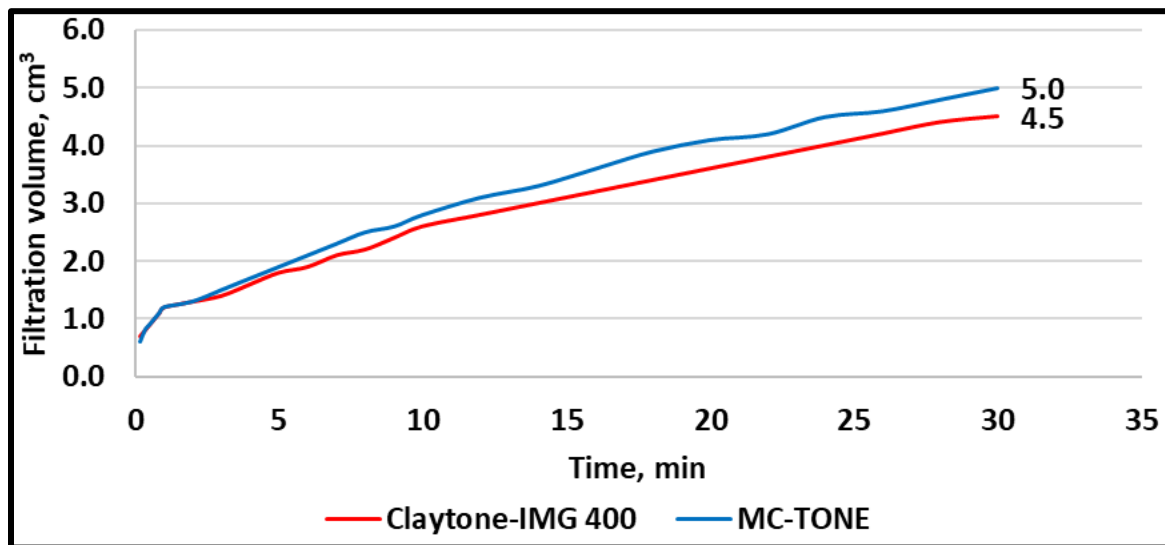


Figure 23 Effect of Claytone-IMG 400 on the filtration volume at 275 °F

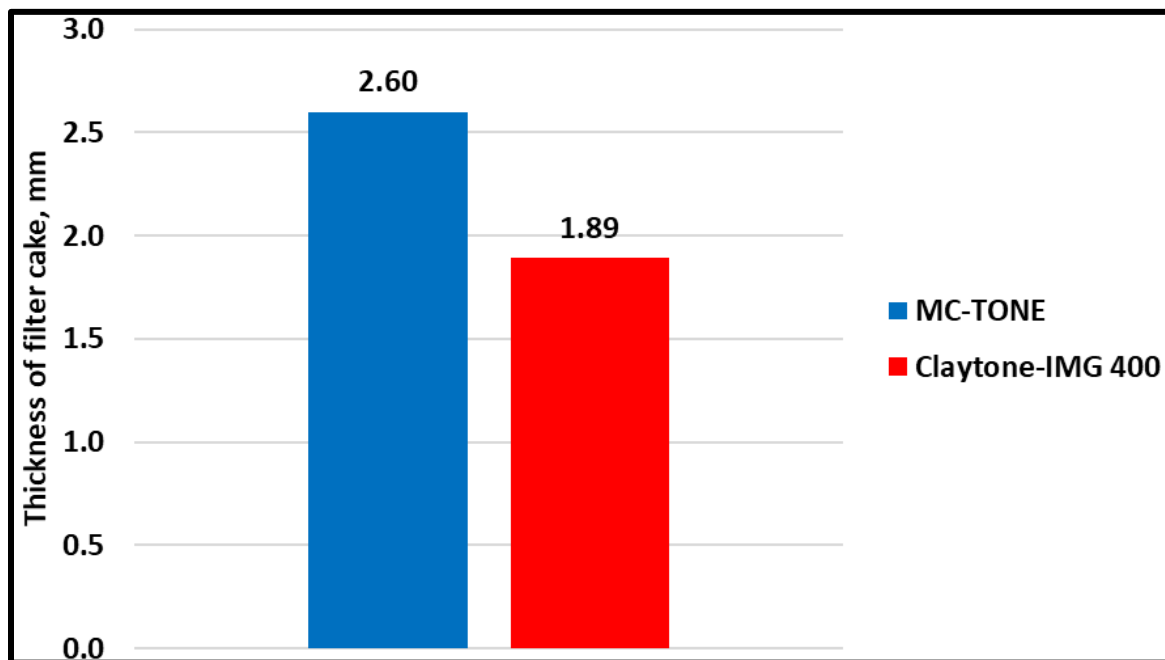


Figure 24 Effect of Claytone-IMG 400 on the filter cake thickness at 275 °F

3.6 Conclusions

A comprehensive experimental study was conducted to evaluate the influence of Claytone-IMG 400 on enhancing the properties of OBDs at HPHT conditions. A comparative analysis was conducted with MC-TONE, a pre-existing OC, to assess the improvements achieved by Claytone-IMG 400. The outcomes of this study are listed below:

1. Claytone-IMG 400 does not affect the drilling fluid density, while it enhances the electrical stability of the invert emulsion with a 9% increment compared to the reference drilling fluid formulated using MC-TONE. This is due to its relatively small particle size and high surface area.
2. Claytone-IMG 400 reduces the static and dynamic sag by imparting thixotropic behavior, contributing to the yield stress, promoting stable particle interactions, and adsorbing onto suspended particle surfaces.
3. The rheological properties were enhanced with Claytone-IMG 400 as it significantly improved the suspension and gelling capabilities of the drilling fluid. Also, key characteristics, such as PV, YP, and AV were improved by 30%, 38%, and 33% increments respectively.
4. The YP/PV ratio increased with a 6% increment from 1.12 to 1.19. This indicates better suspension and carrying capacity for drill cuttings, which is crucial for maintaining hole cleaning and preventing sag or settling of cuttings during drilling operations.

5. The gel strength and viscoelastic properties increased with Claytone-IMG 400 which indicated better suspension and hole cleaning performance. Claytone-IMG 400 results in increased complex viscosity, indicating a higher resistance to flow under oscillatory shear.
6. The filtration volume was reduced by 10% to 4.5 cm³, and the filter cake thickness had a 37.5% reduction from 2.60 mm to 1.89 mm.

CHAPTER 4

EVALUATING THE EFFECT OF CLAYTONE-EM ON THE PERFORMANCE OF OIL-BASED DRILLING FLUIDS

This paper was published in ACS Omega:

Mahmoud, A., Gajbhiye, R., & Elkatatny, S. (2024). Evaluating the Effect of Claytone-EM on the Performance of Oil-Based Drilling Fluids. *ACS omega*, 9(11), 12866-12880.

4.1 Abstract

The study provides a detailed characterization and evaluation of Claytone-EM as a rheological additive to enhance the performance of oil-based drilling fluids (OBDFs) under high-pressure high-temperature (HPHT) conditions. It also offers a comparative evaluation of the effectiveness of Claytone-EM with an existing organoclay (OC), analyzing their mineral and chemical compositions, morphologies, and particle sizes. A series of experiments are performed to evaluate Claytone-EM's influence on crucial drilling mud properties, such as mud density, electrical stability, sagging tendency, rheology, viscoelastic properties, and filtration properties, to formulate a stable and high-performing OBDF.

Results indicated that Claytone-EM had no significant impact on mud density but remarkably enhanced emulsion stability. Claytone-EM effectively mitigated sagging issues under both static and dynamic conditions, leading to improvements in plastic viscosity (PV), yield point (YP), apparent viscosity (AV), and the YP/PV ratio. The PV, YP, AV, and YP/PV ratio were improved by 11%, 85%, 28%, and 66% increments respectively compared with the drilling fluid formulated with MC-TONE. The addition of Claytone-EM resulted in heightened gel strength (GS) and improved filtration properties of the drilling fluid. The filtration volume was reduced by 2% from 5.0 cm³ to 4.9 cm³, and the filter cake thickness had a 13% reduction from 2.60 mm to 2.26 mm.

These findings highlight Claytone-EM as a valuable additive for enhancing OBDP performance, particularly in challenging HPHT conditions. Its ability to provide emulsion stability, reduce static and dynamic sag, and filtration control holds the potential to enhance drilling operations, minimize downtime, and bolster wellbore stability. The study acknowledges certain limitations, including the study's temperature range, which could benefit from exploration at extreme temperatures. Additionally, the absence of flow experiments limits a comprehensive understanding of sag effects, and further research and field-scale evaluations are recommended to validate and optimize the application of Claytone-EM in OBDPs.

4.2 Introduction

Drilling fluids, also known as drilling muds, are critical components in drilling operations for oil and gas extraction. These fluids perform various functions that involve cooling and lubricating the drill bit, carrying the cuttings to the surface, controlling formation pressures,

and maintaining wellbore stability (Caenn et al., 2011; Caenn & Chillingar, 1996; Khodja et al., 2010; Mahmoud et al., 2023; Werner et al., 2017; Zamora-Ledezma et al., 2022). Drilling fluids can be classified into three main types: water-based, oil-based, and synthetic-based, each with unique properties and applications (Amani et al., 2012b; Karakosta et al., 2021; Tahr, Ali, et al., 2023).

Oil-based drilling fluids (OBDFs) present various advantages in certain drilling applications when compared to water-based drilling fluids (WBDFs). OBDFs exhibit superior thermal stability in comparison to WBDFs, making them suitable for high-temperature drilling operations (Jiang, Shi, et al., 2022). This stability ensures that OBDFs can sustain their rheological and filtration properties even under extreme temperature conditions, thereby ensuring efficient drilling and wellbore stability (Zhuang, Zhang, et al., 2019; Zhuang, Zhang, Peng, et al., 2018b). Moreover, OBDFs offer enhanced lubrication to the drill string, drill bit, and other downhole components compared to WBDFs (J. R. Zhang et al., 2020). This enhanced lubrication reduces friction, thereby resulting in reduced rates of equipment wear, decreased torque and drag, and ultimately, extended equipment lifespan and lowered costs (Fakoya & Ahmed, 2018). Additionally, OBDFs display lower reactivity with shale formations due to their reduced water content and wettability properties (Mahmoud et al., 2021). This reduced reactivity aids in the prevention of shale swelling, dispersion, or sloughing, which can give rise to wellbore instability and other drilling-related problems (M. Ali et al., 2020b).

The efficiency, safety, and success of drilling operations are heavily influenced by the properties of the drilling fluid (Jiang, Sun, et al., 2022). These properties can be broadly classified into rheological properties, physical properties, and chemical properties

(Karakosta et al., 2021; J. R. Zhang et al., 2020). Regular testing and analysis of these properties, along with appropriate adjustments to the composition or treatment of the fluid, are vital aspects of drilling fluid management. The selection and utilization of drilling fluid additives are determined by various factors such as the type of formation being drilled, the drilling depth, and environmental regulations (J. A. Ali, Ahmed, et al., 2022). These additives are viscosifiers, fluid loss control agents, weighting agents, thinners, and lost circulation materials (LCM) (Herzhaft et al., 2003). By properly selecting and using additives, it is possible to optimize drilling fluid performance and minimize the risk of formation damage and other problems during drilling operations (Aftab et al., 2017; Akpan et al., 2020).

OCs are used as additives to control the rheological properties and enhance the performance of drilling fluids, particularly in OBDFs and synthetic-based drilling fluids (SBDFs), due to their ability to adsorb and stabilize oil droplets and other non-polar substances within the fluid (Bergane & Hammadi, 2020; de Brito Buriti et al., 2022; Ghavami et al., 2018b; Msadok et al., 2020).

Clay minerals have favorable rheological properties and are used to increase the viscosity and stability of aqueous dispersions by forming a gel-like structure at low solid contents (Luckham & Rossi, 1999). In recent years, the use of organoclays (OCs), which result from the reaction of smectite clay and amine cation groups (Jordan, 1949, 1961), has received interest due to their notable physicochemical properties in oil media (Burgentzlé et al., 2004; Hato et al., 2011; Moraru, 2001). OCs are formed naturally by modifying clay materials with organic ammonium salts such as alkyl ammonium cations and are widely used in industrial applications as rheology modifiers, such as grease, and cosmetics, as well

as in the preparation of OBDFs (de Paiva et al., 2008). Since OCs have been synthesized from naturally abundant clay minerals, they are relatively low cost viscosifiers to manufacture. The modification process involves replacing the cationic particles on the surface of the clay with an organic compound, typically quaternary ammonium compounds (de Paiva et al., 2008; Ogawa & Kuroda, 1997a). The properties of the OC suspensions depend on the interactions between the organophilic ions and the solvent, the type of the exchanged ion, and the chemical characteristics of the solvent (Bergaya & Lagaly, 2013; King et al., 2007; Moraru, 2001). As a result, OCs possess unique properties that make them highly suitable for utilization in OBDFs (Jordan, 1961). One of the major advantages of OCs is their ability to increase viscosity and suspension properties while maintaining low shear rates, thereby preventing cuttings from settling within the wellbore and improving hole stability. Additionally, OCs offer benefits such as improved filtration control and rheological stability, which enhance overall efficiency during the drilling operation (Patel & Santra, 2020; Weng et al., 2018; Zhuang, Zhang, Yang, et al., 2018). OCs are used as additives to control the rheological properties and enhance the performance of drilling fluids, particularly in OBDFs and synthetic-based drilling fluids (SBDFs), due to their ability to adsorb and stabilize oil droplets and other non-polar substances within the fluid (Akkal et al., 2013; Hermoso et al., 2015, 2017; Hermoso, Martinez-Boza, et al., 2014; Msadok et al., 2020; Weng et al., 2018). The search for new OCs with favorable properties for use in OBDFs is an area of active research. Table 4 provides a comparative overview of the focus and findings of the current study with other relevant research in the application of OCs in OBDFs.

Table 4 Summary of recent studies on the application of OCs in OBDFs

Objective	Organoclay Type	Findings	Reference
Studied the influence of the viscosity modifier and concentration on the rheological properties of OBDFs.	B34 and B128	The nature and concentration of the OC strongly influenced the viscous flow behavior of OBDFs.	(Hermoso, Martinez-Boza, et al., 2014)
Studied the effect of OC concentration (1 and 3 wt. %) and aqueous phase volume fraction on the rheology of organo-montmorillonite (OMMT) in invert-emulsion OBDFs.	Bentone 128	1. At low concentrations of OC, the yield stress varied linearly; on the other hand, at high OC concentrations, the yield stress varied according to a power law model. 2. Increasing the OC concentration led to an increase in viscosity.	(Hermoso et al., 2015)
Studied the rheological properties and thermal stabilities of OBDFs using organopalygorskite (OPAL) modified with cationic and nonionic surfactants	Praepagen WB (cationic surfactant), Ultramina T50, and Ultramina TA20 (nonionic surfactants)	OPAL can be used as an additive to OBDFs due to its enhanced thermal stability and better rheological properties when compared with dispersions prepared with olefin at a high temperature (150°C).	(de Brito Buriti et al., 2022)
Investigated the effects of three different OCs, namely organo-sepiolite (OSEP), organo-hectorite (OHEC), and OMMT on the rheological properties of OBDFs at high temperatures.	Diocetadecyldimethylammonium (DODMAC)	The study found that the OHEC particle-stabilized invert emulsion fluid provides better rheological properties than the other two OCs at high temperatures.	(Geng et al., 2019)
Investigated the effect of using modified Tunisian clay with different	OC modified with a cationic surfactant.	1. The rheological properties of the suspensions were influenced by the concentration of the surfactant used. As the	(Msadok et al., 2020)

cationic surfactant concentrations on the rheological properties of OBDFs.		surfactant concentration increased, the yield stress and consistency concentration increased. The best behavior was observed for the 3.0 CEC concentration. 2. The OC sample at 10 wt.% showed the highest Herschel-Bulkley parameters, indicating that it could be used as a viscosity enhancer in OBDFs.	
Studied the rheological behavior and microstructure OBDFs using organo-bentonite (OBEN), specifically focusing on the effect of the surfactant type, amount of OBEN, temperature, and pressure.	Hexadecyltrimethylammonium (HDTMA-MMT) and PM199.	OBENs with a paraffin-type surfactant arrangement, like PM199, showed potential as control additives for OBDFs under high temperatures and pressure due to their ease of particle dispersion.	(Ghavami et al., 2018b)
Studied the impact of VG69 OC on the rheological properties of gasoil-based drilling fluids, specifically focusing on the yield stress, viscosity, viscoelasticity, thixotropic properties, and stability of the drilling fluids.	VG69	1. The addition of V69 OC increased yield stress, viscosity at infinite shear rate, and viscoelastic and thixotropic properties of the gasoil-based drilling fluids. 2. The addition of 3g of V69 OC increases yield stress by 230%, viscosity at infinite shear rate by 3.4%, and improves mud stability by 70%.	(Bergane & Hammadi, 2020)
Evaluated the effect of Claytone-EM on the performance of OBDFs and compared it with a pre-existing OC.	Claytone-EM	Claytone-EM enhances emulsion stability, prevents sagging, and improves the rheological and filtration properties of OBDFs under HPHT conditions.	This study

Claytone-EM is a high-efficiency rheological additive suitable for use in ODBFs and SBDFs to increase the carrying capacity and hole cleaning capabilities. It is a chemically modified smectite clay, derived from bentonite, that has been treated with a quaternary ammonium compound through ion exchange. The specific gravity of Claytone-EM is 1.6 g/cm³, and it has a bulk density of 23 lb/ft³. This modification enhances the clay's affinity for nonpolar organic compounds and improves its rheological properties. Claytone-EM is an organophilic phyllosilicate. Phyllosilicates, commonly known as sheet silicates, are a group of minerals that are characterized by their sheet-like structure, consisting of tetrahedral and octahedral layers (Jaber & Miehé-Brendlé, 2008). Organophilic phyllosilicates are a subset of these minerals that have been modified to have an affinity for organic molecules. This modification is typically achieved through an ion exchange process where inorganic cations (such as Na⁺, K⁺, or Ca²⁺) in the mineral structure are replaced with organic cations (such as quaternary ammonium ions) (Brigatti et al., 2013; Murray, 1991). The resulting organophilic phyllosilicates exhibit a range of chemical and physical properties including hydrophobicity, swelling capacity, thermal stability, thixotropy, and high surface area (Mahmoud et al., 2023; Zhuang, Zhang, et al., 2019). In the oil and gas industry, organophilic phyllosilicates are used as additives in drilling muds. Their ability to swell in organic liquids helps to seal the walls of boreholes, control the viscosity of drilling fluids, and facilitate the removal of drill cuttings from the well (Mahmoud et al., 2023; Zhuang, Zhang, et al., 2019).

From an environmental perspective, Claytone-EM offers benefits such as improved filtration control and rheological stability, which enhance overall efficiency during drilling operations. It contributes to the reduction of fluid loss, aiding in the prevention of potential

damage to the formation and ensuring the stability of the wellbore. Additionally, Claytone-EM is effective in stabilizing reactive clays and shales, which can mitigate wellbore instability issues, such as fluid loss and differential sticking. These properties align with environmentally friendly practices by minimizing the impact on the surrounding geological formations and ecosystems.

The cost-effectiveness of Claytone-EM as an additive for OBDs is evident from its ability to positively influence critical drilling mud properties such as emulsion stability, sagging prevention, rheology, gel strength, and filtration properties. The application of Claytone-EM has demonstrated notable enhancements in these characteristics. These improvements contribute to more efficient drilling operations, reduced downtime, and enhanced wellbore stability. Furthermore, the use of Claytone-EM as a rheological additive has the potential to minimize the need for additional treatments or additives, leading to cost savings in drilling operations.

The objectives of this study are to evaluate the impact of Claytone-EM on the rheological and filtration properties of OBDs under HPHT conditions. The study aims to compare the performance of Claytone-EM with an existing OC (MC-TONE) and assess its potential to enhance the suspension, gelling, and filtration capabilities of OBDs. Mud properties including mud density, electrical stability, sagging tendency, rheology, viscoelasticity, and filtration were analyzed to develop a stable and high-performing formulation. Results show that the introduction of Claytone-EM enhances emulsion stability, prevents sagging in static and dynamic conditions, and improves plastic viscosity (PV), yield point (YP), apparent viscosity (AV), YP/PV ratio, gel strength (GS), and filtration properties. Additionally, the study seeks to analyze the mineral and chemical compositions,

morphologies, and particle sizes of the OCs to understand their impact on the drilling fluid rheology and filtration performance. The ultimate goal is to optimize the performance of OBDFs and contribute to the efficiency, stability, and cost-effectiveness of drilling operations.

The study provides a detailed characterization and evaluation of Claytone-EM as a rheological additive to enhance the performance of OBDFs under HPHT conditions. It also offers a comparative evaluation of the effectiveness of Claytone-EM with an existing OC, analyzing their mineral and chemical compositions, morphologies, and particle sizes. The impact of the introduction of Claytone-EM on various mud characteristics, including emulsion stability, sagging tendency, rheology, viscoelastic properties, and filtration properties, is evaluated through a series of experiments.

By effectively preventing sagging issues and improving the rheological properties of OBDFs, Claytone-EM can contribute to safer drilling operations with reduced risks of wellbore instability and drilling-related problems. Moreover, the enhanced performance of Claytone-EM in terms of stability, suspension, and flow properties can lead to more efficient drilling operations, reducing downtime and improving overall productivity.

The study presents clear and quantifiable results, demonstrating the impact of Claytone-EM on mud density, emulsion stability, sagging issues, rheological properties, gel strength, and filtration properties. Furthermore, the use of Claytone-EM as a rheological additive can potentially reduce the need for additional additives or treatments, resulting in cost savings for drilling operations.

4.3 Materials and Experiments

4.3.1 Materials

Two invert emulsion samples were prepared using a practical field formulation at ambient conditions using a Hamilton beach mixer. Table 5 highlights the mud formulation describing the sequence, amounts, mixing duration, and functional role of each component. The mixing was done at ambient conditions and the rotational speed was 10000 revolutions per minute (rpm). The primary emulsifier (MC-PE) is the main emulsifying agent responsible for forming and stabilizing the oil-water emulsion. It can effectively disperse and solubilize both polar and nonpolar components. The secondary emulsifier (MC-SE), also known as a co-emulsifier or a wetting agent, is used in conjunction with the primary emulsifier to enhance the stability and performance of the emulsion. It assists in reducing interfacial tension between the oil and water phases, improving emulsion stability, and preventing phase separation. The secondary emulsifier is chosen based on its compatibility with the primary emulsifier and its ability to synergistically enhance the emulsification process. In these mud samples, the continuous phase was the diesel, and the internal phase was the water. Also, other functional additives were mixed to control the viscosity, alkalinity, fluid losses, shale swelling, and filter cake formulation. The additives used to prepare these mud recipes were obtained from a drilling fluid service provider, while the diesel was obtained from a local gas station.

Table 5 Mud formulation used in this study

Additive	Quantity (ppb)	Mixing time (mins)	Function
Diesel	154.46	-	Continuous phase

Primary emulsifier (carboxylic acid-terminated fatty polyamide)	8	10	Emulsion stabilization
Secondary emulsifier (carboxylic acid-terminated fatty polyamide)	6	5	Enhance emulsion stability
Lime	6	5	Alkalinity control
CaCl ₂ brine (25% weight)	65.53	15	Dispersed phase/ shale stabilization
Organoclay	7	10	Viscosifier
Organophilic lignite	8	10	Fluid loss control
Barite	377	10	Weighting material

4.4 Experimental Work

The following procedure was performed in order to evaluate the effect of using Claytone-EM on the drilling fluid properties:

1. Prepare the drilling fluid mixture at ambient temperature.
2. Measure the density and electrical stability at ambient temperature.
3. Perform the static sag test at 275 °F and 500 psi differential pressure under vertical and inclined (45°) conditions.
4. Perform the dynamic sag test using the sag shoe and the rheometer at 150 °F and 100 rpm.

5. Perform the amplitude sweep test at 275 °F and 500 psi differential pressure to determine the linear elastic region of the fluid.
6. Perform the angular frequency test at 275 °F and 500 psi differential pressure to determine the storage modulus of the invert emulsion drilling fluid.
7. Perform the time sweep test at 275 °F and 500 psi differential pressure to determine the fluid's viscosity changes over time and assesses its thixotropic behavior.
8. Measure the rheological properties at 275 °F and 500 psi differential pressure.
9. Measure the filtration properties at 275 °F and 500 psi differential pressure.

4.4.1 Material Characterization

The two OCs used in this study were characterized using particle size distribution (PSD), X-ray diffraction (XRD), X-ray fluorescence (XRF), and scanning electron microscopy (SEM) to understand their mineral compositions, elemental compositions, and morphologies.

4.4.2 Density and Electrical Stability

The mud density and emulsion stability of the two samples prepared were measured using the mud balance and electrical stability tester at ambient conditions. The effect of the novel OC on the stability of the mud is evaluated. The recommended value for the electrical stability is >400 Volt (Zanten et al., 2012b). Density is a critical parameter in drilling operations as it affects hydrostatic pressure, wellbore stability, and the ability to control the well.

4.4.3 Sagging Tests

The static sagging test is used to evaluate the tendency of a drilling fluid to settle or sag when subjected to minimal or no movement. This test provides insights into the stability and structural properties of the drilling fluid, particularly its ability to suspend solids and prevent settling over time (Ofei et al., 2022; Saasen, 2002b). The static test was carried out at vertical and 45° slanted positions by applying a pressure of 500 psi and a temperature of 275 °F on the drilling mud that will then age in a cell for 24 h. Nitrogen gas was used to apply a pressure of 500 psi to prevent fluid vaporization. The weights of 10 cm³ of the fluids from the upper and bottom parts of the aging cell were measured to calculate the sag factor using the following equation. The recommended sag factor is 0.50–0.53 (Maxey, 2006).

$$SF = \frac{\rho_{\text{bottom}}}{\rho_{\text{bottom}} + \rho_{\text{top}}} \quad (6)$$

Dynamic sagging tests are used to evaluate the rheological properties of drilling fluids under dynamic conditions, simulating the fluid's behavior while being circulated through the wellbore during drilling operations (Amighi & Shahbazi, 2010b). The viscometer was used to provide a rotation of 100 rpm for 30 min at atmospheric pressure and 150 °F to determine the dynamic sagging magnitude. The recommended viscometer sag shoe test (VSST) value is 0–1 (Aldea et al., 2001).

The following procedure was performed for the dynamic sag test:

1. Insert the sag shoe into the thermocup and put it together on the viscometer plate.

2. Pour the drilling fluid inside the thermocup and raise it until the upper surface touches the lower part of the viscometer sleeve. Then lower the cup around 7 mm.
3. Heat the 140 mL drilling fluid with the sag shoe to 150 °F.
4. Set the viscometer at 100 rpm and start a 30 min timer.
5. Using the syringe with the cannula, extract a 10 mL sample and record the weight of the drilling fluid-filled syringe (W_1).
6. Stop the viscometer after 30 min and take another sample of 10 mL.
7. Record the weight of the drilling fluid-filled syringe (W_2).
8. Calculate the VSST using the equation below.

$$VSST = 0.833 \times (W_2 - W_1) \quad (7)$$

4.4.4 Amplitude, Frequency, and Time Sweep Tests

An amplitude sweep test involves subjecting the drilling fluid to a range of shear amplitudes while maintaining a constant frequency. The test measures the fluid's response to varying shear stress amplitudes, typically by applying oscillatory shear using a rheometer. An Anton-Paar rheometer was used to conduct oscillatory amplitude, frequency, and time sweep tests. The resulting data helps determine the fluid's viscoelastic behavior (storage modulus G' and loss modulus G''). This test can provide insights into the fluid's ability to suspend solids and resist sagging or settling under different stress levels. This test evaluates the linear viscoelastic region (LVE) of the drilling fluid by varying the applied shear strain while maintaining a constant frequency. The LVE is the range where the fluid exhibits a linear relationship between the applied stress and the resulting strain.

The point at which the fluid's response deviates from linearity is considered its yield point, which is a measure of the fluid's ability to carry cuttings. The test helps to identify the optimal range of shear stress or strain for subsequent frequency and time sweep tests. Oscillatory amplitude tests were conducted to study the effect of using the novel OC on the storage modulus G' and loss modulus G'' . The amplitude sweep test was carried out at a fixed frequency equal to 10 rad/s while the shear stress was varied.

In a frequency sweep test, the drilling fluid is subjected to a range of shear frequencies while maintaining a constant shear stress or shear rate. This test measures the fluid's response to different shear frequencies and provides information about its viscoelastic behavior at varying rates of deformation. The data obtained from this test helps characterize the fluid's dynamic behavior, such as its ability to maintain suspension and prevent sagging or settling under different drilling conditions. For the frequency sweep test, the angular frequency varied while the strain value was kept constant.

A time sweep test involves subjecting the drilling fluid to a constant shear stress or strain for a specific time. The test measures the fluid's viscosity changes over time and assesses its thixotropic properties, which is the ability of the fluid to recover its viscosity after being subjected to shear. This test helps evaluate the fluid's stability, gel strength, and ability to suspend solids during drilling operations. The rheometer will record the fluid's viscoelastic properties, such as storage modulus G' and G'' , at regular time intervals during the test for 60 min.

4.4.5 Rheology Tests

Rheology tests are performed to measure the flow and deformation behavior of drilling fluids. The rheological properties of OBDs are crucial for their performance. The rheological properties were measured at 500 psi differential pressure and 275 °F by using a rheometer. The plastic viscosity (PV), yield point (YP), and apparent viscosity (AV) were measured using Grace viscometer (model M3600) to evaluate the effect of the novel OC on the drilling fluid rheology and compare with the base drilling fluid. Gel strength (GS) was estimated directly from dial reading at 3 rpm after different time periods (i.e., 10 s, 10 min, and 30 min). The following formulas were implemented to estimate the PV, YP, and AV:

$$PV = \phi_{600} - \phi_{300} \quad (8)$$

$$YP = \phi_{300} - PV \quad (9)$$

$$AV = \frac{\phi_{600}}{2} \quad (10)$$

4.4.6 Filtration Tests

Filtration tests are performed to evaluate the fluid's ability to control fluid loss and the formation of a filter cake on the wellbore wall. These tests assess the fluid's filtration properties and its ability to prevent the invasion of formation fluids and the migration of solid particles. HPHT filtration tests are conducted under elevated temperature and pressure conditions to simulate harsh downhole environments. These tests assess the fluid's filtration performance under more extreme conditions. The filtration tests were conducted at 500 psi differential pressure and 275°F using an Ofite HPHT fluid loss tester and filter

paper as the filtration medium. Digital Vernier calipers measured the filter cake thickness. The filtrate volume was measured as a function of time for 30 min and the thickness and weight of the filter cake were recorded.

4.5 Results and Discussions

4.5.1 Material Characterization

Figure 25 shows the XRD pattern and the plot of the identified phases of Claytone-EM. The results show that illite-IM (NR) with 99% predominates in Claytone-EM mineral composition with 1% of vermiculite. Figure 26 shows the XRD pattern and the plot of identified phases of MC-TONE. MC-TONE is composed of 35.9% feldspar, 29.4% orientite, 25.1% cristobalite, and 9.6% calcite. XRF results showed that Claytone-EM has 52.64% of silicon, 34.51% of aluminum, 11.61% of magnesium, and 1.24% of iron, while the components of MC-TONE are silicon with 53.67%, aluminum with 14.67%, chlorine with 11.84%, iron with 11.09%, calcium with 7.08%, and 1.65% with potassium as shown in Table 6.

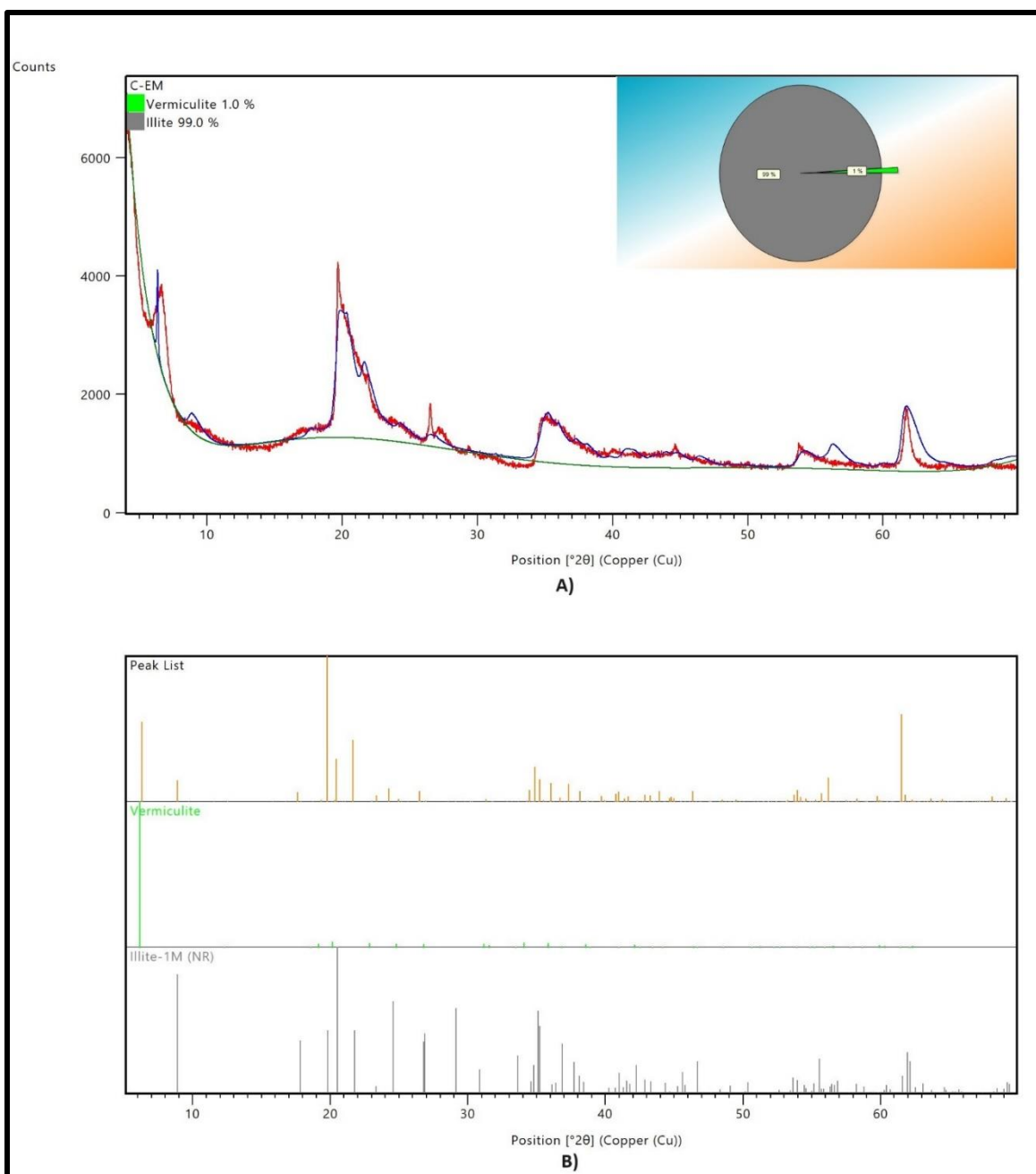


Figure 25 The A) XRD pattern and B) plot of identified phases of Claytone-EM

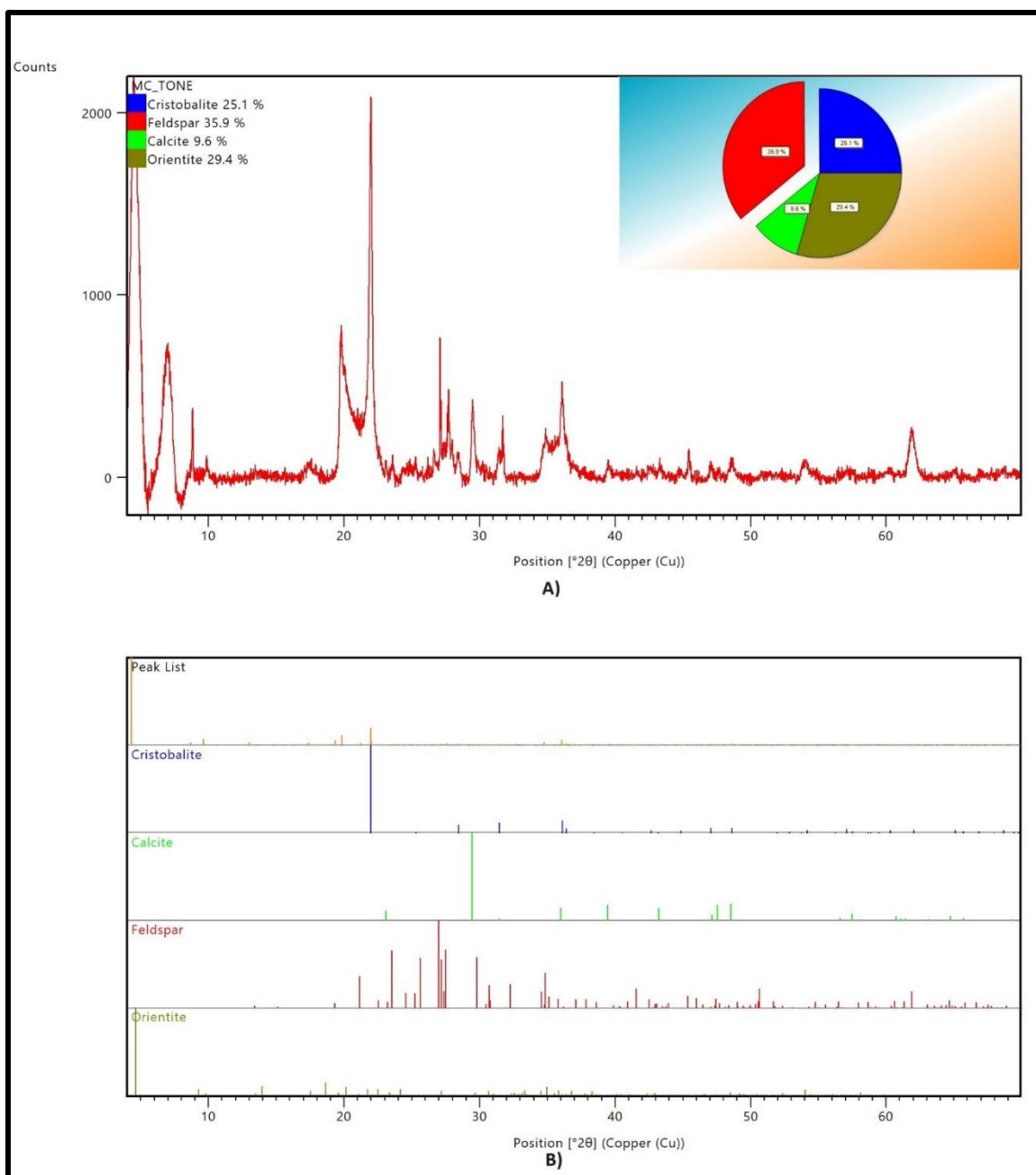


Figure 26 The A) XRD pattern and B) plot of identified phases of MC-TONE

Table 6 XRF analysis results for the OCs used in this study

Sample ID/ Chemical composition (%)	Mg	Al	Si	Fe	Cl	K	Ca
Claytone-EM	11.61	34.51	52.64	1.24	-	-	-
MC-TONE	-	14.67	53.67	11.09	11.84	1.65	7.08

The PSD indicated that the average particle size (D_{50}) of Claytone-EM is $17.95\ \mu\text{m}$ compared to $40.01\ \mu\text{m}$ for the base OC MC-TONE as shown in Figure 27. The smaller PSD of Claytone-EM improves dispersion and the overall stability of the drilling fluids system.

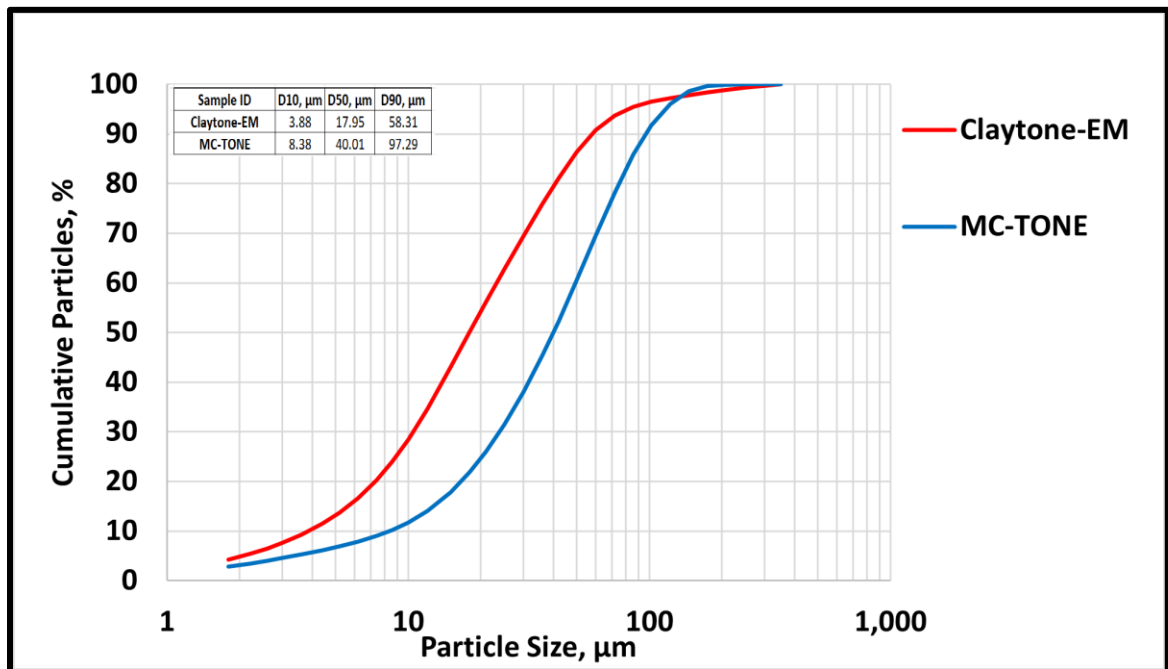


Figure 27 PSD for Claytone-EM and MC-TONE

SEM images of Claytone-EM and MC-TONE are shown in Figure 28. SEM images of Claytone-EM unveil the presence of plate-like particles possessing a stacked structure. These particles appear as thin, flat platelets with irregular edges. Additionally, it is common to observe a collection of small, irregularly shaped particles with a relatively smooth

surface texture. The particles appear to be loosely packed together, forming a porous structure with many small voids and channels. This porous structure is due to the irregular shape of the particles and the way they pack together. Furthermore, the particles emerge as distinct platelets or stacks that are connected by several interactional mechanisms such as ion-dipole interaction, hydrogen bonds, acid-base reactions, charge transfer, electrostatic interaction, and van der Waals forces (de Paiva et al., 2008; Guégan, 2019; Zhuang, Zhang, Wu, et al., 2017). Moreover, the homogeneity and small size distribution apparent in SEM images imply that Claytone-EM is suitably dispersed within non-polar fluids such as OBDFs. In comparison to Claytone-EM, MC-TONE displays heightened irregularity and more defined particle edges, thereby escalating its tendency to sag.

4.5.2 Density and Electrical Stability

The results showed that using Claytone-EM does not affect the mud density, as it stays at 15.0 ppg. Figure 28 shows that Claytone-EM slightly enhanced the electrical stability of the invert emulsion with a 1% increment to 872 Volt compared to 863 Volt for the mud prepared using the base OC. This can be attributed to the particle size of Claytone-EM, which is relatively small and possesses a high surface area (Sinha Ray & Bousmina, 2005). Claytone-EM has been chemically modified with organic compounds that create a hydrophobic layer on the surface of the clay particles. This layer acts as an insulator, reducing the electrical conductivity of the drilling fluid. By inhibiting clay hydration, Claytone-EM helps to maintain the electrical stability of the drilling fluid (Barati et al., 2017; Khodja et al., 2010). In addition, Claytone-EM can reduce the affinity of water droplets for the solid surfaces present in the fluid system. This reduction in water wetting can help to minimize the contact between water and conductive solids, thereby reducing

the potential for electrical conductivity and stability issues (Borges et al., 2022; Growcock et al., 1994; Magalhães et al., 2016). Also, Claytone-EM can form a stable network within the drilling fluid. This helps maintain the suspension and dispersion of solid particles, preventing their settling and aggregation. This will contribute to the electrical stability by minimizing the formation of conductive pathways in the fluid (Fakoya & Ahmed, 2018; Ofei et al., 2022). Moreover, Claytone-EM helps to prevent coalescence and destabilization of water droplets, thereby maintaining the stability of the emulsion. This stabilization effect indirectly contributes to the electrical stability of the drilling fluid by reducing the potential for phase separation and minimizing changes in electrical properties (Ansari et al., 2021; Y. Chen et al., 2022; Meng et al., 2020).

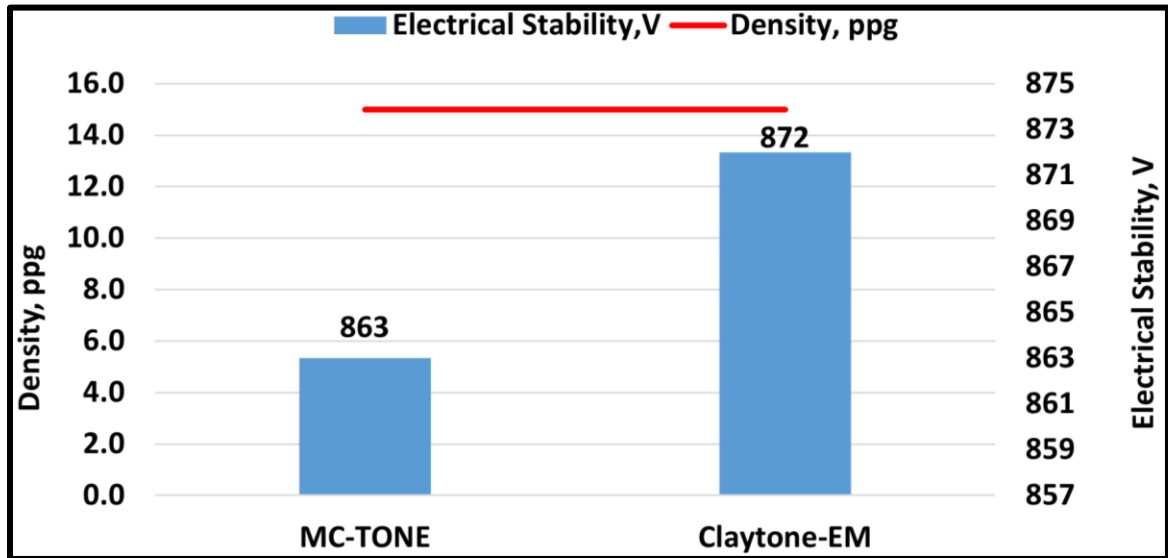


Figure 28 Effect of Claytone-EM on the mud density and electrical stability

4.5.3 Sagging Tests

Figure 29 shows the vertical and inclined conditions sag factors for the base OC fluid and Claytone-EM OC fluid. Results show that Claytone-EM increased the vertical static sag factor to 0.525 compared to the base fluid 0.515 but this increase is still within the

acceptable range. Furthermore, the inclined sag factor decreased greatly from 0.531 in the base fluid case which is higher than the recommended safe range of 0.50–0.53 (Maxey, 2006) to 0.520. Claytone-EM is effective in preventing static sag due to its ability to serve as a rheology modifier and its impact on the suspension stability of the fluid system. It possesses thixotropic properties, allowing for reversible changes in viscosity under shear stress. The organophilic nature of Claytone-EM allows it to interact with the oil phase, forming a barrier that inhibits the settling of solids. This reduction in settling rate helps maintain the suspension of solids during static conditions, thereby minimizing sagging in the drilling fluid. When the drilling fluid is in circulation, the shear forces reduce its viscosity, enabling easy flow and pumping. However, during static periods, the removal of shear forces causes the fluid to regain its higher viscosity, thus preventing the settling of particles (Maxey, 2006). This effect can be particularly beneficial in applications where prolonged static conditions are encountered, such as during well shut-ins or long periods of inactivity. Additionally, Claytone-EM contributes to the yield stress of the fluid system, which determines the minimum stress required to initiate flow. A higher yield stress enhances the fluid system's ability to withstand the gravitational force acting on the suspended particles, thereby preventing static sag and maintaining a stable suspension. Moreover, the interaction between Claytone-EM particles and the other components in the fluid system can impact the overall suspension stability. These particles can create a network structure within the fluid, providing support and stability to the suspended particles and preventing their settling or separation. Furthermore, Claytone-EM can adsorb onto the surfaces of suspended particles, leading to changes in their surface properties and

improving the overall stability of the suspension. The adsorption of these particles can hinder aggregation and settling, thus contributing to the prevention of static sag.

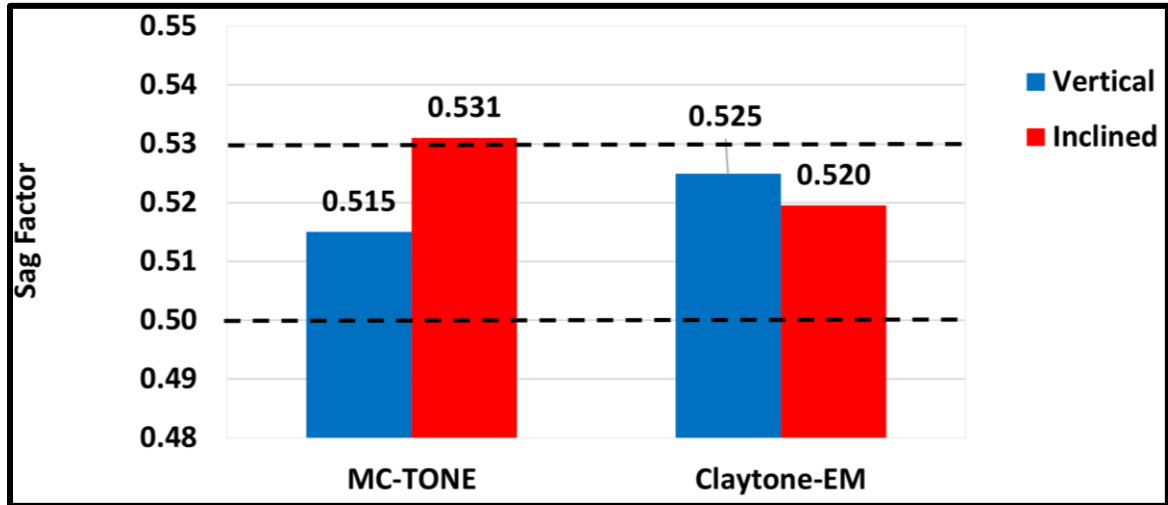


Figure 29 Sag factors under static conditions

Figure 30 shows the VSST sag factors for both OCs. The results show a reduction in the VSST value from 0.869 ppg to 0.667 ppg. Claytone-EM can help improve the suspension properties of the drilling fluid by effectively dispersing and suspending solid particles, such as weighting agents and cuttings. This prevents the settling or sagging of solids during high shear or dynamic conditions. Incorporating Claytone-EM into the drilling fluid helps to enhance the suspension and stability of solid particles under dynamic conditions. The organophilic nature of Claytone-EM allows it to interact with the oil phase, forming a three-dimensional network that resists settling and maintains the particles in suspension. The OC interacts with the solid particles and forms a network that impedes their settling. This effect is particularly significant in dynamic conditions where fluid movement tends to promote particle settling. By reducing the settling rate and sedimentation, Claytone-EM contributes to improved stability and reduced sagging in the drilling fluid during dynamic operations. Also, Claytone-EM can contribute to the yield stress of the fluid system, which is the

minimum stress required to initiate flow. A higher yield stress helps the fluid system resist the component of gravitational force acting during dynamic motion more effectively, preventing dynamic sag and maintaining a stable suspension. In addition, Claytone-EM can enhance the stability of the oil-water emulsion, ensuring that the fluid remains homogeneous even under high shear conditions. This stability helps prevent the sagging and settling of the oil and water phases. In dynamic applications, Claytone-EM can increase the viscosity and gel strength of the drilling fluid, providing better resistance to sagging. The clay particles form a three-dimensional network structure that helps maintain the fluid's integrity and prevents sagging. Moreover, adsorption can help prevent aggregation and settling of particles in dynamic applications, contributing to the prevention of dynamic sag. Furthermore, it allows the fluid to flow and level out easily during application and then rapidly increase in viscosity when subjected to dynamic forces, preventing the sagging, or settling of particles due to its positive effect on the thixotropic behavior of the fluid. Furthermore, Claytone-EM exhibits shear thinning behavior, meaning that the fluid's viscosity decreases under shear stress. This property allows the drilling fluid to flow easily during circulation, reducing the likelihood of sagging and improving overall fluid performance. Lastly, Claytone-EM helps prevent the formation of gels or flocculation in OBDs. Gels and flocculated particles can contribute to sagging and hinder fluid flow. Claytone-EM acts as a stabilizer, preventing the interaction between solid particles and other components of the fluid that lead to gelation or flocculation. This stabilizing effect helps maintain the fluid's integrity and reduces sagging tendencies during dynamic conditions.

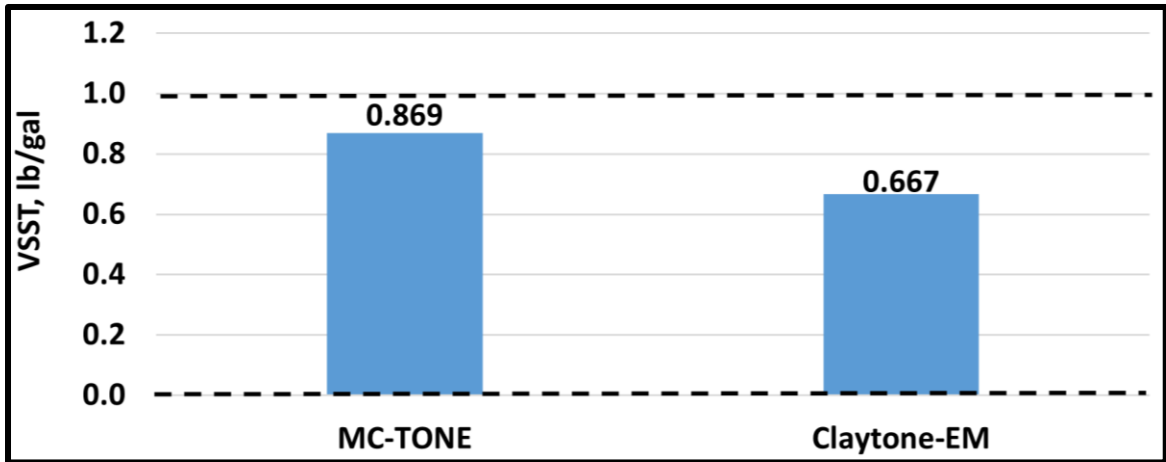


Figure 30 Sag factors under dynamic conditions

4.5.4 Amplitude, Frequency, and Time Sweep Tests

The oscillatory amplitude test showed that Claytone-EM results in a small increase for both G' and G'' in the LVE region that is limited to 0.1% shear strain compared to the base OC fluid as shown in Figure 31. This results in better elasticity, sag resistance, and a solid-like behavior. Adding Claytone-EM can enhance the yield stress of the drilling fluid, making it more resistant to flow under high shear conditions. This effect is beneficial in preventing fluid loss and maintaining wellbore stability. Also, Claytone-EM can increase the elastic or solid-like behavior of a formulation, which is reflected in a higher G' value. This can be beneficial in applications where good sag resistance, thixotropic behavior, or suspension properties are desired. Furthermore, the presence of Claytone-EM can also affect the viscous or liquid-like behavior of a formulation, as shown by changes in the G'' value. An increased G'' value can lead to better leveling or flow control in specific applications. Moreover, the addition of Claytone-EM can enhance the overall viscoelastic properties of a formulation. This can lead to improved performance in terms of flow control, stability, and resistance to deformation. In addition, incorporating Claytone-EM into a formulation can result in increased complex viscosity, indicating a higher resistance to flow under

oscillatory shear. This can be beneficial for applications that require shear-thinning behavior or improved sag resistance. Furthermore, Claytone-EM can promote thixotropy in OBDs, allowing them to regain viscosity after experiencing shear. This property is crucial for the effective suspension of cuttings during drilling operations. Lastly, Claytone-EM can modulate the viscosity of OBDs during the amplitude sweep test. As the shear amplitude increases, the viscosity of the fluid may change. Claytone-EM can help maintain a consistent viscosity across a range of shear amplitudes, thereby stabilizing the fluid's rheological properties during the test.

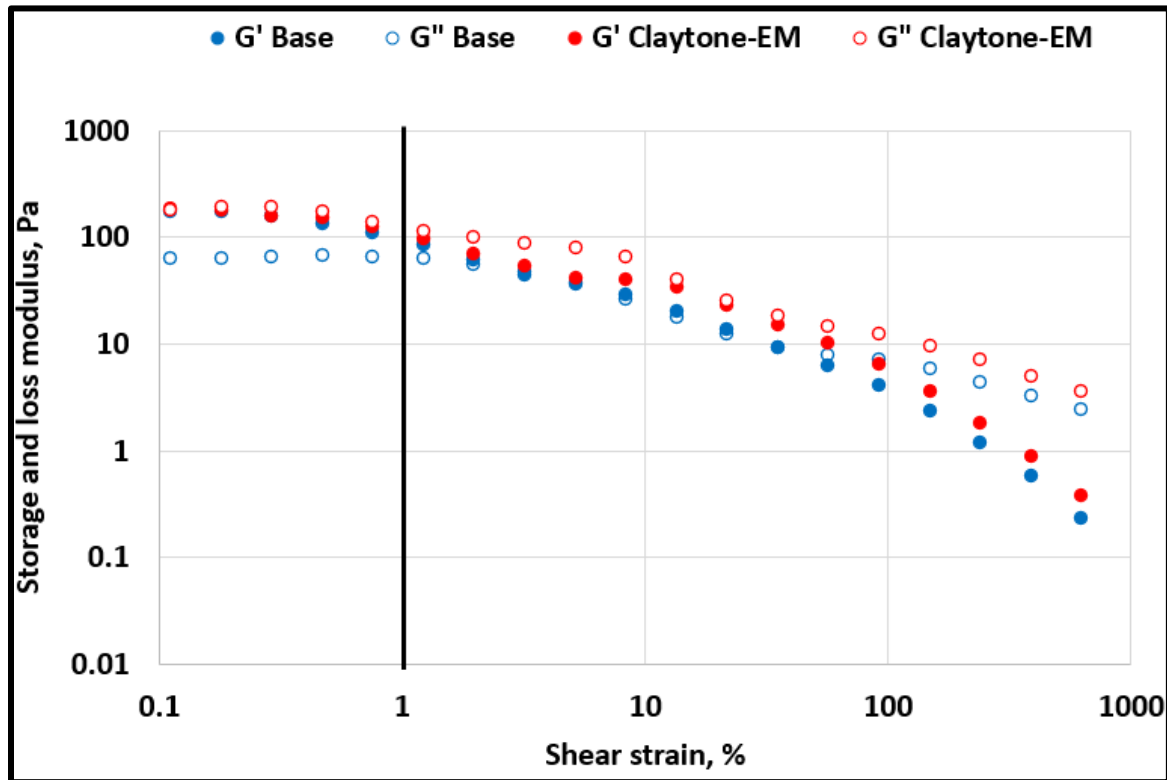


Figure 31 Amplitude oscillatory tests

The results of the oscillatory frequency sweep tests are shown in Figure 32. When Claytone-EM is added to a drilling fluid, it has been shown to enhance both G' and G'' , indicating improved elasticity and viscous behavior. This means that at varying

frequencies, the fluid will maintain its desirable flow properties without experiencing sagging or settling. This effect is particularly important in mitigating wellbore instability issues, such as fluid loss and differential sticking. Furthermore, Claytone-EM improves suspension properties within drilling fluids by preventing solids from settling out and causing issues such as blockages or pump wear. Also, Claytone-EM increases the material's storage modulus and improves its mechanical strength, which could be beneficial for applications that require high stiffness or resistance to deformation. Moreover, Claytone-EM also increases the material's viscosity and reduces its flowability, which could be beneficial for applications that require high thixotropy or sag resistance. The addition of Claytone-EM can improve the stability of a formulation by increasing its yield stress and resistance to deformation. In a frequency sweep test, this can be observed as an increase in G' at low frequencies, indicating enhanced elastic or solid-like behavior. In addition, Claytone-EM can impart shear thinning behavior to OBDFs during the frequency sweep test. Shear thinning refers to the reduction in viscosity as the shear rate or frequency increases. Claytone-EM helps to reduce the fluid's viscosity under higher shear rates or frequencies, facilitating easier flow and improved pumpability. This shear thinning behavior allows the fluid to maintain good suspension properties for solid particles while ensuring efficient circulation and transportation. Moreover, Claytone-EM can enhance the stability of OBDFs during the frequency sweep test. It helps to maintain the fluid's rheological properties, such as viscosity and elasticity, over a range of frequencies. This stability ensures consistent fluid behavior and performance in response to varying shear rates or frequencies encountered during drilling operations. Claytone-EM ability to resist frequency changes contributes to the overall stability and reliability of the drilling fluid

system. Lastly, the addition of Claytone-EM can influence the frequency dependency of the drilling fluid's rheological properties. Different frequencies can affect the fluid's response, including viscosity, elasticity, and phase angle, which measures the relationship between the applied stress and strain. Claytone-EM can modify the fluid's frequency-dependent behavior, allowing it to exhibit more stable viscoelastic properties across a range of frequencies during the frequency sweep test.

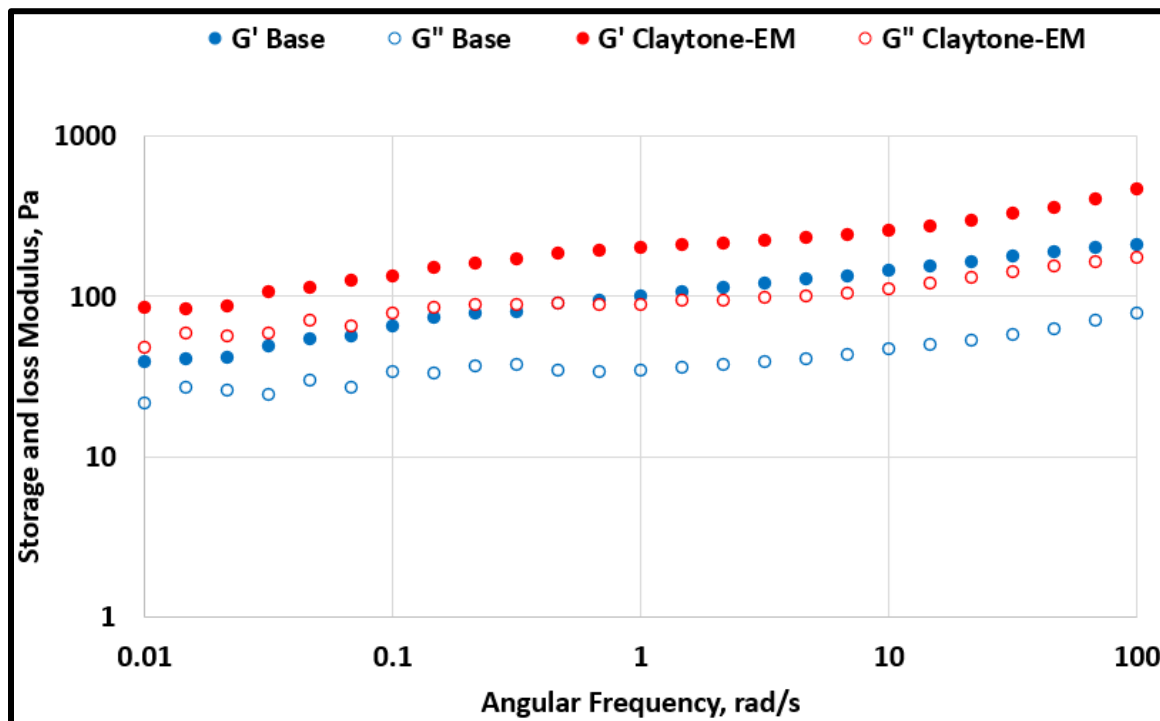


Figure 32 Frequency oscillatory tests

The results of the time sweep tests are shown in Figure 33. Claytone-EM increases the G' of the material, indicating improved solid-like behavior and resistance to deformation. The change in G'' over time may provide insights into the material's viscosity and liquid-like behavior. Furthermore, the addition of Claytone-EM also affects the G'' of the material. Moreover, Claytone-EM enhances the thixotropic behavior of a formulation, allowing it to thin under shear stress and recover its initial viscosity once the stress is removed. This

property can be observed through the recovery of G' and G'' after a change in applied stress, demonstrating the material's ability to regain its structure over time. Claytone-EM can influence the behavior of the drilling fluid during a time sweep test. It can contribute to the formation of a stable gel structure, improving suspension properties and maintaining fluid stability over time. In addition, Claytone-EM can contribute to the long-term stability of OBDFs by preventing the settling and sagging of solids. This effect ensures consistent fluid performance over extended periods. Also, Claytone-EM can contribute to the stability of viscosity and elasticity in OBDFs during the time sweep test. The OC forms a network within the fluid, which helps to maintain the rheological properties over time. This stability is particularly important in drilling operations, as it ensures consistent fluid behavior and performance throughout the duration of the operation. Furthermore, Claytone-EM can help reduce the changes in viscosity and elasticity of OBDFs over time. The addition of Claytone-EM improves the resistance of the fluid to shear and deformation, resulting in minimal variations in rheological properties. This reduction in viscosity and elasticity changes allows for better control of the fluid's behavior and performance during drilling operations. Lastly, Claytone-EM can impart shear thinning behavior to OBDFs during the time sweep test. Shear thinning refers to the reduction in viscosity as shear rate increases. Claytone-EM helps to reduce the fluid's viscosity under higher shear rates, allowing for easier flow and improved pumpability. This shear thinning behavior aids in the circulation and transportation of the fluid while maintaining good suspension properties for solid particles.

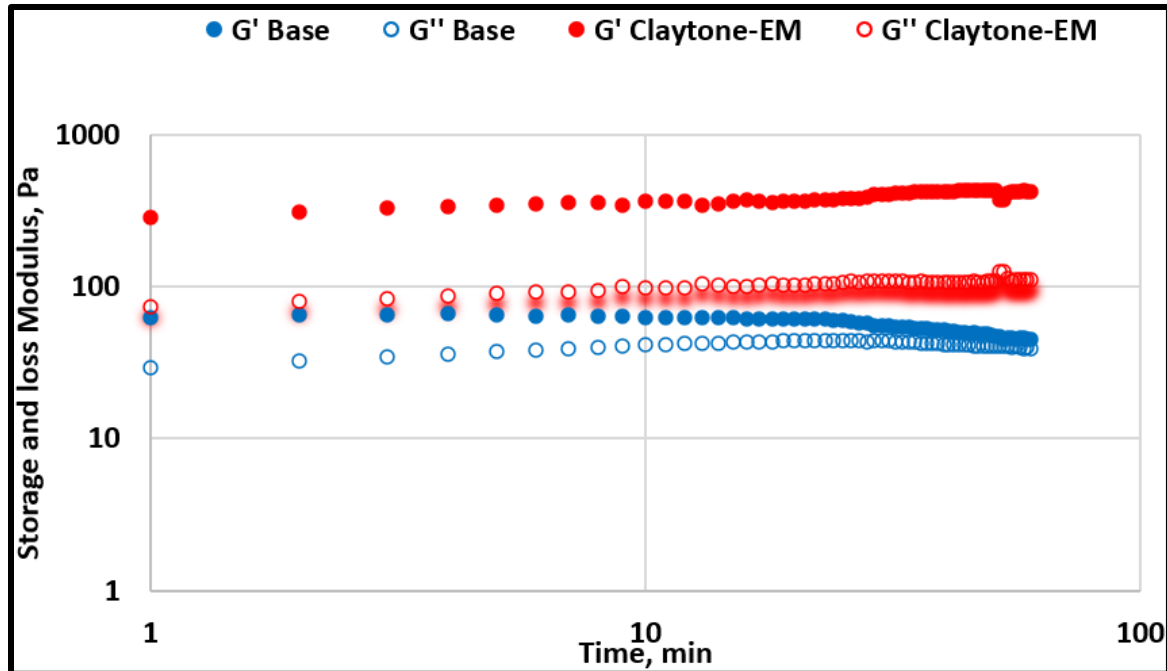


Figure 33 Time oscillatory tests

4.5.5 Rheology Tests

The effect of Claytone-EM on the drilling fluid rheology was assessed and compared with the base mud. Figure 34 confirms that Claytone-EM shows higher shear stress and viscosity in the low shear range. This results in better suspension performance, gelling, and sag. The effect of Claytone-EM on the mud rheology is shown in Figure 35 at 275°F. The plastic viscosity (PV) was increased by an 11% increment from 22.45 cP for the base mud to 24.96 cP with Claytone-EM OC. Claytone-EM can enhance the PV of drilling fluid by forming a network structure within the fluid. This network aids in the improvement of the fluid's flow resistance, which can be advantageous for the suspension and transportation of drill cuttings as well as the maintenance of appropriate hole cleaning. Drilling fluids typically demonstrate non-Newtonian behavior and exhibit shear-thinning characteristics, wherein their viscosity reduces as the shear rate increases (Werner et al., 2017). Claytone-EM imparts shear-thinning behavior to the drilling fluid. Shear-thinning implies that the

viscosity of the fluid decreases under shear stress, such as when it flows through the drill bit. This attribute enables the easier pumping of the fluid during drilling operations while maintaining the desired suspension and carrying capacity. Furthermore, the yield point (YP) increased significantly by an 85% increment from 25.06 lb/100ft² to 46.43 lb/100ft² due to the high dispersion of Claytone-EM. Claytone-EM forms a network structure within the fluid, which enhances the interparticle interactions and cohesion. This increased interparticle bonding and structure contribute to a higher yield point value, indicating greater resistance to flow at low shear stresses. This elevation in YP enhances the fluid's ability to suspend and transport drill cuttings, which is crucial for the proper maintenance of hole cleaning and the prevention of sag or settlement of cuttings during drilling operations. Additionally, a higher yield point can contribute to the preservation of borehole stability by providing improved support to the borehole walls. The introduction of Claytone-EM can enhance the drilling fluid's capacity to counteract deformation and flow under low-stress conditions, thereby averting the collapse or sloughing of the borehole walls during drilling operations. Furthermore, the YP plays a role in the development of an effective filter cake on the borehole walls. A drilling fluid with a higher yield point can create a more stable and uniform filter cake that aids in minimizing fluid loss and stabilizing the borehole. Moreover, Claytone-EM can augment the thixotropic behavior of a drilling fluid, allowing it to thin under shear stress and rapidly restore its initial viscosity once the stress is relieved. This property contributes to the fluid's capacity to uphold its yield point and carrying capacity during drilling operations, while simultaneously guaranteeing that it flows effortlessly through the system when necessary. The apparent viscosity (AV) increased by a 28% increment from 34.98 lb/100ft² to 44.70 lb/100ft².

Claytone-EM can increase the viscosity of the drilling fluid by forming a network-like structure that hinders the flow of the fluid. The interparticle interactions and the formation of a clay particle network contribute to the increased apparent viscosity. This can be beneficial in certain drilling operations where higher viscosity is desired for better hole cleaning and cutting suspension. Also, Claytone-EM can exhibit thixotropic behavior, which means that the viscosity of the fluid decreases under shear stress and recovers when the stress is removed. This property allows the fluid to flow more easily during pumping and circulation, while maintaining its viscosity when static. Moreover, Claytone-EM can also cause the drilling fluid to exhibit shear thinning behavior, where the viscosity decreases as the shear rate increases. At higher shear rates, the fluid's viscosity decreases, allowing for easier flow and improved pumpability. This shear thinning effect can help maintain good circulation of the drilling fluid while still providing sufficient apparent viscosity under high shear conditions. The YP/PV ratio increased by a 66% increment from 1.12 to 1.86. A higher YP/PV ratio indicates better suspension and carrying capacity for drill cuttings, which is crucial for maintaining hole cleaning and preventing sag or settling of cuttings during drilling operations (Caenn et al., 2011; Caenn & Chillingar, 1996). Figure 36 shows that the high viscosity at a low shear rate of Claytone-EM enhanced the suspension ability and gelling strengths. The gelling strengths at 10 s, 10 min, and 30 min were increased from 10.76, 10.56, and 11.15 100ft² for the base fluid to 18.00, 18.00, and 16.63 100ft² respectively. Claytone-EM forms a network structure within the fluid, resulting in enhanced interparticle interactions and the formation of a gel-like structure. This increased interparticle bonding and gel formation contribute to a higher gel strength, indicating greater resistance to flow under static conditions. Claytone-EM contributes to

the development of gel strength in drilling fluids. The gel structure formed by Claytone-EM can exhibit thixotropic behavior, meaning it can recover its strength after being sheared or agitated. Adequate gel strength is crucial for preventing fluid loss into permeable formations, maintaining wellbore stability, and preventing sagging or slumping of the drilling fluid.

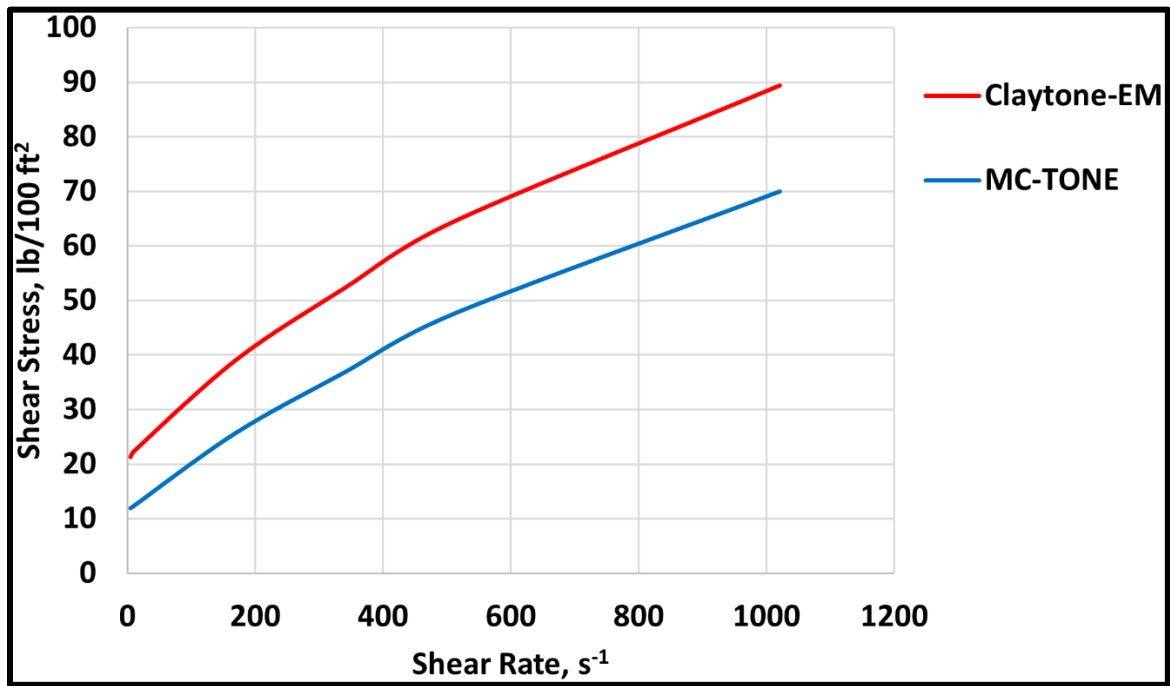


Figure 34 Effect of Claytone-EM on the stress-strain relationship at 275°F

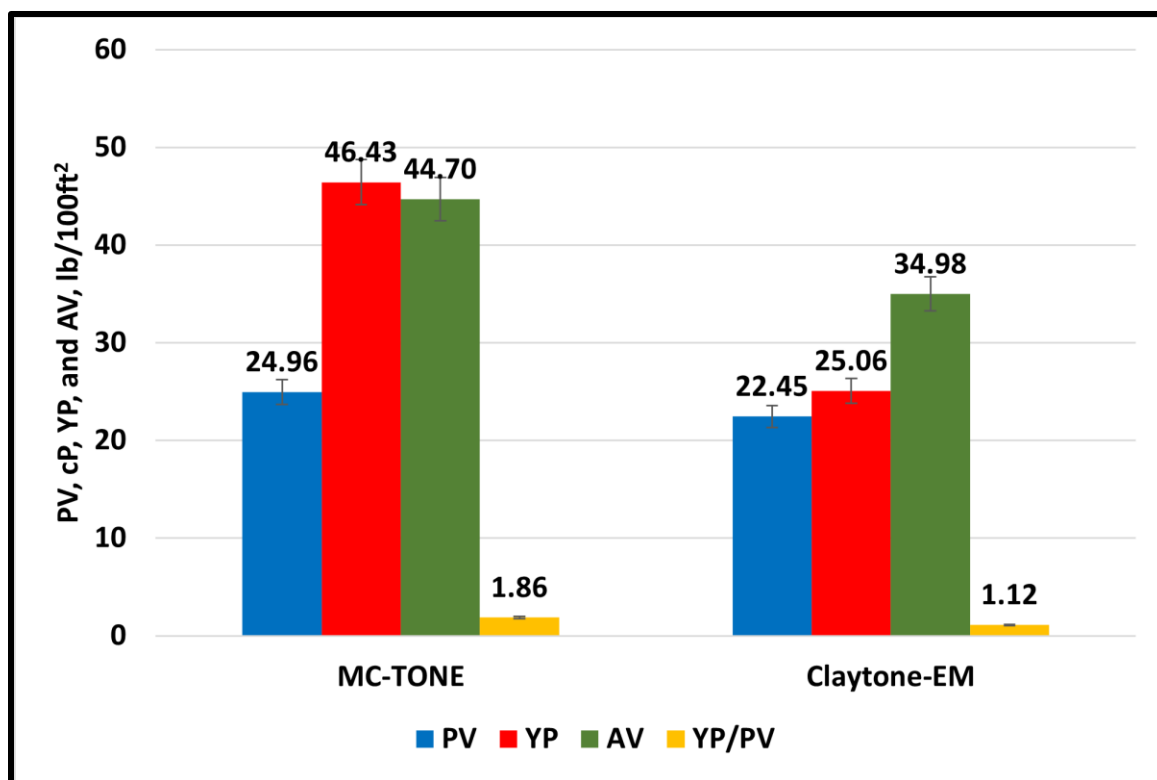


Figure 35 Effect of Claytone-EM on mud rheology at 275 °F

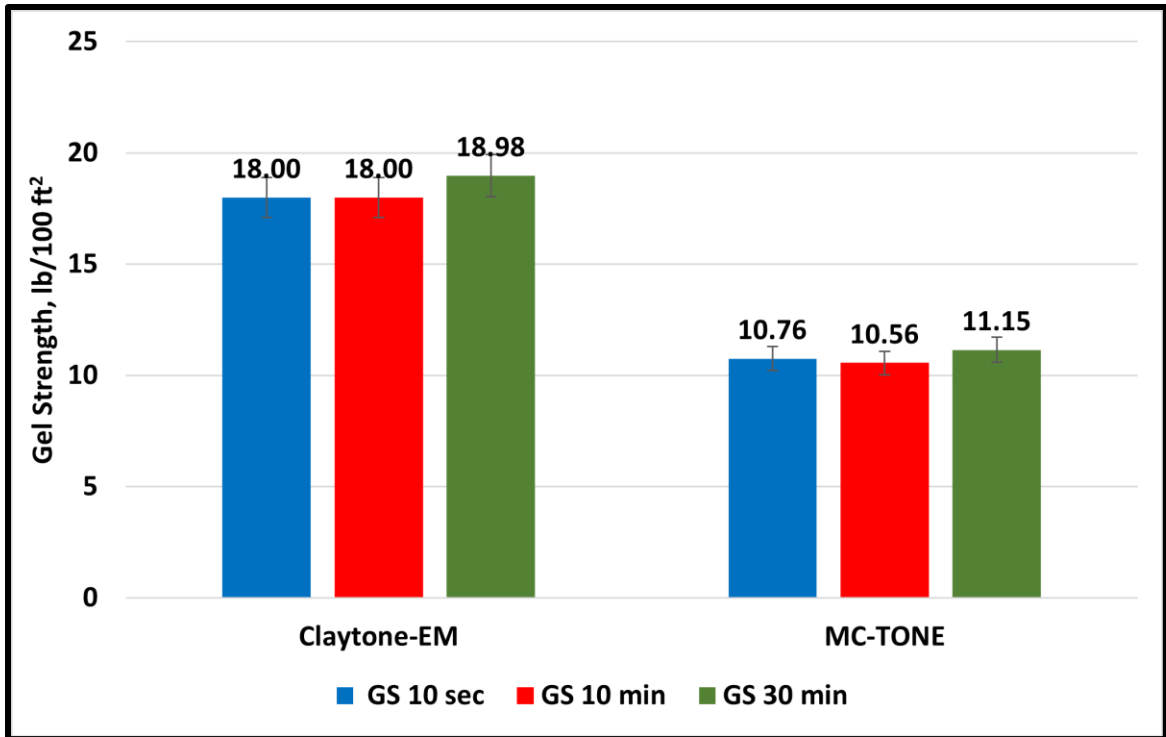


Figure 36 Effect of Claytone-EM on gel strength at 275 °F

4.5.6 Filtration Tests

The filtration test results show that Claytone-EM enhanced the filtration properties. Figure 37 shows a 2% reduction in the filtration volume from 5 to 4.9 cm³. Figure 38 shows a significant decrease of 13% from 2.60 to 2.26 mm in the filter cake thickness. The addition of Claytone-EM resulted in a decrease in fluid loss by enhancing its AV and GS. These particular rheological characteristics possess the potential to produce a more efficient filter cake, consequently aiding in the prevention of fluid loss to the formation during drilling operations. Claytone-EM has a significant impact on the fluid's rheological properties and the formation of a filter cake. It can contribute to the formation of a more effective filter cake, which reduces fluid loss and minimizes the invasion of formation fluids. The reduction of fluid loss is of significant importance to ensure the stability of the wellbore and minimize any potential damage to the formation. One of the primary functions of

drilling fluid is to establish a protective layer, commonly referred to as a "cake," along the walls of the wellbore, effectively hindering the loss of fluid into the formation. Moreover, Claytone-EM particles can create a compact layer on the filter medium, restricting the passage of drilling fluid and preventing fluid loss. This contributes to maintaining wellbore stability and minimizing formation damage.

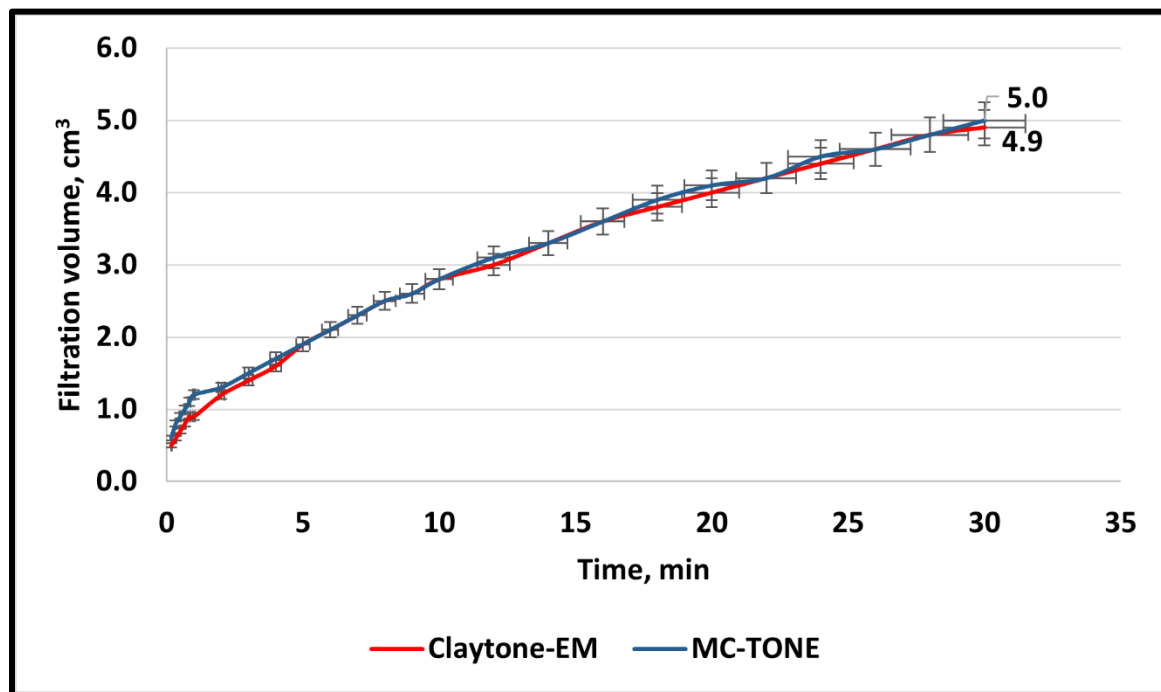


Figure 37 Effect of Claytone-EM on the filtration volume at 275 °F

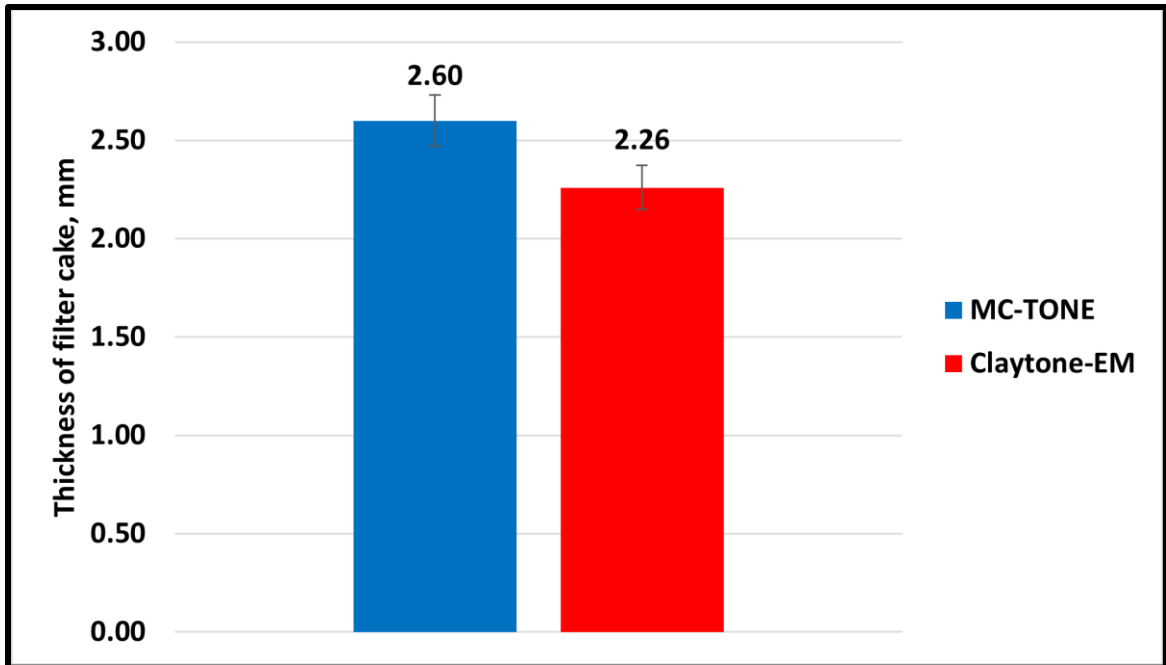


Figure 38 Effect of Claytone-EM on the filter cake thickness at 275 °F

4.6 Attributes of Claytone-EM

After conducting a comprehensive study on the use of Claytone-EM as a rheological additive in OBDs under HPHT conditions the advantages and disadvantages of Claytone-EM can be summarized in Table 7.

Table 7 Advantages and disadvantages of Claytone-EM

Advantages	Disadvantages
1. Rheological Control. Provides excellent rheological control and modification capabilities in various systems, including drilling fluids, paints, coatings, adhesives, and sealants. It can improve viscosity, suspension, sag resistance, and overall stability of these systems.	1. Limited Compatibility with Water-Based Systems. Claytone-EM is primarily formulated for oil-based systems and may not be compatible or exhibit the same level of effectiveness in water-based systems. Its performance in water-based formulations may be limited, and alternative additives may be required for such applications.

2. Suspension and Anti-Settling Properties. Claytone-EM enhances the suspension and anti-settling properties of fluids by effectively dispersing and suspending solid particles. It helps prevent settling and sagging, which is particularly beneficial in applications where solid particles need to be maintained in suspension over extended periods.	2- Concentration Sensitivity. The performance of Claytone-EM can be sensitive to its concentration within a formulation. Finding the optimal dosage is essential to achieve the desired rheological properties and stability. Incorrect dosage levels may result in inadequate performance or undesirable effects.
3. Compatibility with Oil-Based Systems. Claytone-EM is specifically designed for use in oil-based systems, making it an excellent additive for OBDFs, lubricants, and other oil-based formulations. It exhibits good compatibility with various oil-based materials, ensuring efficient performance in these systems.	3- Dependency on shearing and mixing. Claytone-EM requires sufficient shear and mixing energy for proper dispersion and activation. Inadequate mixing may result in poor dispersion, reduced effectiveness, or inconsistent performance.
4. Temperature Stability. Claytone-EM demonstrates good thermal stability, allowing it to maintain its rheological properties and performance across a wide range of temperatures. This stability is crucial in applications where the fluid or system is subjected to high-temperature conditions.	
5. Enhanced stability. Claytone-EM improves the stability of formulations by preventing settling, sagging, and phase separation. They form a three-dimensional network that helps suspend and stabilize solid particles, ensuring consistent performance over time.	

The study concludes that Claytone-EM is a promising additive for improving the performance of OBDFs under high pressure high temperature conditions, providing better rheological characteristics, emulsion stability, and suspension properties. The use of Claytone-EM as a new rheological additive address drilling challenges and meets specific performance criteria for formulating drilling fluids. The limitations of the study include the

temperature range at which the study was carried out which can be further studied at extreme temperatures. Also, the sag effects are not fully captured without performing flow experiments. Furthermore, cutting transport is not studied in this work. Further research and field-scale evaluations are recommended to validate and optimize the application of Claytone-EM in OBDs.

4.7 Discussion

The experimental results reveal a notable enhancement in the rheological properties of OBDs when Claytone-EM is employed instead of MC-TONE, particularly in HPHT drilling environments. Claytone-EM demonstrates superior performance by enhancing electrical stability, minimizing static and dynamic sag, and improving filtration control through the creation of a more efficient filter cake. This improvement can be linked to the mineral and chemical composition disparities between Claytone-EM and MC-TONE, as evidenced by the XRD and XRF results.

The action mechanism of Claytone-EM differs from that of MC-TONE due to their distinct chemical compositions and properties. Claytone-EM, a chemically modified smectite clay derived from bentonite, is organophilic, meaning that it has been altered to have an affinity for organic molecules. This modification is achieved through an ion exchange process, where inorganic cations in the mineral structure are replaced with organic cations. The resulting enhancement in Claytone-EM's affinity for nonpolar organic compounds improves its rheological properties. It forms a network structure within the fluid, leading to augmented interparticle interactions and the creation of a gel-like structure. This

strengthened interparticle bonding and gel formation contribute to higher GS, improved emulsion stability, and enhanced rheological and filtration properties of OBDFs.

On the other hand, MC-TONE does not possess the same organophilic properties as Claytone-EM. It exhibits increased irregularity and more defined particle edges, potentially escalating its tendency to sag. Unlike Claytone-EM, MC-TONE may not contribute to the same level of gel formation and interparticle bonding, leading to reduced stability and performance in OBDFs.

4.8 Conclusions

This comprehensive laboratory study has conclusively demonstrated Claytone-EM's capability to effectively address challenges encountered in HPHT drilling operations. The findings reveal that the inclusion of Claytone-EM significantly (1) improves the electrical stability of inverted emulsions, (2) diminishes static and dynamic sags through thixotropic behavior, and (3) improves filtration control by creating a more efficient filter cake. Consequently, it also improves the rheological properties of the mud; these improvements lead to the stability of the wellbore, improving the overall performance of OBDFs.

Claytone-EM's introduction has exhibited promising outcomes in enhancing the rheological characteristics of OBDFs. These improvements hold substantial implications for both wellbore stability and the safeguarding of the formation during drilling operations. This study underscores the potential of Claytone-EM as a valuable additive, contributing to the overall performance and stability of OBDFs under challenging HPHT conditions.

The results obtained pave the way for further exploration of Claytone-EM's broader applications and the development of advanced drilling fluid formulations aimed at boosting the operational efficiency and wellbore stability in demanding conditions. Future research and field applications can provide insight into the practical implementation of Claytone-EM in drilling operations. Additionally, its potential in addressing other challenges within the petroleum industry warrants further investigation. This study serves as a foundation for ongoing efforts to harness the full potential of Claytone-EM in optimizing drilling processes.

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Thesis title: Study of Flow Characteristics of Reservoir Rock
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- Assisted lead course professors in grading homework, proctoring exams & quizzes, and addressing student concerns related to course projects.
- Courses supported:
 1. Introduction to Petroleum Engineering
 2. Well Performance
 3. Surface Facilities
 4. Well Completion
 5. Advanced Reservoir Management

6. Drilling Engineering

Trainee at Petrobel (Belayim Petroleum Company), Gulf of Suez

August 2012 — September 2012

- Drilling and Completion Tools Interactive Learning.
- Oil Field Processing Interactive Learning.
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Publications

Master's thesis

Mahmoud, A. A. A.(2019).*Study of Flow Characteristics of Reservoir Rock Using Digital Rock Physics*(Master's thesis, King Fahd University of Petroleum and Minerals (Saudi Arabia)).

Journals

1. **Mahmoud, A.**, Gajbhiye, R., & Elkatatny, S. (2024).
Evaluating the Effect of Claytone-EM on the Performance

of Oil-Based Drilling Fluids.*ACS omega*,9(11), 12866-12880.

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1. **Mahmoud, A.**, Gajbhiye, R., & Elkatatny, S. Evaluating the

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1. **Mahmoud, A.**, Gajbhiye, R., & Elkatatny, S. Evaluation of Claytone-ER as a Novel Rheological Additive for Enhancing Oil-Based Drilling Fluid Performance under HPHT Conditions. Clays and Clay Minerals.

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3. **Mahmoud, A.**, Gajbhiye, R., & Elkatatny, S. A Novel Organoclay for Enhanced Stability and Rheological Properties of Oil-Based Drilling Fluids in HPHT Conditions. Journal of Molecular Liquids.

Manuscripts in Preparation (Targeted for Submission)

1. **Mahmoud, A.**, Gajbhiye, R., & Elkatatny, S. Novel Approach to Enhancing Oil-Based Drilling Fluids Properties Using Combined Organoclays.

2. **Mahmoud, A.**, Gajbhiye, R., & Elkatatny, S. Enhanced Performance of Oil-Based Drilling Fluids through Synergistic Combination of Organoclays.
3. **Mahmoud, A.**, Gajbhiye, R., & Elkatatny, S. Optimizing the Performance of Oil-Based Drilling Fluids by Incorporating a Mixture of Two Organoclays.
4. **Mahmoud, A.**, Gajbhiye, R., & Elkatatny, S. A Two-Organoclay Formulation Approach for Enhanced Rheological Properties of Oil-Based Drilling Fluids.
5. **Mahmoud, A.**, Gajbhiye, R., & Elkatatny, S. A Study on the Performance of a Mixed Organoclay Formulation in Oil-Based Drilling Fluids.
6. **Mahmoud, A.**, Gajbhiye, R., & Elkatatny, S. A Mixed Organoclay Approach for Enhanced Oil-Based Drilling Fluids Performance.
7. **Mahmoud, A.**, Gajbhiye, R., & Elkatatny, S. Advances in Drilling Fluid Technology A Review of Recent Developments and Future Trends.
8. **Mahmoud, A.**, & Gajbhiye, R. Hydrogen's Role in the Oil Industry's Energy Transition Challenges and Opportunities.

Conferences

1. **Mahmoud, A. A.**, AL-Dogail, A. S., Gajbhiye, R. N., & AlSultan, A. S. (2023, March). Development of Emulsified Acid System Using Organoclays. In *SPE Gas & Oil Technology Showcase and Conference*(p. D021S025R002). SPE.
2. **Mahmoud, A. A. A.**, Gajbhiye, R., & Li, J. (2021, September). Evaluating Flow Characteristics of Reservoir Rock Using Digital Rock Physics (DRP). In *Offshore Mediterranean Conference and Exhibition*(pp. OMC-2021). OMC.

Accepted Conferences

1. International Petroleum Technology Conference (IPTC), February 2025, Kuala Lumpur, Malaysia. ePoster presentation: "Enhancing The Performance Of Oil-based Drilling Fluids With A Novel Modified Clay" (Paper number: IPTC-25075-MS). Authors :**Mahmoud, A.**, Gajbhiye, R., & Elkatatny, S.

Conferences Under Review

1. SPE/IADC International Drilling Conference and Exhibition, March 2025, Stavanger, Norway. Paper

submitted for presentation: "Assessing The Impact Of A Novel Organoclay On The Efficacy Of Oil-based Drilling Fluids", Authors:**Mahmoud, A.**, Gajbhiye, R., & Elkatatny, S.

2. SPE Gas & Oil Technology Showcase and Conference

(GOTECH), April 2025, Dubai, United Arab Emirates.

Paper submitted for presentation: "A Novel Rheological Additive For High-performance Oil-based Drilling Fluids in HPHT Conditions", Authors:**Mahmoud, A.**, Gajbhiye, R., & Elkatatny, S.

3. SPE International Conference on Oilfield Chemistry, April

2025, Texas, United States of America. Paper submitted for

presentation: "A Novel Organoclay For Optimizing Oil-based Drilling Fluids in HPHT Environments",

Authors:**Mahmoud, A.**, Gajbhiye, R., & Elkatatny, S.

4. SPE Oklahoma City Oil and Gas Symposium, April 2025,

Oklahoma, United States of America. Paper submitted for

presentation: "Optimizing Oil-based Drilling Fluid

Performance In HPHT Environments With A Novel

Organoclay Additive", Authors:**Mahmoud, A.**, Gajbhiye,

R., & Elkatatny, S.

Research Data

1. **Mahmoud, A., & Gajbhiye, R.** (2023). Five Segmented Carbonate Images with Porosity and Permeability Measurements. Figshare.
[<https://doi.org/10.6084/m9.figshare.24878397.v1>].

2. **Mahmoud, A., & Gajbhiye, R.** (2023). Six Segmented Sandstone Images with Porosity and Permeability Measurements. Figshare.
[<https://doi.org/10.6084/m9.figshare.24878373.v1>].

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