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How does Rock Type and Lithology Affect Drilling Fluid's Filtration and Plastering?

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Abstract

There are many variables that affects drilling fluid's filtration and mud plastering. Most of these variables have either been ignored or over simplified in previous drilling fluids filtration studies. Mud particle composition, rate of penetration, formation type, eccentricity and rotation, formation permeability and porosity, temperature, chemical reaction of mud with formation fluids, and pressure are some of the known variables that influence mud filtration. While some of these variables may have little impact on filtration and plastering, others are critical in determining mud filtration pattern and drilling fluid's invasion rate.

The main objective of this paper is to highlight and justify the importance of lithology and rock type, on dynamic mud filtration and plastering. We used a statistical approach to design our experiments, carefully selecting some of the important variables mentioned above. Previous researchers have only considered static-linear filtration conditions. In this study, we used a real time, dynamic-radial filtration system, that accounts for rotary speed, temperature, pressure, and eccentricity. We studied the effects of actively including lost circulation material (LCM) in a mud formulation, and compared the results of using limestone, sandstone, chalk, and homogenous ceramic disk as the porous media. Our results revealed the importance of rock mineralogy, porosity, and permeability in dictating dynamic filtration pattern, mud invasion rates, and plastering effect. The results from ceramic disk, often undermines the effect of rock type which can be misleading. These results cannot represent the actual porous media complexities. In cases where vertical fractures were created and sealed, the combined effects of LCM and low permeability were defined in the reduced mud filtration results and mud cake plastering effects.

Introduction

The effects of drilling fluids filtration and mud plastering have been studied in recent years; especially with the increase in wellbore stability issues and lost circulation challenges in complex reservoirs. When bottomhole pressure forces well sized mud particles to penetrate the near wellbore, these particles tend to accumulate and form a stable filter cake (Ezeakacha et al., 2016, Farahani, et al., 2014, Civan 2007). This process is usually referred to wellbore stabilization or mud cake wellbore strengthening. Wellbore strengthening can be described as a variety of approach that gives room for drilling a wellbore, or an interval of interest, with an increased fracturing pressure. Research shows that wellbore strengthening can be achieved through mechanisms such as fracture opening and closure, as well as, mud cake plastering (Dorman et al., 2015, Contreras et al., 2014, Guo et al., 2014, Nwaoji et al., 2013, Salehi et al., 2012,). The primary goal is to increase the fracture gradient in operational mud window especially when drilling through a depleted reservoir.

The initial invasion of mud solids into the near wellbore pore spaces occurs when the formation is exposed to the drilling mud. This is known as "high energy spurt loss" and it is usually measured in 10 seconds during laboratory fluid loss experiments. Constant differential pressure across the wellbore wall tends to force more solids to invade the pores in what is known as "lower energy, steady state particle transport", over a period of time. If the size distribution of the mud solids, in high concentration, are in the range of the average pore throat size, a strong internal filter cake is formed within the surrounding pore spaces. The mechanism of particle packing, is important, as it dictates the efficiency of the bridge, which must be formed to prevent subsequent mud influx. Early formation of internal filter cake, reduces the formation permeability, and prevents further drilling fluids from contaminating the rock fluids. The pressure of the newly invaded fluid particles depends on the formation pressure. Hence, the internal filter cake will tend to lower the increase in pore pressure behind it after evolving (Cook et al., 2016). Salehi and Kiran (2016), concluded that when drilling through a permeable formation, the evolution of a low permeability internal mud cake can positively change the effective stress around the borehole wall. This makes mud cake wellbore strengthening a successful process**.** Drilling fluids filtration occurs when drilling fluid particles deposit on the wellbore surface to form an external filter cake. The external is the visible filter cake with two surfaces. The cake undergoes thickening and compaction during filtration (Tien et al., 1997). At some point, within the filtration process, drilling fluids particle migration and erosion rates become the same. The outcome of this is a heterogenous external filter cake, comprising of different particle size at the surface of the wellbore, and small particles open to the wellbore fluid flow direction (Wang et al., 2016, Elkatatny et al., 2013, Loeppke et al., 1990),

Drilling fluids filtration is a time dependent process that varies with the mud particle size distribution (PSD), and flow conditions of the wellbore fluids. Lost circulation materials (LCM) have been recognized for reducing lost circulation and mud filtration. Including LCM in mud formulations can significantly influence the PSD of the wellbore fluid and can enhance filter cake properties such as thickness, cohesion, and tightness (Kiran and Salehi 2016). Using well sized LCM in low concentration, (preventive treatment), is more effective than using double the concentration in remedial treatment (Guo et al., 2014). It's worth mentioning that to a certain degree, the average pore size distribution of the rocks dictates the type, sizes, and/or combination of LCM to add for effective pore bridging. However, in real time drilling, it is difficult, if not impossible, to predict the actual pore size distribution and/or fracture geometry. This makes it quite difficult to design a drilling fluid, with the right PSD, to achieve an optimum plastering effect. In order to have a general idea of matching fluid particles to pore throat sizes, wellbore drilling fluid particles can be categorized as follows: particles smaller than the average pore size, particles much greater that the average pore size, and particles with sizes equal or nearly equivalent to the average pore sizes. Mud particles that are smaller than the average pore size have greater potential for migrating further into the formation. If these particles migrate in high concentration, but have poor particle packing mechanism, they cause formation damage. Research shows that the shape, morphology, and size distribution of wellbore fluid particles have strong impact on particle packing mechanism. (Chellappah et al., 2012). Therefore, smaller mud particle, with strong agglomeration, will form a rigid internal mud cake to prevent further formation damage while increasing the near wellbore hoop stress. The morphology of particles can be analyzed using the sphericity and roundness chart by Powers (1953). Particles greater than a target pore size will not partake in forming an internal filter cake but may act as external filter cake material (Loeppke et al., 1990).

There has been considerable amount of studies that have been conducted to quantify the pore throat and fracture sealing efficiency of drilling fluids particles from various mud formulations (Ezeakacha et al., 2016, Salehi et al., 2014, Kumar et al., 2011, Hettema et al., 2007, Aston et al., 2004). However, most of these studies used filter paper and ceramic disk as the porous filter medium. They considered static-linear filtration condition. The heterogeneity and minerology of actual rocks were not account for, and the effects of temperature were underestimated. In our study, we payed attention to the effects of rock mineralogy, permeability, and porosity, in dynamic drilling fluids filtration. We carefully formulated preventive and remedial drilling fluid recipes, to meet acceptable rheological properties, for field operation. The experiments were conducted at an elevated temperature using a dynamic-radial filtration machine. The real-time filtration data indicates that each of the rocks had different cumulative fluid loss, invasion rates, and filtration patterns. The effects of LCM, in mitigating fluid invasion, was clearly defined. An effective mud plastering was observed, in the rock specimens, where fractures were created and sealed.

Experimental Design and Rock Description

In our experimental study, we consider cumulative filtrate and mud invasion rate, as the response dependent variables. The two independent variables, are the types of rock and types of mud. The goal is to characterize dynamic drilling fluids filtration, for different lithologies, at specified experimental conditions. We used the full factorial design of experiment approach. This is a statistical method used to design and account for all possible experimental combinations in which there are two or more independent variables having various discrete levels. We chose two levels of mud type and six levels of rock type which cumulates to twelve experimental runs. We also ran two additional experiments, using ceramic disk, under the same conditions.

We chose water based mud (WBM) and formulated the first recipe (base mud) with mud solids that would have no influence on the mud filtration property. The second recipe (LCM mud) was formulated with the same mud solids as the first recipe. However, 10% by weight of LCM (calcium carbonate) was included in the design. Tables 1 and 2 show the different mud designs. From a fluid loss data base, we selected 11ppg as the design mud weight. The measured mud weights of the base mud and LCM muds were 10.97ppg and 11.02ppg respectively. For the rheological properties, we developed Herschel-Bulkley rheological models showing the flow behavior index, consistency index, and yield stress for both mud samples. The velocity profile equations for Herschel-Bulkley fluids also show comparable shear stress versus shear rate profile with conventional pseudo-plastic fluids (Omosebi and Adenuga 2012). The high yield stress value of the LCM mud indicated a higher viscosity of 15.81cp compared to the 12.8cp that was recorded for the base mud. The presence of calcium carbonate in the LCM mud recipe increased its viscosity by 3cp. The mud recipes also exhibited acceptable gel strength patterns.

Table 1: Base mud design

Products	lb/bbl	% by weight	% by volume
Water	306.1	66.2	87.5
Gel	20.0	4.3	2.4
Caustic Soda	0.5	0.1	0.1
Lignite	4.0	0.9	0.8
Desco	4.0	0.9	0.7
Barite	128.6	27.8	8.6

Table 2: LCM mud design

Products	lb/bbl	% by weight	% by volume
Water	298.1	64.5	85.2
Gel	20.0	4.3	2.4
Caustic Soda	0.5	0.1	0.1
Lignite	4.0	0.9	0.8
Desco	4.0	0.9	0.7
Calcium Carbonate	46.0	9.9	4.9
Barite	90.1	19.5	6.0

The type of rock is the second, and most important independent variable, impacting mud invasion rates and mud cake evolution. Table 3 shows the rock properties of the lithologies categorized into: Clastic (Bandera Brown Sandstone, Berea Upper Grey Sandstone, and Michigan Sandstone) and Carbonate (low permeability Indiana Limestone, high permeability Indiana Limestone, and Austin Chalk). The main underlying difference, between these rocks, is their mineralogical and chemical composition. Sandstones are largely made up of quartz and feldspar, while carbonates are composed of carbonate minerals, most of which are calcite. In addition to mineral composition, their grain orientation and cementation are also distinguishing features. The grain structure in sandstones is influenced during the physical weathering and sedimentation. Their pores are often interconnected, and quartz is the primary cementing material in most sandstones. In unconsolidated sands or loose sands, the quartz cementation is found to be weak (Churcher et al., 1991). The pore network structure in carbonate rocks are found to be influenced by chemical dissolution, secondary solutions, and recrystallization of fossil fragments, from which their grains are formed. Most carbonate rocks are found to be highly cemented by calcite and their grains can be crystalline or granular (Churcher et al., 1991). Their pores may be highly interconnected, and may not be interconnected. Vuggy pores, cavities, and solution channels, are also found to be existing in carbonate rocks such as Limestones. Fig. 1 shows some of the core specimens that were cut from *heterogeneous core samples.* Fig. 2 shows *homogenous* ceramic disks, whose dimensions are boundary conditions, for the core holder in the filtration unit.

Table 3: Rock properties

Lithology	Formation	Brine Perm. (md)	Porosity (%)
Bandera Brown Sandstone	Kansas	7	23
Upper Grey Sandstone	Kipton	105	18
Michigan Sandstone	NA	350	24
Indiana Limestone	Bedford	2.4	14
Indiana Limestone	Bedford	70	19
Austin Chalk	Edwards Plateau	3	25

Figure 1: Core specimens

Salehi et al. (2014), performed a similar research on two formations, where they used a static-linear filtration unit. In reality, bottomhole conditions are often in a dynamic mode because of constant fluid movement during tripping, circulation, and drilling. A greater percentage of drilling fluids invasion occur when the wellbore fluid is in dynamic condition. The inertia state of the mud is surpassed by the hydrodynamic condition of mud particles and the fluids shearing action along the wellbore wall. To simulate this condition, we used the dynamic-radial filtration machined, shown in Fig. 3. We were able to track the real-time data of filtrate loss, rotary speed, temperature, pressure, torque, and eccentricity. Based on previous tests and preliminary calibrations, we selected a temperature of 120^0F and a rotary speed of 50RPM. The filtration machine has a proprietary software which permits the user to program experimental steps. For the purpose of our dynamic drilling fluids filtration study, we programed our experiments in three steps: heating, mud filtration, and cooling. The first step allows the mud sample to attain a specified temperature under dynamic conditions. The second step is programed to align with the API standard filtration time of 30 minutes under specified pressure, temperature, and rotary speed conditions. The third step allows for cooling before dissembling the setup. In addition, we programed the software such that we to acquired data every five seconds. Thus, we obtained accurate mud invasion profiles, for all the rock types.

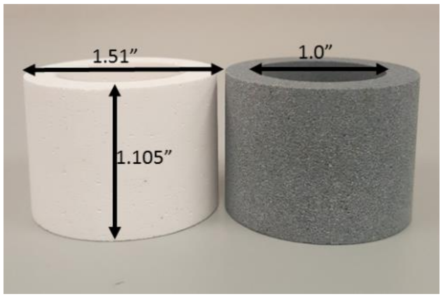

Figure 2: Ceramic disk

Figure 3: Dynamic-radial filtration set up

Results and Discussions

Dynamic-Radial Filtration in Sandstones

The filtration pattern in Berea Upper Grey Sandstone is shown in Fig. 4 for the experimental conditions specified in the procedure. The LCM mud had lower cumulative filtrate when compared to the base mud. A notable observation is the filtrate breakthrough time. In this study, we define filtrate breakthrough time as the time taken to observe a significant flow of mud filtrate after attaining experimental conditions. Filtrate breakthrough time is determined by rock permeability, porosity, and bridging solid cluster mechanism. The filtrate breakthrough, in Berea Upper Grey, occurred earlier with the base mud because it did not form a rigid internal filter cake, hence, experienced faster and greater filtrate loss. The LCM mud had more particle packing which is believed to have been influenced by the LCM. The filtration pattern in Michigan Sandstone is shown in Fig. 5. Filtration results show about 4cm^3 spurt which is followed by steady increase in filtrate loss. The difference between the filtrate breakthrough times, for both mud samples, proved minimal. We attribute the late filtrate breakthrough in the LCM mud to the presence of $CaCO_3$. Using the LCM mud, the cumulative filtrate loss was reduced by more than 5cm^3.

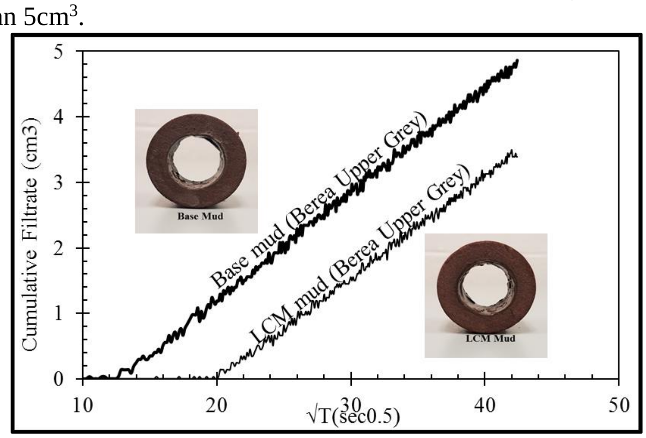

Figure 4: Dynamic filtration pattern in Berea Upper Grey

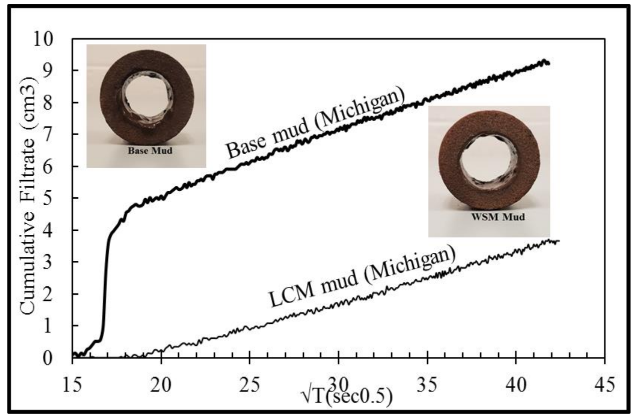

Figure 5: Dynamic filtration pattern in Michigan

We compared the filtration values of both sandstones to understand the impact of their permeabilities. The first difference is in their cumulative filtrate. After the base mud experiments, 4.858cm^3 and 9.381cm^3 were collected for Berea Upper Grey and Michigan sandstones, respectively. After the LCM mud experiments, 3.442 cm^3 and 3.704cm^3 were collected for Berea Upper Grey and Michigan sandstones, respectively. Evidently, the higher permeability sandstone (Michigan) had more cumulative filtrate than the lower permeability sandstone, using both mud recipes. The difference in their filtrate breakthrough times is attributed to their permeabilities. With the LCM mud, the filtrate breakthrough in Michigan is seen to be less than the breakthrough time in Berea Upper Grey sandstone by fractions of seconds. On the other hand, the breakthrough time in Berea Upper Grey was less than the breakthrough time in Michigan as observed in base mud experiments. The high spurt loss in Michigan compensated for the late filtrate breakthrough compared to Berea Upper Grey.

Dynamic-Radial Filtration in Carbonate Rocks

In this subsection, we present the filtration results from the high and low permeability Indiana Limestones, as well as, Austin Chalk. We also discuss the results from the ceramic experiments and compare them with the results from the rocks. Fig. 6 shows the dynamic filtrate loss pattern for 2.4mD Indiana Limestone. After performing the LCM mud experiment, a reduced cumulative filtrate was observed. We also observed an early filtrate breakthrough during the base mud experiment. Fig. 7 shows the dynamic filtrate loss pattern in the 70mD Indiana Limestone. Cumulative mud filtrate in the LCM mud experiments were lowered compared to the base mud experiment. We recorded early filtrate breakthrough in the base mud experiment. As observed with the sandstones, early evolution of internal filter cake within the pores and strong mud particle agglomeration can be linked to the better performance of the LCM mud.

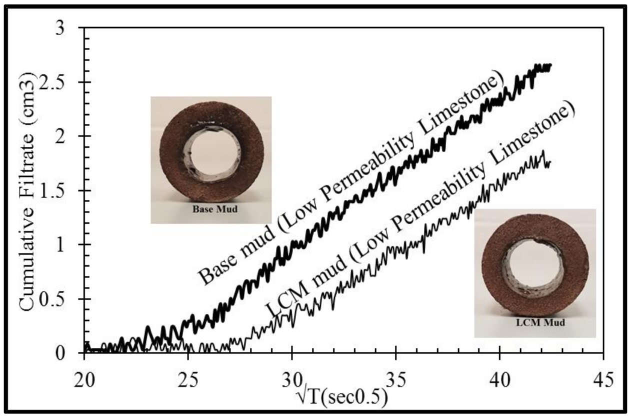

Figure 6: Dynamic filtration pattern in 2.4mD Limestone

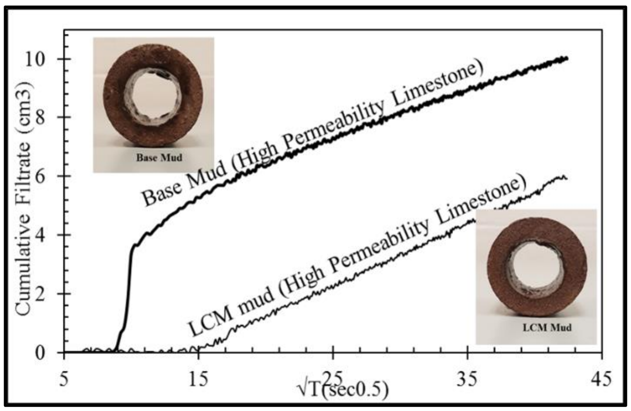

Figure 7: Dynamic filtration pattern in 70mD Limestone

The role of Limestone permeability is also defined by these results. A petrographic study was conducted by Churcher et al., (1991), to differentiate the low permeability Limestone from the high permeability Limestone. Per their study, the two factors that distinguishes the low permeability Limestone from the high permeability Limestone are the amount of cementing calcite and degree of oxidation. After the base mud experiments, we collected 2.652 cm^3 and 10.052 cm^3 from the low and high permeability Limestones, respectively. After the LCM mud experiments, we collected 1.763 cm^3 and 5.96 cm^3 from the low and high permeability Limestones, respectively. In both mud recipes, cumulative filtrate is significantly lower in the 2.4mD Indiana Limestone, clearly defining the role of Limestone rock permeability in drilling fluids filtration. Filtrate breakthrough occurred earlier in the 70mD Limestone. The tortuosity of these rocks may also be a plausible factor affecting filtrate breakthrough time. Tortuosity is a term that is usually used to describe the ease of a fluid flow path, and it's often linked to the permeability of a lithology. In addition, the low cumulative filtrate, observed in low permeability Limestone, may also be related to poor interconnectivity of the interstitial pore spaces.

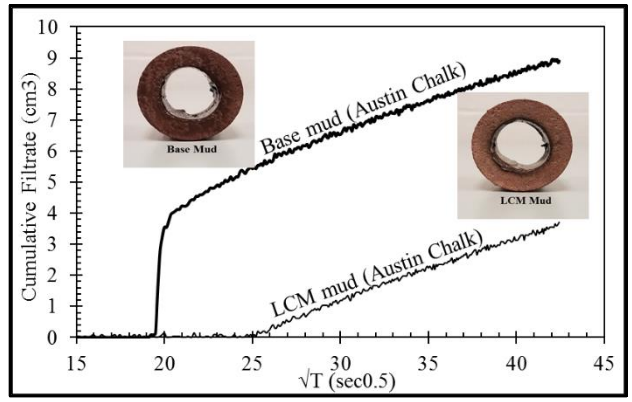

Figure 8: Dynamic filtration pattern in Austin Chalk

The filtrate curves for Austin Chalk lithology are shown Fig. 8 above. In the LCM mud experiment, we recorded late filtrate breakthrough and filtrate was lowered by 4.984 cm^3. In this study, we considered Austin Chalk (3mD) and 2.4mD Limestone as low permeability carbonate rocks. Using both mud recipes, the cumulative filtrate values from the latter are significantly lower than the values from the former. The difference in their filtrate values lie in their grain orientation, structure, and porosity. Austin Chalk is a soft and porous carbonate rock, with 25% porosity, compared to the 14% porosity of the 2.4mD Limestone. High porosity and intergranular grain structure in Austin Chalk may have also compensated for a possibly low tortuosity factor; hence, high filtrate loss. The spurt invasion value and filtrate breakthrough time, from Austin Chalk, also corroborates its high porosity.

Fig. 9. shows the filtrate curves of ceramic disk, whose permeability, approximately, calibrates to 400mD. LCM effect in reducing filtrate was observed. Common industry practice often relies on tests from filter paper or homogenous ceramic disks. However, these cannot represent the true porous media complexities in mud filtration study. Our choices of sandstone and carbonate rocks captured close-to-real field dynamic drilling fluids invasion profiles and the bridging effects of mud particles that cover a wide range of permeability in different lithologies. The mineral compositions and pore structures of the actual rocks cannot be compared with a homogenous ceramic disk. The results from ceramic underscores the role of rock heterogeneity, permeability, and porosity. Cumulative filtrate values, obtained with ceramic disk (6.222 cm^3 and 2.917 cm^3), are closest to the values from Berea Upper Grey sandstone (4.858 cm^3 and 3.442 cm^3). However, the approximated permeability of the 5µm ceramic disk is four times more than the permeability of Berea Upper Grey sandstone.

Overall, the 70mD Limestone had the highest cumulative filtrate using both mud formulations. Although, using the base mud, this value (10.052 cm^3) is only 0.734 cm^3 greater than 9.318 cm^3, from the highest permeability rock, 70mD is five times less than the permeability of Michigan sandstone. This may not be surprising because of the variation in rock mineralogy, grain network structure, and cementation. The petrographic study, carried out by Churcher et al., (1991), suggests that high permeability Indiana Limestones experience more chemical weathering, during the sedimentary process. These weathering processes, secondary solution, and recrystallization, result in natural cavities, channels, and vuggy pores, within this Limestone. These features, which are not present in sandstones, can be related to the overall high filtrate loss observed in the 70mD Limestone.

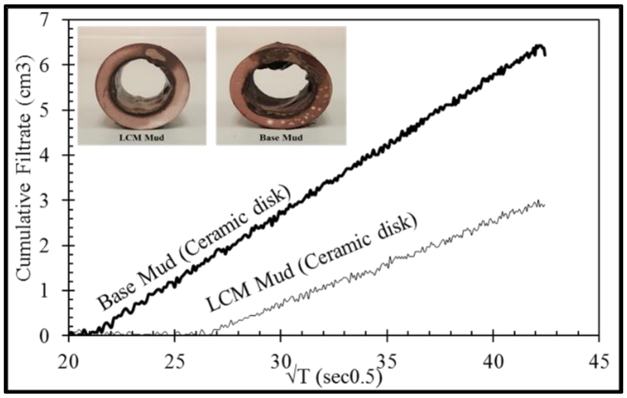

Figure 9: Dynamic filtration in 5µm Ceramic Disk

Dynamic-Radial Filtrate Invasion Rate

Mud invasion rate is a critical filtration property that can be used to quantify the role of formation permeability and LCM. Mud filtration generally occurs in two conditions that vary more in the rate of filtrate loss over time. The first condition, static filtration, occurs when there is no mud circulation in the wellbore and the mud particle transport, towards the external filter cake, is not interrupted. The growth of external filter cake under this condition reduces the filtrate invasion rate. Under dynamic condition, particle accumulation at the wellbore wall and external filter cake surface, sustains only for some minutes or hours (Allen et. al 1991). The inertia condition, as observed in static filtration, is superseded by the mud shearing action at the wellbore wall, hence, particle accumulation at the external filter cake surface is impeded. Eventually, a time dependent equilibrium, between particle deposition rate and particle erosion rate, will be reached. This will change constantly until a critical invasion rate appears. (Allen et. al 1991).

Fig. 10 shows the base mud dynamic filtrate invasion rates, for all the lithologies, while Fig 11 shows the filtrate invasion rates from the LCM mud experiments. In the base mud experiments, the critical invasion rate is seen for 2.4mD Limestone and Berea Upper Grey sandstone after 30 minutes. The critical invasion rates for Austin Chalk, 70mD Limestone, and Michigan, was not observed after 30 minutes. However, the curves show that the critical invasion rate may start to appear if the experimental time extends beyond 30 minutes. In the LCM mud experiments, we observed the critical invasion rate for Austin Chalk, Berea Upper Grey, and Michigan. In general, if the experiments were conducted beyond 30 minutes, the critical invasion rates would most likely appear for all samples. A notable observation in the figures is the time and invasion rate axes. Compared to the LCM experiments, the invasion rates, in the base mud experiments, were generally observed to have appeared earlier. The base mud invasion rates are also higher than the LCM mud invasion rates. In addition, we observed rough filtrate invasion rate patterns, for the LCM mud experiments, compared to the smooth base mud invasion rate curves. We attribute these differences and observations to the active presence of $CaCO_3$ in the LCM mud. The late appearance and rough invasion rate patterns are due to the strong agglomeration of LCM mud particles which make them form a good internal filter cake within the pores of the lithologies and form an effective external filter cake. The stability of the entire filter cake, formed by the LCM mud, creates the required resistance necessary to impede further filtrate influx.

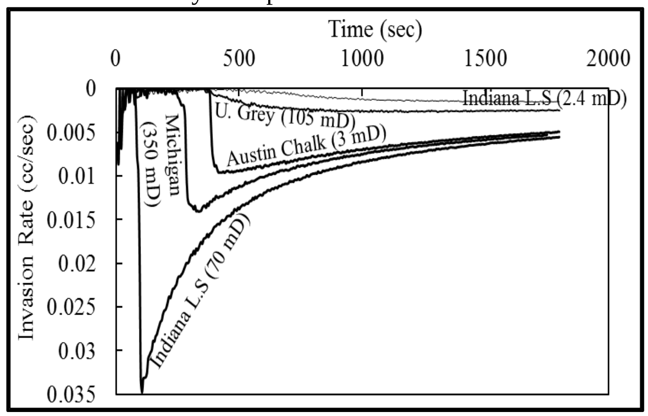

Figure 10: Base mud dynamic filtrate invasion rates

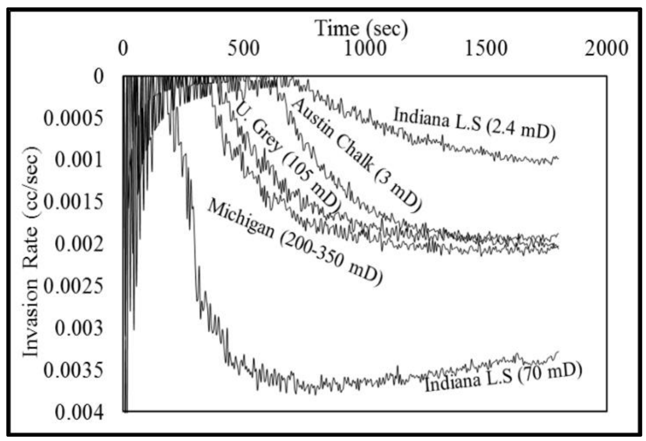

Figure 11: LCM mud dynamic filtrate invasion rates

Mud Plastering Effect

Mud plastering property is important because it reveals the mechanical properties of a mud cake and impedes the absolute open hole flow possibilities in a reservoir section. Mud cake plastering effects have been attributed to the increase in wellbore fracturing pressure and successful wellbore strengthening observed in the Casing Drilling application (Salehi et al., 2012, Rosenberg and Gala 2012). This phenomenon is defined as the smearing of mud solids to the borehole wall and induced fractures, creating a thin and firm mud cake. Fig.12 is used to describe mud cake plastering which was observed in Bandera Brown. During mud filtration experiments with this rock, vertical fractures were created. First, we conducted the base mud experiment, which initiated one vertical fracture. Second, we conducted the LCM mud experiment using another Bandera Brown specimen, initiating two vertical fractures. The amount of filtrate collected was expected to be more with the two-fracture rock specimen. Our LCM mud experimental results show cumulative filtrate of 2.786 cm^3, with two vertical fractures, created in the rock specimen. Comparing this value to the base mud filtrate (3.803 cm^3), with one vertical fracture, we can cautiously conclude that fracture sealing is more effective with the WSM mud. This is resulted from the high surface area of active calcium carbonate that enhanced mud particle interaction among themselves and the walls of the fractures. However, more tests are to be conducted with various mud recipes to confirm this phenomenon.

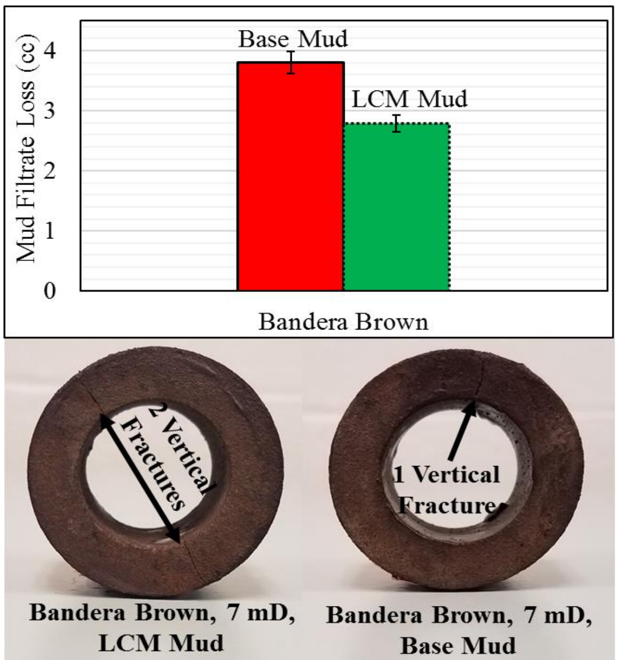

Figure 12: Mud cake plastering effects in Bandera Brown Sandstone

In general, the mud cake that has been plastered around the wall of the rock specimens, and inside the fractures, has properties that enable them to act as a stable bridge to impede subsequent mud loss. Those properties are: thickness, cohesion, and tightness. LCM's are generally recognized for their influence on these mud cake properties. Mud cakes are elastic in nature and are capable of undergoing plastic deformation under a shear failure condition. The cohesive property of a mud cake is sometimes referred to as its compressive strength. The primary source of mud cake cohesive strength is *particle to particle* contact. (Cook et al., 2016). Ezeakacha et al., (2016) refers to this as *particle-particle* and *particle-pore interlocking*. Their study revealed that the interlocking effect serves to increase the cohesive strength of the mud cake for resisting erosive shearing stresses that are caused by the circulating fluid.

Conclusions

This paper summarizes the results of dynamic drilling fluids filtration and plastering for various rock types. Our study has provided a clearer insight to quantifying the effects of rock properties and LCM on mud filtration, as well as, their impact on mud cake wellbore strengthening. The following conclusions have been made:

1. Using the LCM mud recipe, in what is referred to as preventative treatment, the cumulative filtrate was reduced by more than half for all the lithologies.
2. High spurt value, early filtrate breakthrough, and high cumulative filtrate are filtration properties that are associated with high porosity and high permeability formations.
3. Dynamic drilling fluids filtration, from ceramic disks, do not represent the true complex filtration patterns observed with the actual rock specimens.
4. Low formation permeability, alone, does not always correlate to low filtration, as observed with Austin Chalk. Rock permeability and porosity should be considered together in designing a good LCM mud recipe.
5. Early evolution of internal filter cake and strong particle agglomeration, impart, determines the filtrate invasion rates.
6. Dynamic filtrate invasion rate is largely influenced by rock type, mud type, and time. While the critical invasion rate appeared for some lithologies, within or less than 30 minutes, other lithologies may require more time.
7. The LCM external filter cake had better cohesion and tightness. This is evident in the reduced mud filtrate observed from the two-fracture Bandera Brown sandstone specimen.

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