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Effect of water-based drilling fluid components on filter cake structure

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ABSTRACT

Filter cake plays an important role in the filtration performance of drilling fluid. Drilling fluid components greatly influence the characteristics of the filter cake. The homogeneity of the filter cake, in turn, influences the properties of the filtration process. This study is devoted to understand the structure of drilling fluid filter cake in the non-reservoir sections and provide a new insight into cake layer structure. The spatial distribution of physical, chemical structure of cake layers was characterized by various analytical techniques, including high-temperature high-pressure (HTHP) fluid loss test, scanning electron microscopy (SEM), energy dispersive spectrum (EDS), particle size distribution (PSD), X-ray diffraction (XRD), and methylene blue test (MBT). The results showed that the filter cake was heterogeneous not only in structure but also in composition. The structures and composition of filter cake change significantly from the top layer to the bottom layer. Drilling fluid components have a non-negligible effect on filter cake characteristics. High clay content would result in reduced compactness of filter cake because of the clay coalescence under high temperature, the critical coalescence temperature decreases with the increase of clay content. SEM images and elemental compositions illustrated that electrolyte contamination results in larger pore size of the filter cake as compared to the cake formed by uncontaminated freshwater based drilling fluid, the "honeycomb" structure collapsed because of its inhibitory action on the hydration and swelling capabilities of the pore wall of filter cake, and the filter cake of high density drilling fluid had a loose structure when compared with that of low density drilling fluid. EDS and XRD studies showed that there was an increase in the mass-ratio of hematite to barite of filter cake from the top layer to the bottom layer. Through the PSD results, the filter cake was found to have a larger particle size in the bottom layer than in the top layer.

1. Introduction

Drilling fluids consist of dissolved and suspended solids, liquids, and treating agents, with the liquid being the continuous phase. To stabilize the wellbore area, the drilling fluid forms a filter cake which bridges the formation face under an overbalanced condition. Filter cake builds up over the face of the porous medium and filtrate invades the formation [1]. The filter cake should allow for minimum filtration, prevent solid invasions to the formation, and withstand high differential overbalance pressures [2]. It plays an important role in the filtration performance of drilling fluid. The filtration procedure of drilling fluids is composed of three stages [3]. Stage ① is spurt loss, which occurs when the drill bit crushes the bottom rock and creates new free surfaces; the time for spurt loss is very short, and because there is no cake on the surface of the bottom rock, the filtration rate is relatively high. Stage ② is dynamic filtration, which occurs following the spurt loss, when the drilling fluid circulates, and creates cakes. An equilibrium cake thickness is achieved when the forces acting to hold colloidal particles on the cake surface are overcome by hydrodynamic shear forces that tend to entrain particles in the flow stream. Stage ③ is static filtration, which occurs when the drilling fluid circulation is suspended (e.g. during trip operation). The filtration rates gradually decline during this period.

The flow rate (q) through a filter cake is described by Darcy's law:

$$q = K\,A\Delta p/\mu h \tag{1}$$

where q is flow rate, cm^3/s. K is cake permeability, m^2. A is area of the filter disk, m^2. Δp is pressure drop across the filter cake, MPa. μ is viscosity of the filtrate, Pa·s. h is thickness of filter cake, m.

The cake permeability (K) embraces the cake properties affecting the nature of fluid flow through the cake, and is related to the filter cake average specific resistance (α) by [4]:

$$K = 1/\rho_s(1-\phi)\alpha \tag{2}$$

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Table 1
Compositions of the suspensions used for PSD and SEM measurements.

Experiment	Freshwater based drilling fluid					Brine based drilling fluid				
	#0	#1	#2	#3	#4	#5	#6	#7	#8	#9
Density (g/cm^3)	–	–	2.10	2.30	2.30	1.22	1.50	1.80	2.10	2.30
Component	Dosage (g)									
Water	400.0	400.0	400.0	400.0	400.0	400.0	400.0	400.0	400.0	400.0
Bentonite (Viscosifier)	8.0	8.0	8.0	8.0	2.0	8.0	8.0	8.0	8.0	8.0
Sodium Sulfomethylated phenolic resin (Filtrate reducer)	–	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
Sodium Hydrolyzed polyacrylonitrile (Filtrate reducer)	–	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
Sodium sulfonated gilsonite (Filtrate reducer)	–	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Polyethylene glycol (Lubricant)	–	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
Dodecyl benzene sulfonate triethyl hydrate amite (Anionic Surfactant)	–	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
KCl	–	–	–	–	–	28.0	28.0	28.0	28.0	28.0
NaCl	–	–	–	–	–	88.0	88.0	88.0	88.0	88.0
Hematite	–	–	473.0	610.0	615.0	–	110.0	240.0	399.0	565.0
Barite	–	–	473.0	610.0	615.0	–	110.0	240.0	399.0	565.0

where ρ_s is solid density, kg/m^3. ϕ is porosity of the filter cake, fraction. α is average specific resistance, m/kg.

The deformable colloidal particles will reduce the cake permeability by blocking pores of various sizes. As a result, a large flow resistance to fluid flow through the filter cake can be produced. Consequently, the absorbed water in the filter cake would be increased and the fluid loss would be reduced. In addition, there is a significant effect of the homogeneity of the filter cake layer on the properties of filtration process [5,6]. Filter cake characteristics are very important in filtration control, which depend on a well-designed combination of additives. Many experimental studies have shown that filter cake on the wellbore surface is the dominant mechanism of filtration control.

Over the past decades, many different methods have been proposed to the characterization of filter cake. The X-ray diffraction (XRD) and Fourier-transform-infrared (FTIR) spectroscopy provide the phase identification of filter cake fabric and determine the quantitative analysis of its composition. Ruessink et al. [7] presented the results of a systematic evaluation of the reliability, applicability and intrinsic accuracy of the two most commonly used analytical techniques for quantitative mineral analysis: XRD and FTIR spectroscopy. The two techniques were found to have comparable accuracies in analysis of bulk mineralogy. For both techniques, 90% of the analyses of synthetic mixtures fell within 5 wt.% of the actual contents. The particle size distribution (PSD) of solids in the filter cake is determined using a conventional laser light scattering instrument [8], a laser diffraction method [9], and a Leica microscope [10]. Scanning electron microscopy (SEM) is generally used to examine the surface morphology of samples and identify the elemental constitution of filter cake [10–13]. This identification is accomplished by generating high-resolution images of the areas of interest within the sample and detecting changes in its chemical composition at microstructural level. Many investigators have tried to obtain a better understanding of the microscopic structure of the filter cakes. The information provided by these investigators could help improve the ability to control filtration processes and reduce the wellbore stability problems. Although cake layer formation is a key factor affecting filtration control performance of drilling fluid, findings from literature review indicate that optimization of filtration control performance suffers a lack of detailed fundamental information about cake layer structure. Cake layer can be defined as porous layer rejected on the wellbore surface due to the adsorption, deposition, and accumulation of all kinds of organic and inorganic particles. There are only a few studies that address the cake layer structure. For example, D. Jiao and M. M. Sharma (1994) [14] had presented a model for the formation of filter cake based on experimental results for the crossflow filtration of concentrated bentonite suspensions and an analysis of the hydrodynamic forces acting on a bentonite particle. Furthermore, Tien et al. [15] point out that when the slurry contains particles of different sizes, the larger particles of the slurry form the skeleton of the filter cake and smaller particles can migrate and deposit within the porous cake formed by the large particles. In recent years, CT (computed-tomography) scan was used to characterize the thickness, porosity and permeability of the filter cake layer by Elkatatny et al. [5,10,16,17]. However, they put a little emphasis on the spatial distribution of physical and chemical structures of the filter cake which are the important internal factors to the filter cake's filtration performance.

Table 2
Chemical formulae of the fluid constituents contributing to the filter cake. The marker elements were used for the interpretation of the SEM.

Compound	Chemical formula or elemental composition	Marker element analysis
Bentonite (viscosifier)	$Al_2O_34SiO_2H_2O$	Si, Al
Sodium Sulfomethylated phenolic resin (filtrate reducer)	C, H, N, S, O, Na	C, N
Sodium hydrolyzed polyacrylonitrile (filtrate reducer)		
Sodium sulfonated gilsonite (filtrate reducer)		
Polyethylene glycol (lubricant)		
Dodecyl benzene sulfonate triethyl hydrate amite (anionic surfactant)		
Barite	$BaSO_4$	Ba
hematite	Fe_2O_3	Fe

Drilling fluid components were found to have a non-negligible effect on filter cake characteristics. The clay content of the filter cake has an influence on the physical properties of the filter cakes. The higher the clay content, the thinner and harder the filter cake will be [8]. Jiao and Sharma [18] observed that the filter cake thickness was a sensitive function of the drilling fluid rheology. Electrolyte contamination (such as high contents of NaCl and KCl) causes the flocculation and aggregation of bentonite and polymers. As a result, particles associate in the form of a loose, open network [3]. This structure persists to a limited extent in filter cakes, causing considerable increases in permeability [19–21]. Weighting materials also have a significant effect on the fluid rheology and the circulating pressure loss. Calcium carbonate, barite, hematite, magnetite, Mn_3O_4 and formate can be used as weighting materials in the field. However, barite is not recommended for the target zone because it causes formation damage and is difficult to be removed or dissolved.

It is not surprising that drilling fluid components greatly affect the filter cake characteristics. There is a shortage of information on spatial distribution of cake layer structure in the literature. In addition, many questions persist about not only the mechanisms underlying leak-off but also ways to mitigate the leak-off when drilling with high-temperature high-pressure (HTHP) water-based drilling fluids. To optimize the performance of filtration control, an adequate understanding of the characteristics of cake layers is crucial. The objective of this