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Study of Filtrate and Mud Cake Characterization in HPHT: Implications for Borehole Strengthening Effects

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Abstract

Wellbore stability issues are continually plaguing the industry and it is important to understand the mud properties that contribute to these issues. The effects of mud cake build up and filtration with time aid the understanding of formation damage and wellbore stability. The increase of drilling in high pressure and temperature zones (HPHT) necessitates studies that can predict filtrate invasion, and particle bridging. Decreasing the near wellbore permeability by forming an ultra-low mud cake can strengthen the wellbore and mitigate further lost circulation problems. Very few studies have investigated filtration and filter cake build up under HPHT situations where effect of different mud particles and bridging solids can be analyzed.

This paper focuses on experimental methods quantifying wellbore strengthening effects in water based muds and investigates effects of particle bridging, filtrate invasion and mud cake permeability. A unique image analysis technique is utilized in this study to optimize Particle Size Distribution (PSD) for wellbore strengthening's pill design. To show the particle bridging effect, high pressure and temperature (HPHT) permeability plugging tests were conducted at different time steps on six sandstone cores with permeability ranging from 15 mD to 1100 md. Further, rock cores and mud cakes were analyzed using Scanning Electron Microscopy (SEM) to verify bridging efficiency. The study concludes a significant reduction in cumulative fluid loss (up to fifty percent) and mud cake permeabilities in range of 10^{-2} to 10^{-3} milliDarcy when using optimum wellbore strengthening's design. Results of this study further prove a pore-pressure reduction wellbore strengthening's mechanism based on forming an ultra-low mud cake in near wellbore vicinity.

Introduction

Lost circulation problem has plagued the drilling industry over the decades. Solutions to mitigate this problem such as advanced loss prevention materials and wellbore strengthening are widely in use by drillers. Wellbore strengthening aims to induce additional wellbore containment in the near wellbore. This can be achieved either through increasing (Alberty and Mclean, 2004) and/or restoring wellbore hoop stress or by decreasing near wellbore permeability by controlling drilling fluid's filtration and preventing pore pressure build up (Tran et al., 2010, Salehi and Nygaard, 2014). Based on analytical models derived by Kirsch, wellbore fracture pressure in ideal non-penetrating situation can be defined as (assuming vertical well in normal faulting regime):

$$P_{fracturing} = 3\sigma_h - \sigma_H - P_p + \sigma_t \quad \text{.................. (1)}$$

Replacing wellbore hoop stress in above equation results in:

$$P_{fracturing} = \sigma_{\theta\theta} - P_p + \sigma_t \quad \text{.............................. (2)}$$

In order to increase fracture pressure (left), one needs to change wellbore hoop stress, pore pressure and/or formation tensile strength.

Proactive control of drilling fluids by adding controlled amount of Lost Circulation Materials (LCM) can help to control filtration (pore pressure build up) and restoring wellbore hoop stress. Forming an ultra-low mud cake while drilling can help to minimize pore pressure build up and increase fracture gradient which often makes wellbore strengthening a time dependent process. Internal filter-cake bridging and time-dependent wellbore strengthening is based on gaining a wellbore strengthening effect when a low permeability internal filter cake is formed inside the fracture which increases fracture resistance. Tran et al., 2010 showed that safe mud weight window can be widened up by 1 gr/cc by having a mud cake with permeability 10^{-3} milliDarcy range (Tran et al., 2010). Results of mud cake permeability calculations in this study are reported in range 10^{-2} to 10^{-3} milliDarcy which can be very beneficial for wellbore strengthening applications.

Selection of LCM's size, type and concentration are always challenging due to some of the unknown downhole conditions. Permeability and heterogeneity of the porous media are often primary factors in mud filtration which are often ignored when conducting normal drilling filtration's test using filter paper and/or ceramic disks. To overcome these limitations, the study here has used rock disks as filtration medium. Using rocks as comparable downhole they had to fit the constraints of the permeability plugging testing apparatus (PPA) used. The filter mediums used in this study are four different sandstones with a wide range of permeabilities (15.9 md, 122 md, 423 md, and 1130 md). Initial permeability and porosity of all sandstone cores were measured by gas permeability methods.

Experiment's Goals and Methodology

Experimental goals from this study are two folds. First, design an optimum PSD based on using image analysis techniques and then conduct HPHT permeability plug tests to observe effects of bridging material's size and concentration on high pressure high temperature fluid loss reduction. Future goals of these experiments are to compare mud ckae permeability that can be achieved by control of drilling fluid's filtrate into the formation. Results of these experiments can be used for wellbore strengthening applications where a better wellbore containment can be proactively achieved.

To reach objectives of this study, several sandstone core samples were prepared and used as filtration medium. Particle size of drilling fluids and additive were also measured suing Malvern laser diffraction particle size analyzer.

Sandstones core samples

Figure 1 and Table1 show the four types and characteristics of sandstone cores used in this study. Testing rocks in wide permeability range help to see effect of formation permeability on mud filtration and to investigate bridging efficiency in different porous medium.

Figure 1: Sandstone slabs used in experiments to prepare rock disks to conduct PPT experiments

Table 1: Sandstone core initial permeability and porosity

Sandstone Description	Permeability, air (md)	Klinkenberg Permeability (md)	Porosity (%)	Formation
Bandera Brown	15.9	13.5	23.78	Kansas
Berea Upper Gray	122	115	19.46	Kipton
Berea Buff	423	411	23.75	Kipton
Michigan	1130	1110	22.58	Unknown

Fluid loss was measured using a permeability plugging testing (PPT) apparatus from spurt to 30 minutes for four different sandstones. Many of the tests were stopped in multiple time steps in order to quantify the bridging by careful study of the cores. Scan Electron Microscopy of the cores were conducted before filtration tests in order to design for Particle Size Distribution using image processing techniques. The goal of this technique is to analyze pore throats in order to optimize PSD design of drilling muds. Several other techniques such as ideal packing theory and modified ideal packing theory have been previously used for drilling fluid's PSD design however none consider rock heterogeneities effect (Chellapah and Aston, 2012). Figure 2 illustrates the steps followed using image analysis technique. Pore throats were obtained from averaging scanning electron microscopy images at the top, and the edge of the core following a methodology similar to the elemental mapping. Similar to the elemental mapping, porosity measurements were performed using scanning electron microscopy images. Prior to analysis, a number of preprocessing steps were required as outlined below. Noise reduction and contrast adjusting are common pre-processing techniques in digital image processing. After the required pre-processing, the scanning electron microscopy image was segmented by pores and grains. The Watershed Algorithm was used to segment the scanning electron microscopy image and find the pore throats. More information is explained elsewhere by Salehi et al., 2014.

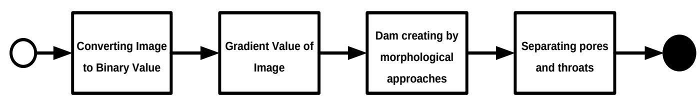

Figure 2: Image analysis technique for analyzing pore throats and PSD design

Experimental Design and Results

A critical factor affecting filtrate and mud cake build up, is the particle size distribution of the solid particles in the mud composition before the blend. Categorizing particle sizes before blending the drilling fluids is important because of its role in the permeability of the filter cake formed on the core. Using image analysis techniques it was found out that a combination of fine, medium and coarse size Calcium Carbonates can help to achieve maximum bridging efficiency. Two different designs of drilling fluids were used, one water based mud using Barite as bridging agent and the other water based mud using Calcium Carbonate as bridging agent. Future tests with mix of Calcium Carbonate and Graphite are under way. Particle size distribution of size Carbonate Calcium used in this study is illustrated in the Figure 3.

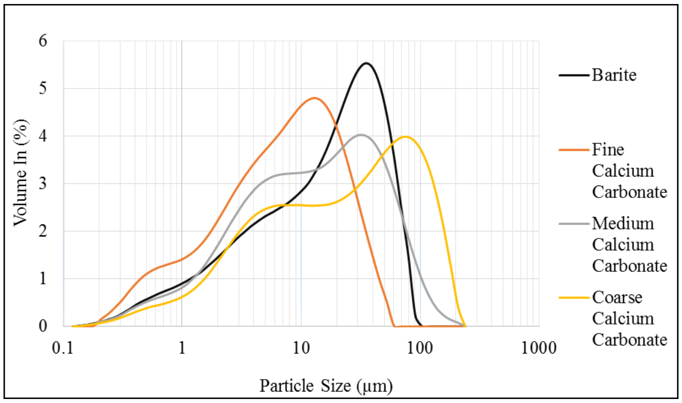

Figure 3. Particle Size Distribution of sized Calcium Carbonate

Results of several filtration tests revealed that the mixing design with having fine size Calcium Carbonate as primary bridging agent has a better performance in reducing filtration. Here, we only report the comparison between the optimal mix and the base case. Figure 4 shows filtration results for all rock cores when using base mud with Barite as a bridging agent.

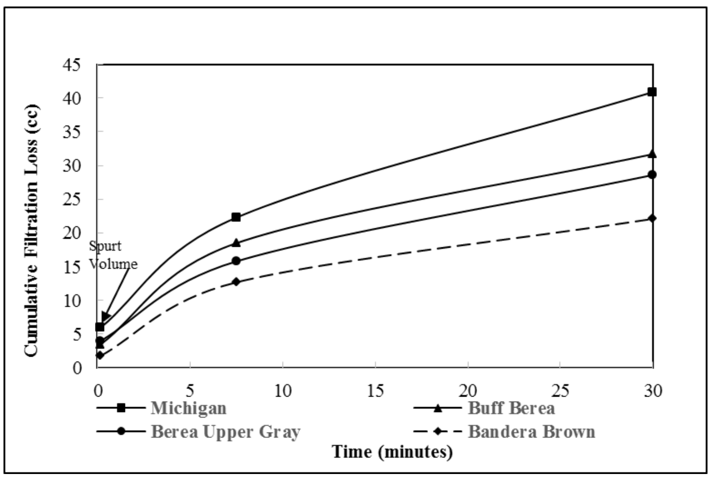

Figure 4. Cumulative filtrate loss using base case water based mud

As illustrated in the figure 4, Michigan sandstone with highest permeability reported highest cumulative filtrate loss with Bandera Brown sandstone having lowest cumulative filtrate loss. Figure 5 illustrates testing results when using optimum design of sized Calcium Carbonate. Comparisons of difference in filtrate loss for the two designs are illustrated in the figure 6.

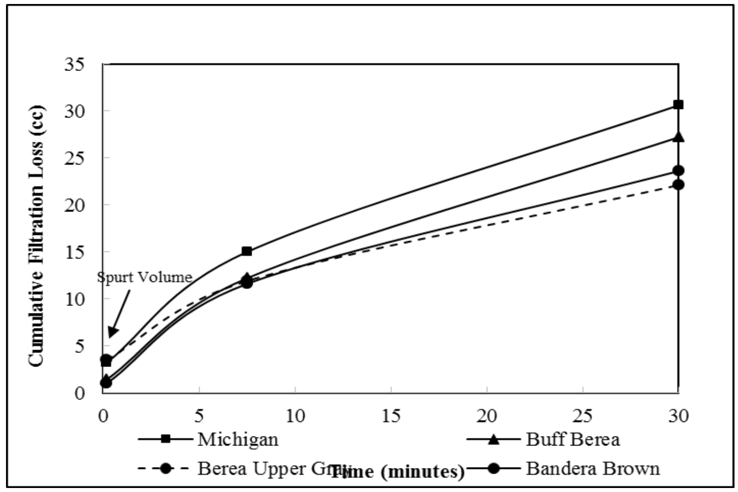

Figure 5. Cumulative filtrate loss using wellbores strengthening water based mud

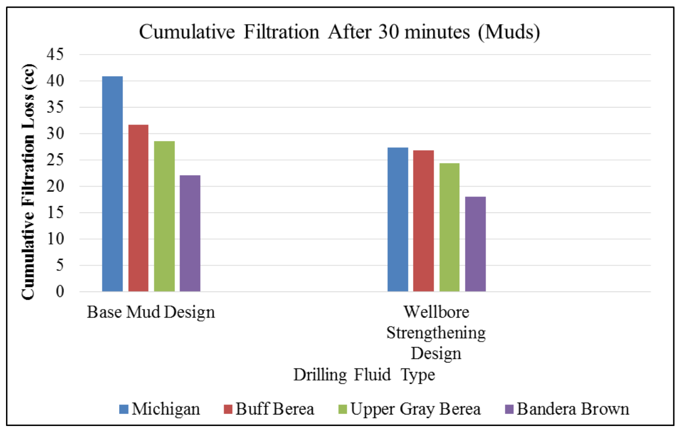

Figure 6. Comparison of cumulative filtrate loss from base design (left) and wellbore strengthening design (right)

Results indicate that up to fifty percent reduction in filtrate loss is observed when using optimum design drilling fluid with sized Calcium Carbonate. All the tests were conducted under 2000 Psi pressure and 200 degree Fahrenheit.

Mud Cake Characterizations

In the next step of testing, mud cakes were carefully removed and sent for SEM analysis. Figure 7 illustrates mud cake cakes after using optimum base design drilling fluid.

Figure 7. Mud cakes using optimum base design drilling fluid

Additionally, data from cumulative filtrate loss from each individual sample was used to calculate mud cake permeability. The permeability calculation was based on the model available in the literature (Civan, 2007) with using slope of the curve from cumulative mud filtrate invasion. This information is available from each set of HPHT PPT test in this study. Results of mud cake permeability calculation confirm the observations from filtration tests where mud cake permeability was significantly reduced (Figure 8). It can be observed that up to 2.5 order of magnitude reduction in mud cake permeability is achieved for Bandera Brown sandstone sample using wellbore strengthening pill design. This further proves effectiveness of approach used in this study to select LCM material's PSD and concentration. It further proves potential application in low permeability rocks similar to ones tested in this study since wellbore strengthening field applications are often limited to only high permeability rocks.

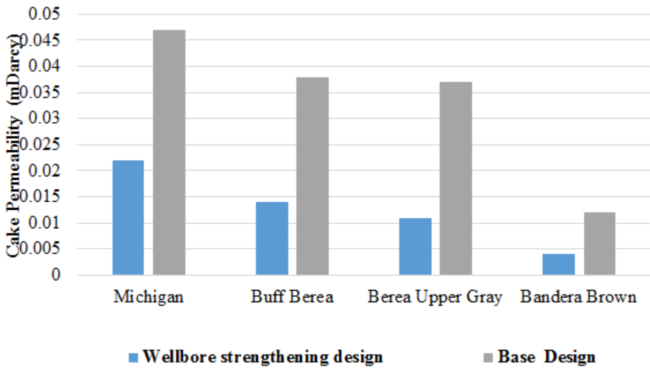

Figure 8. Comparison of mud cake permeability calculated for base design and wellbore strengthening design

SEM Analysis

One of the research objectives is to investigate time dependent particle bridging and the bridging efficiency when using optimum fluid's design. Scanning Electron Microscope was used to study the degree of particle plugging within the pore spaces of the rock cores. SEM images of core top (face of core in contact with the mud) and bottom (face of core in contact with the cell cover) were taken and analyzed. Additionally, elemental mapping by SEM energy dispersive x-ray spectrometry (EDS) was also employed in characterizing various core disks.

Figure 9 & 10 illustrates SEM of the Michigan cores after filtration tests using base case mud (Figure 9) and wellbore strengthening fluid's design (Figure 10). A raw observation of the figures indicates that wellbore strengthening fluid's design has been very efficient in plugging the pores and reducing the filtrate loss. Post-processing of SEM images using similar algorithm presented earlier this paper shows up to 25% bridging efficiency in Michigan core for wellbore strengthening pill design (based on comparison of pore throats before and after testing)

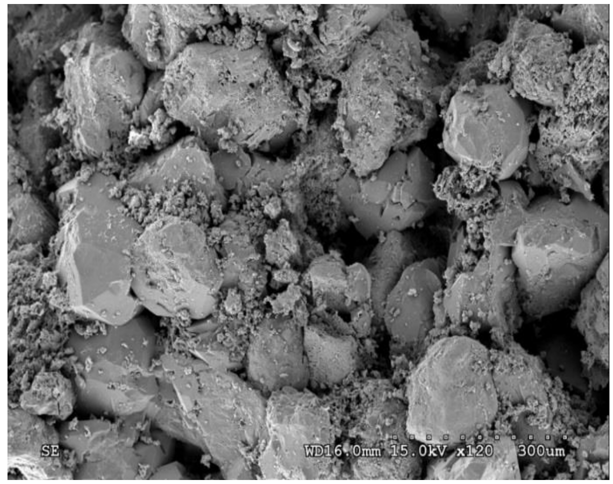

Figure 9. SEM analysis of Michigan core after filtration tests using base case drilling fluids

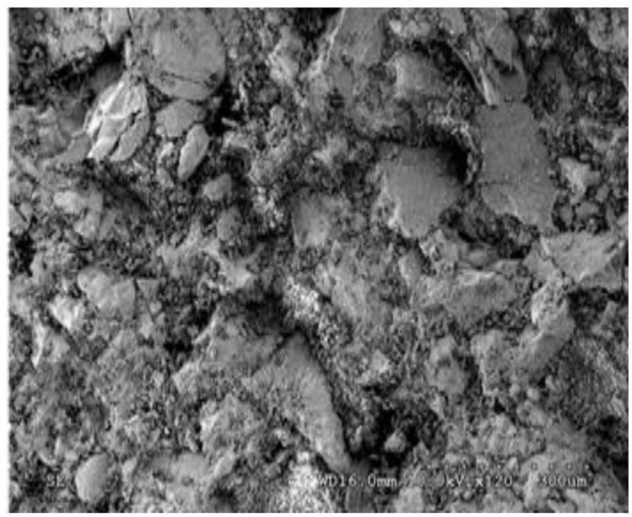

Figure 10. SEM analysis of Michigan core after filtration tests using wellbore strengthening fluid's design

Conclusion

This study presents results of filtration tests using PPT apparatus under high pressure and high temperature conditions for four different types of sandstones. Additionally, rock cores and mud cakes were further analyzed to investigate bridging efficiencies of different particles used in wellbore strengthening's fluid design. A novel approach based on image analysis techniques was employed to study pore throats size to design Particle Size Distribution (PSD) of bridging particles. Based on the results and observations from the study, the following conclusion can be drawn:

- PSD design based on image analysis technique can be used to optimize particle size distribution. This technique

can capture heterogeneity effects which can affect PSD design.
- Cumulative HPHT filtration was significantly reduced when using an optimum PSD of Calcium Carbonates ($CaCO_3$) in wellbore strengthening pill design.
- Calculated mud cake permeabilities indicate a significant reduction in permeability values (up to 2.5 folds). Mud cake permeability values were reported in range of 10^{-2} to 10^{-3} milliDarcy which can be very beneficial for wellbore strengthening applications.
- SEM analysis further verifies bridging efficiency in wellbore strengthening pill design.
- Results of filtration tests are consistent for all tests conducted using different sandstone cores.
- This study verifies wellbore strengthening mechanism based on pore pressure reduction by forming an efficient internal and external mud cake.

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Nomenclature

$P_{fracturing} = Fracturing\ pressure\ (psi)$
$\sigma_h = Minimum\ horizontal\ stress\ (psi)$
$\sigma_H = Maximum\ horizontal\ stress\ (psi)$
$\sigma_t = Tensile\ strength\ (psi)$
$\sigma_{\theta\theta} = Hoop\ stress\ (psi)$
$P_p = Pore\ Pressure\ (psi)$