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Drilling Unconventional Shale with Innovative Water-Based Mud – Part II: Mud Formulations and Performance

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Abstract

Shale gas plays and other unconventional resources have gained significant importance worldwide. Historically, synthetic-based drilling fluids (SBM) are preferred for performance when environmental concerns allow and may be required where wellbore stability demands are high. This paper presents an improved water-based drilling fluid (WBM) that is simple in formulation and maintenance that shows excellent rheological properties, maintains wellbore stability, and has a good environmental profile. Well-known and economically affordable materials are combined with new nanotechnology to achieve desired rheological properties and wellbore stability.

The use of nanoparticles to decrease shale permeability by physically plugging nanoscale pores holds the potential to remove a major hurdle in efficiently applying WBM in drilling shale formations. This study focuses on silica nanomaterials. Leveraging their commercial availability, these materials can be engineered to meet the specifications of the formation. Characterization of the nanoparticles was completed with Transmission Electron Microscopy (TEM), rheological properties and fluid loss together with other important properties such as shale stability and anti-accretion properties. New laboratory methods are described which were used to investigate mud properties ranging from typical rheology profiles and fluid loss tests to the Shale Membrane Test that measures both fluid loss and plugging effects.

Introduction

Natural gas plays a very important role in the U.S. energy supply. The development of gas plays, such as the Barnett or Marcellus shale, has been pushed by rising energy prices as a result of depleting conventional fields around the world. The need to find local sources of energy and lower the dependency on foreign oil is becoming increasingly important.

Shale gas is a natural gas produced from shale formations that typically acts as both a reservoir and source rock for the natural gas. Geologically, it is a sedimentary rock that is composed mostly of clay-sized particles. The very fine, sheet-like formation causes severe wellbore stability issues during the drilling operation.

When drilling in overbalanced conditions, mud pressure will gradually penetrate into the formation; due to a combination of saturation and low permeability, only a small volume of filtrate penetrates into the wellbore. However, the low permeability characteristic of the shale limits the deposition of a filter cake on the formation walls which would normally limit the further transmission of drilling fluid into the formation. Shales are generally not chemically reactive to water but over time even a small amount of filtrate can lead to sloughing. Exposure of more shales derive from this mechanism.

Lack of stability is an especially important factor that must be considered in horizontal drilling, which is largely used because of the ability to drain a larger expanse of the reservoir layer than a vertical well. Generally, synthetic-based drilling fluids (SBM) are the preferred systems used in these regions due to the higher stability in the formation and the higher lubricity during horizontal drilling.

Shale stability when using a water-based drilling fluid (WBM) can be achieved by minimizing the mud penetration on the wellbore or physically plugging the formation. In shale rock, commercially available fluid loss agents are not able to form a filter cake due to the low level of fluid movement into the shales and therefore do not form a protective barrier to stop the intrusion of fluid or water. Combinations of such technologies with nano-sized inert materials seem to achieve the goal quite successfully.

Background

Environmental agencies, from the U.S. EPA to local authorities, are ensuring that the operators in the gas play areas regulate their drilling operation by adhering to certain protocols and activities. The WBM described in this paper was developed with the goal of meeting the needs of these regions: low-cost, freshwater-based fluids that avoid the use of chlorides and hydrocarbons, and a straight-forward design for easy application with a minimum number of components.

Shale inhibition is critical in achieving wellbore stability with WBM. Shales, in general, have low chemical reactivity; therefore, a typical shale inhibitor such as an amine or salt has little or no effect. **Table 1** represents the typical geological composition and properties of Marcellus shale. The CEC value and the smectite percentage are relatively low indicating low reactivity.

The low permeability and saturation characteristic of the shales will not allow for filtrate to penetrate and equilibrate the pressure at the wellbore. Consequently, this creates a less stable wellbore condition. In **Figure 1**, a well-preserved Marcellus core was exposed to freshwater at 150°F. After several days, fractures with widths between 5 and 45 μm were observed, primarily parallel to the bedding plane. These results illustrate how the Marcellus shale does not show a reactive profile with water but is still prone to fracture, which can lead to wellbore instability especially when drilling along the formation planes.

Table 1. Marcellus Shale Composition*	
Smectite (%)	4
Illite (%)	25
Quartz (%)	47
Feldspar (%)	10
Pyrite (%)	5
Chlorite (%)	6
Ankerite (%)	3
CEC (meq/100 g)	3
Permeability @ 3000 psi (nD)	19
Permeability @ 6000 psi (nD)	6
Porosity (%)	10
Total organic content (%)	9
*Core taken from 6711.05 to 6711.6 ft	

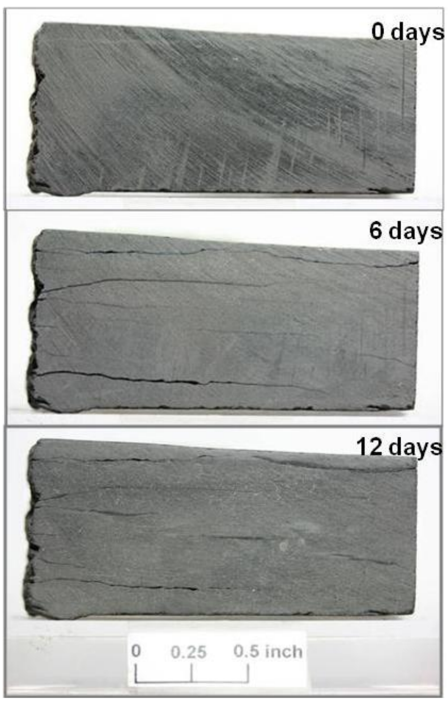

Figure 1 – Marcellus shale micro-fracturing in freshwater at 150°F.

Nanoparticles and Nanosilica

Traditionally, nanoparticles have been defined as objects with a diameter less than 100 nm. The recognition that particles might be nano in one or two dimensions, but not in all dimensions has lead to other proposed definitions including those based more on the surface area than the diameter, but no clear size cut-offs exist.

Silica is the common name for silica dioxide (SiO_2) which is found in different forms: amorphous or crystalline, porous and non-porous, anhydrous and hydroxylated. From a structural point of view, the Si atom is in tetrahedral coordination with 4 atoms of oxygen. Silica is mainly synthesized from an aqueous solution, by dissociating monomeric silic acid or from the vapor of a silicon compound; many other synthesis routes are also available. **Figure 2** shows several methods available in the industry to produce silica.

Traditional dispersions of nanosilica are made with two phases: a dispersed and a continuous phase. If the formed dispersion is not stabilized, then the particles will agglomerate and precipitate. Typically, dispersants are used to prevent the phase separation through steric or electrostatic means after being absorbed onto the dispersed particles. Typical examples of surface modifying groups are silanes, organic acids, or even alcohols. A different method increases the viscosity of the continuous phase, thus preventing the separation of dispersions.

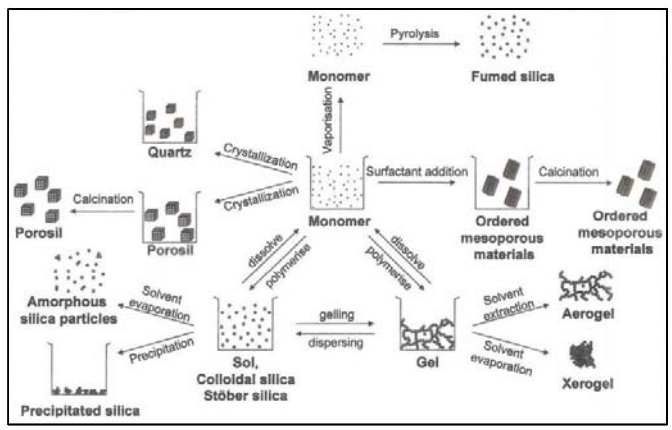

Figure 2 – Available industrial methods to produce silica.[1]

Research Approach

The use of nanosilica particle solutions was investigated as a plugging tool to decrease the penetration of water into the nanometer-sized pores in the shales. The design of such additives must consider factors such as economics, compatibility with the other mud additives without changing the rheology, thermal stability, and be able to withstand contamination with solids.

Nanosilica solutions are widely used in several industries, are available in a large variety of sizes, from 5 to 100 nm, and use different suspension packages. The effect on the performance depends greatly on both size and suspension package. **Figure 3** shows a cryo Transmission Electron Microscope (TEM) of two different nanosilica particles with the same particle size but different stabilization/suspension packages. It is clear that one has a more ordered aspect than the other which could help conform better in the pore spaces.

The surfactant-based suspension package could greatly impact the rheology of the drilling fluid, potentially leading to syneresis or gelling in the pore space in a worst case scenario. All of these aspects were taken in consideration in the choice of the candidates selected for testing.

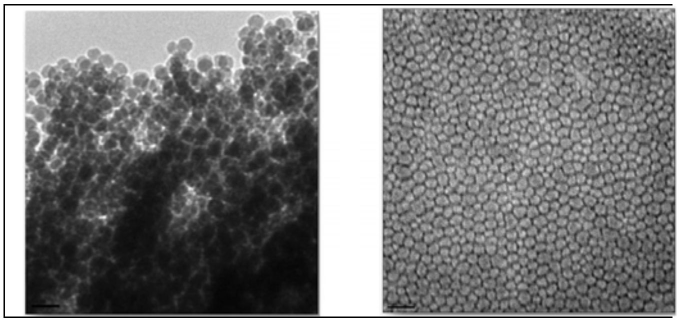

Figure 3 – TEM image of two 20-nm nanosilica samples.

Fluid Properties and Test Equipment

While SBMs can easily be applied in nearly every shale play where environmental regulations and economics permit, a typical WBM cannot. WBMs are much more chemically active and sensitive to temperature, salinity, pH, and contaminants. To minimize these effects, WBMs are customized to the particular target formation. Drilling fluid design must consider not only performance but also environmental, economic and logistic issues.

The water-based drilling fluid with nanosilica (nano-WBM), that was developed to achieve the goals described, is a freshwater-based drilling fluid in which components target specific properties and ease of use by the operator. Freshwater was chosen to avoid the chlorides which would be environmentally problematic for land drilling operations. The viscosity package is a derivative of a natural polymer and provides the desired rheology profile with a low-end rheology able to suspend drilling cutting. The fluid-loss package is comprised of a blend of water-dispersible polymers, which together with the nanoparticles, physically plugs the formation pores. Finally, the system contains a lubricant package as well as encapsulation for cuttings. The construction of the fluid was such that each one of these components could be adjusted easily on the rig according to the needs of the operator. The nanosilica was added at a volume of 10.5 lb/bbl as the optimal dosage.

A typical rheology profile for the nano-WBM is shown in **Table 2**. The fluid was heat aged for 16 hours at 150°F and then rheology measured on a Fann 35 viscometer.

Table 2 – Typical Rheology Profile* for nano-WBM for Shale Gas Plays

600 rpm Dial Reading	120
300 rpm Dial Reading	46
200 rpm Dial Reading	36
100 rpm Dial Reading	24
6 rpm Dial Reading	8
3 rpm Dial Reading	6
10-s Gel (lb/100 ft^2)	6
10-min Gel (lb/100 ft^2)	8
PV (cP)	28
YP (lb/100 ft^2)	18
HTHP @ 250F	5 ml
*Aged 16 hr at 150°F	

The HTHP fluid loss was tested on filter paper, but the real advantages of the nano-WBM are explained later on using the SMT machine. Several other studies were conducted where the nano-WBM fluid was contaminated with OCMA clay (10 and 35 lb/bbl), cement (15 lb/bbl) and Rev Dust (35 lb/bbl). The fluid was hot rolled at 150°F for 16 hours before the fluid properties were tested. As shown in **Table 3**, there was little or no effect in the rheology profile due to contamination.

Table 3 – Effect of Contamination on nano-WBM After Heat Aging

	OCMA 10 lb/bbl	OCMA 35 lb/bbl	Cement 15 lb/bbl	Rev Dust 35 lb/bbl
600 rpm	67	72	70	79
300 rpm	45	48	46	54
200 rpm	40	39	38	41
100 rpm	26	28	27	28
6 rpm	8	11	9	9
3 rpm	6	9	7	7
10-s Gel	9	10	9	7
10-min Gel	10	12	11	10
PV	22	24	24	25
YP	23	24	22	29
*Aged 16 hr at 150°F				

Lubricity is a very important parameter that was considered in the study due to the long, extended-reach characteristic of these wells. The nano-WBM system used a low cost, general-purpose lubricant achieving 25% reduction in torque in the lab (**Figure 4**). The choice of the lubricant can be changed depending on availability and location of the well.

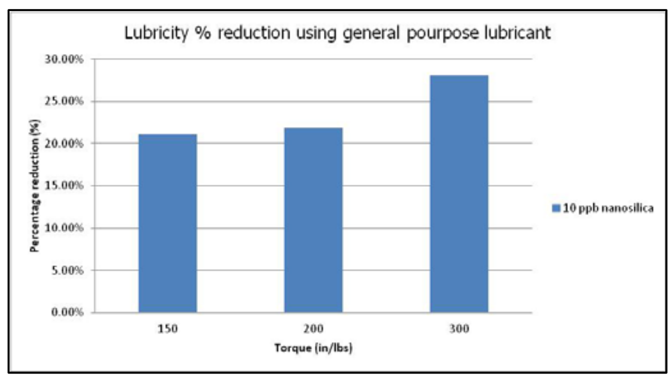

Figure 4 – Lubricity study using a general-purpose lubricant.

A Shale Membrane Test (SMT),[2] or pressure penetration test, was used to study the effect of physical plugging on shales with the nanosilica particles. In the SMT apparatus (**Figure 5**), a test fluid is pumped to flow across the top surface of a shale sample at a constant pressure (P2, P3), while measuring the pressure buildup in the bottom reservoir (P1). Shale sample permeability for the test fluid can be interpreted from buildup of the bottom pressure (P1). Permeability changes (as measured by lack of pressure transmission to the bottom of the test cell) with respect to various test fluids (brine and the nano-WBM) using the same shale sample, are treated as indicators of physical plugging by solids and nanosilica particles in the WBM. The more significant the permeability reduction between the WBM and initial brine, the better the physical plugging by the solids and nanoparticles and the more stable the shale is to exposure to the drilling fluid.

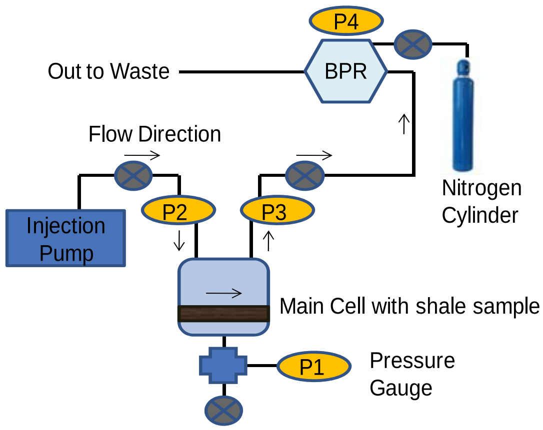

Figure 5 – Schematic of Shale Membrane Tester.

Typically, brine and WBM are tested in a SMT test. Brine is tested first to determine the initial permeability of the shale sample. The mud is then tested in order to evaluate the performance of the physical plugging for the mud. The test procedure is a follows:

- Fill the reservoir with a brine solution to match the shale a_W (water activity) of the shale
- Apply a back pressure of 50 psi (P1) and top pressure (P2) of 300 psi
- Measure the bottom pressure (P1) for pore fluid (brine) pressure transmission for initial shale permeability
- Displacement of upstream fluid with test solution (mud)
- Measure the change in bottom pressure for fluid pressure transmission for shale post-plugging permeability

Figure 6 shows the effect of several concentrations of nanosilica using Atoka shales.[3]

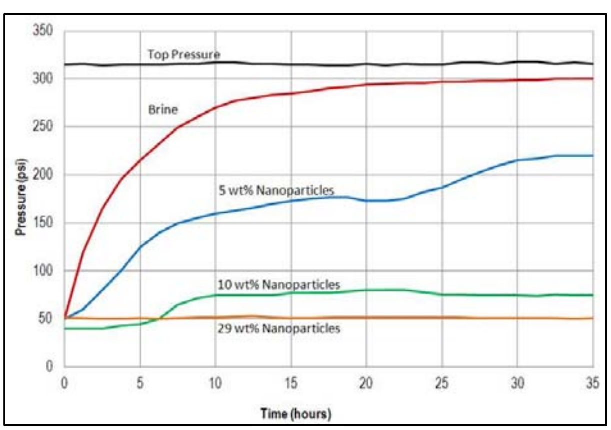

Figure 6 – Plugging effect with different nanosilica concentrations.

As the concentration of nanosilica was increased from 5 to 29 Vol%, an increase in plugging properties was observed. However, such a high dosage would not be practical in the field. The system described in this paper uses only 3 vol % and the main results are shown in **Figure 7**.

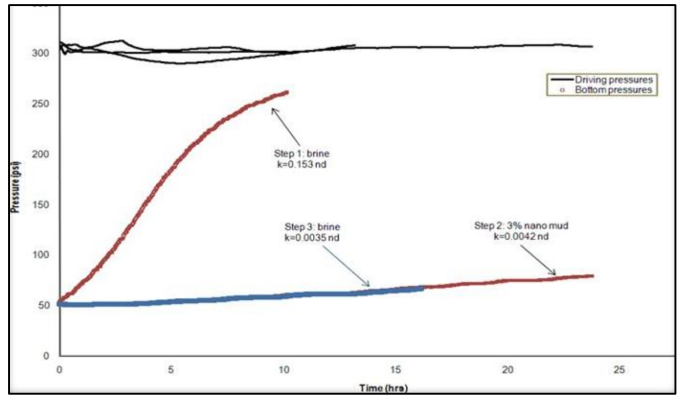

Figure 7 – Experimental results using nano-WBM.

In Step 1, the shale was tested with a 4% NaCl solution, which has the same a_w as the shale sample itself. After 10 hours with a 250-psi pressure differential, the bottom fluid pressure had increased due to fluid transmission across the shale sample and gradually equilibrated with the top driving pressure.

In Step 2, the brine was displaced with a conventional WBM, for comparison purposes.

In Step 3, the brine was displaced with the nano-WBM and after 25 hours at 250-psi pressure differential, there no pressure transmission. This shows that the shale has been properly sealed.

In Step 4, the drilling fluid was once more displaced with a 4% solution of NaCl brine and the test repeated. There was no bottom pressure transmission that registered. This meant that the shale had been physically plugged and that the plugging was sustainable.

The permeability was calculated and a 97.2% decrease in permeability was achieved using the nano-WBM (**Table 4**). This significant permeability reduction proves that there is excellent physical plugging with the nano-WBM. With the nano-WBM, very little water invaded into the shale, which would prevent problems such as shale swelling in the field. Therefore, shale stability can be effectively maintained during drilling with this mud.

Table 4 – Permeability Reduction

Step	Test Fluid	Permeability (nD)	Permeability Reduction (%)
1	4% NaCl Brine	0.153	-
2	WBM without nanosilica	0.035	77.1%
3	Nano-WBM with 3% w/v of nanosilica	0.0042	97.2%
4	4% NaCl Brine	0.0035	97.6%

The nanosilica material showed also a good synergic effect when larger fractures are present. Consider a typical Texas gas shale where fractures of 10-50 µm are present **(Figure 8**) and high permeability would be expected. The composition of this low-reactive clay gas shale is shown in **Table 5**.

Figure 8 – Picture of a Texas gas shale. The fracture shown is 35 µm.

Table 5 – Typical Texas Gas Shale Composition	
Smectite (%)	4
Illite (%)	10
Calcite (%)	62
Quartz (%)	21
Pyrite (%)	2
Siderite (%)	1
CEC, meq/100 g	3

Even in these conditions when a core sample is tested through the SMT, we see a physical plugging of the shale reducing dramatically any pressure transmission. **Figure 9** shows such results. It is immediately visible that 4% NaCl brine is passed through the shale very quickly, within minutes due to the large, interconnected fractures in the sample. When a WBM system without nanoparticles is added, an initial reduction in pressure transmission is seen, however after 14 hours the pressure transmission increases dramatically. When the nano-WBM (10.5-lb/bbl nanosilica) is run, the pores are physically plugged.

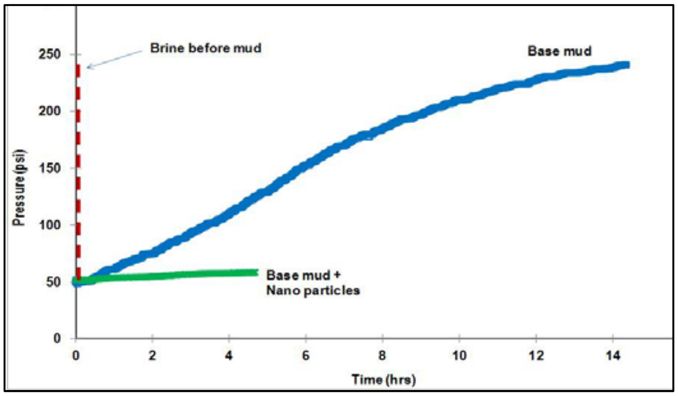

Figure 9 – SMT result on Texas gas shale.

Conclusions

The use of an improved water-based drilling fluid with nanosilica particles (nano-WBM) that is simple in formulation and maintenance shows excellent rheological properties, maintains wellbore stability, and provides a good environmental profile has been developed and lab tested. A combination of well-known and economically affordable material is combined with new nanomaterials to achieve desired rheological properties and wellbore stability in shale gas plays.

Acknowledgments

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Nomenclature

Aw = *water activity*
SBM = *Synthetic-Based Drilling Fluid*
SMT = *Shale Membrane Test*
TEM = *Transmission Electron Microscope*
WBM = *Water-Based Drilling Fluid*

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