Rheological and flow analysis of water-based drilling slurry

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Abstract

This research article deals with the experimental analysis of the rheology and flow properties such as pressure gradient, wall shear stress etc. of the water based drilling slurry. For the water based drilling slurry, combination of the water with bentonite, as primary additive, forms the base solution. Along with bentonite effect of other additives has also been analyzed. These slurries are basically non-Newtonian in nature. Rheological measurements have been carried out by the Marsh funnel and the flow analysis has been carried out by pipeline setup. Rheological measurement of water-bentonite slurry for bentonite at various concentrations (0%, 2%, 4%, 5%) with & without other additives have been carried out. Comparison between the theoretical and experimental results of pressure gradients for various drilling slurries has been also presented. for various values of drilling slurry velocity

Keywords: Water-bentonite suspension, additives, oil well drilling, rheology, wear rate.

Introduction

Slurry flow through pipes is one of the very important industrial situations. Amongst the various types of slurries two types of slurry namely; Water-fly ash slurry and water-bentonite slurry are very important. Flow of the water-fly ash is part of the fly ash disposal system in the thermal power plants. Whereas water-bentonite slurry form the basic constituent of the water-based drilling fluids which is like blood for the oil and gas well drilling process in oil and gas industries.

Water – bentonite suspensions is a vital part of the most of the water based drilling fluids used by the oil and gas well drilling industries. There is always a trial to find the newer additives which can alter the rheology and hydraulic features of the water – bentonite suspensions. Such additives should promote the cutting transport properties of the drilling fluids, should reduce the pump power requirements, to provide the strength to the drilling fluids to suspend the cuttings generated etc. like multiple targets. It is important thus to study both rheology and hydraulic aspects of the drilling fluids considering the effects of various additives.

To some degree, flow of drilling fluids can be related to the slurry transportation through pipeline. There are common aspects to both of these types of flow systems. The reduction of the frictional losses and maintenance of turbulent flow situation are common amongst the various common aspects. In the last 5o years researchers primary area of interest is to reduce the pressure drop and hence energy consumption in the slurry pipeline system. The frictional pressure drop can be reduced by modifying slurry rheological properties. Basically additives bring out change in the rheology which further culminates in the form of the improvement in the transportation efficiency[1-4]. By addition of the caustic soda and by addition of the domestic use detergent powder there is reduction in the friction losses of the slurry flow[4,5]. This is going to be useful for incorporation of these additives for the case of drilling fluid flow, carrying the cuttings generated while drilling process, through the drill pipes.

Apart from this the various researches have been carried out already to explore rheological aspects of water – bentonite suspensions. Guria *et al.* have used Marsh funnel device [Marsh, 1931] and developed a procedure to obtain yield point, apparent viscosity and plastic viscosity of drilling fluid etc.[2] Balhoff *et. al.* had developed new model for the same purpose using the drainage time data obtained from the Marsh funnel and had worked for various non-Newtonian fluids[6,7]. Mahato *et al.* have done rheological behavior investigations for an eco-friendly drilling fluid such as tamarind gum PAC etc on water based drilling suspensions. They have presented a method for calculation of the wall shear rate in turbulent flow through pipe by the design of turbulent flow viscometers[9].

Regarding the study of the flow and rheology of the water – bentonite based composition drilling fluid with various additives have been discussed by many researches from various angle of vision. Dolz *et al.* considered the bentonite concentration from the range of 6–12% bentonite with different amount of the CMC sodium carboxymethyl cellulose. He studied thixotropy as well as the flow behavior also and obtained yielded an empirical formula indicating shear stress as a function of the formulation concentrations of bentonite and sodium carboxymethyl cellulose, stirring time and shear rate. Still the bentonite particle used for the sample preparation was of the colloidal range. This implies the amount of sandiness is very minimal in the bentonite[10].

Problem description: Understanding the importance of the rheology, presence of the turbulence in the flow and importance of the wall shear stress in the drilling fluid flow, these features have been explored as target. Usually only one out of these three aspects is presented in the various works by the researchers. But, authors feel that there is need to present all these three aspects together to see the interplay of the addition of the additives in the drillings fluids.

The followings aspects have been explored for the water–bentonite slurries: i. Rheological properties of the water–bentonite slurries and effects of additives on the slurry. ii. Experimental determination of flow parameters, such as pressure gradient and wall shear stress etc., for the flow of the water–bentonite slurries and effects of additives on this parameter.

Experimental

Rheology of fluid is complex for non Newtonian as compare to Newtonian fluid. In Newtonian fluid plot between shear stress and shear rate is straight line, so a constant viscosity is obtained. But in non Newtonian case is different. Rheology property is basically is yield point, apparent viscosity, plastic viscosity. Density measurement for both cases is same. Rheology measurement can be taking from Rheometer, Fan 35, Marsh funnel. In this experiment Marsh funnel was used. To mathematically describe the rheology of a fluid, a constitutive equation must be chosen and the empirical constants (e.g. m, n') must be determined by experimentally[8].

Marsh funnel has been used for the rheological analysis of the drilling slurry. In the Marsh funnel rheological measurements, the drainage volume flow rate of suspension volume of 1500 cm^3 is measured. This becomes the basis for rheological properties of the fluid being measured. Rheological properties had been measured based on the procedure adopted by Guria *et al.* using the marsh funnel apparatus[7]. Slurry samples under considerations are given in Table-1.

**Table-1:** Sample details for rheological and flow analysis.

Sample No	Water	Bentonite	Additives
A	Remaining	2 % wt/wt	--
B	Remaining	4 % wt/wt	--
C	Remaining	5 % wt/wt	--
D	Remaining	5 % wt/wt	0.2 % wt/wt Na_2Co3 (Caustic Soda)
E	Remaining	5 % wt/wt	0.3 % wt/wt Na_2Co3 (Caustic Soda)
F	Remaining	5 % wt/wt	0.3 % wt/wt Na_2Co3 (Caustic Soda) + 0.015 wt/wt Tide Detergent

Bentonite powder sample has been considered to be of the 300 micron size based on the D_{75} criteria (i.e. almost 75 % of the sample is in the range of 300 – 150 microns sieve size.). The particle size distribution in cumulative and individual manner is shown in the table 2 as obtained from the sieve analysis.

Particle sizes of the bentonite chosen are very categorically taken above the 30 μm size. Particle sizes lower than this cause a colloidal solution of the bentonite with water. Thus bentonite works as viscosifying agent as well as helpful to provide gel strength and thus enhances the cutting carrying capacity of the drilling fluids. But higher particle size needs more turbulence levels to be in the suspension. Such large size particles do not provide the viscosifying effect to the water. Thus if proper turbulence level is not maintained then it will form a heterogeneous slurry with the water. Thus considering the situation of the slurry flow the additives are chosen which reduces the frictional losses for the slurry transportation of the minerals[4,5].

**Table-2:** Particle size distribution of the bentonite sample taken (1 kg).

Sieve size (μm)	Particle size	Weight(gm) crossed	Cumulative % passed the screen
>300	300	1000	100.00
300-150	150	747.5	74.75
150-63	63	127	12.70
63-53	53	80	8.00
53-45	45	33.1	3.30
45-38	38	12.5	1.25
<38	<38	0	0.00
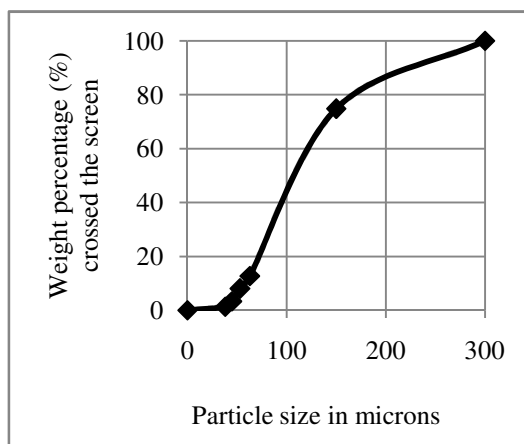
Rheological measurements have been conducted based on the procedure of the works of Guria *et al.* by using the Marsh funnel see Figure-1(a) and 1(b)[7]. This is well known device used for practical quick estimation of the drilling fluid viscous properties. Complete details such as assumptions, procedure and mathematical descriptions etc. are available in the research works Guria *et al.* and Balhoff et al.[7, 8].

(a) Marsh funnel used in rheology experimentation
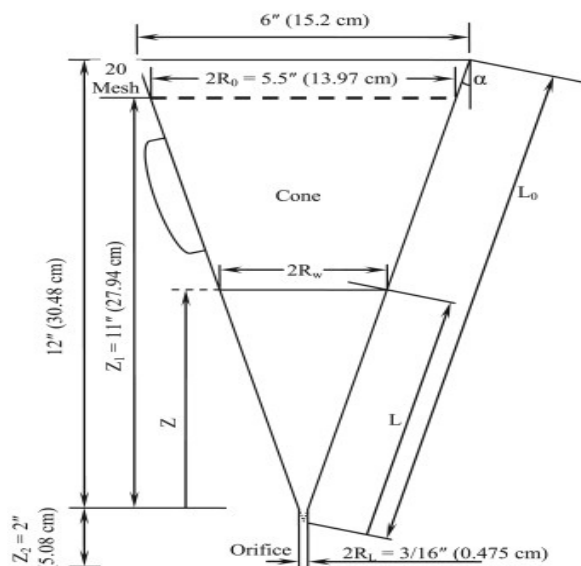
(b) Dimensions of the Marsh funnel[13]

Figure-1: Schematic of the standard Marsh funnel used (presently) along with dimensions.

Pressure drop experimentation was conducted in a pilot plant test loop, whose schematic diagram is shown in Figure-2. The test loop has been developed to conduct the pressure drop studies for particulate slurries at different concentrations with different velocities with and without the addition of additives. The primary components of pilot plant test loop are centrifugal pump, pipeline, slurry tank, flow measuring tank, pressure gauges, flexible pipe. A 1 hp self priming centrifugal Mud pump (Kirloskar Pvt. Ltd make) is installed on the pump base of 2.5 feet, 2.5 feet and 3 feet length, breadth and height respectively[11-13].

A 7 meter MS pipe with 40 mm diameter connection is done in between the pump and mixing tank. The test section is kept 4 m length for a significant pressure drop measurement [Chandel *et.al.* 2009]. The pressure gauge of 2 bar capacity with 0.025 mm accuracy is welded in the MS pipe. The pressure gauge of 1 bar capacity with 0.025 mm accuracy welded at the end of the test piece. The slurry tank (mixing tank) is made of 0.715 meter diameter with 0.50 meter height with a capacity of 200 liters. The flow measuring tank is marked with different capacity of 15 L, 60 L and 100 L for velocity calculation.

Results and discussion

According the objectives of this research work, the results have also been organized in the same fashion. First, the rheological analysis of the water-bentonite slurry suspensions using the Marsh funeel has been discussed. In the second section, Flow analysis using the pipe flow experimentations have been dealt with.

Rheology of the water-bentonite slurry with and without additives: Rheological characteristics of the water – bentonite slurry depends upon the particle size of the bentonite taken and obviously on the type and amount of the additives (if any). The rheological data for the various samples has been tested and curve fitted in the power – law model for the non-Newtonian fluid. Thus consistency index, power law index, apparent viscosity and plastic viscosity are the parameters requited to define the behaviors of these samples. These rheological parameters are shown in the Table-3.

Rheology experiments for all the six samples A to F viz. bentonite 2%, 4%, 5% (wt/wt) and different concentration of additives 0.2% Na2CO3, 0.3% Na2CO3, (.3% Na2CO3+.15% Tide) in 5% (wt/wt) bentonite is carried out. Afterwards, flow behaviour index (n') values are calculated from figure 3 and 4, using the curve fitting methods. These have been table in the table 3 for all the samples A to F. The average values of n for 2.0%, 4.0%, 5% (wt/wt) Bentonite loading are calculated and found to be 0.511, 0.52 and 0.535 respectively. For different concentration of additives 0.2% Na_2CO_3, 0.3% Na_2CO_3 and 0.3% Na_2CO_3 + 0.15% Tide in 5% (wt/wt) bentonite are calculated and found to be 0.535, 0.5344 and 0.53384.

Marsh Funnel consistency plots (i.e. wall shear stress vs. wall shear rate) have been generated for all the suspension using funnel readings. These have not been shown due to its being procedural part. From these consistency plots for all suspensions the rheology parameters like apparent viscosity (μ_a) and plastic viscosity (μ_p) have been calculated and are reported in the Table-3.

Table-3: Rheological parameters of the samples taken.

| Sample no	Density	Power law relation	Apparent viscosity $\mu_a(cP)$	Plastic viscosity $\mu_a(cP)$
A Bentonite 2% (wt/wt)	982	$\tau_w = 0.92586\ \Upsilon^{0.511}$	16.85	32.55
B Bentonite 4% (wt/wt)	995	$\tau_w = 0.881093\ \Upsilon^{0.52}$	17.46	36.13
C Bentonite 5% (wt/wt)	1010	$\tau_w = 0.848193\ \Upsilon^{0.535}$	19.22	48.45
D Bentonite 5% (wt/wt) + 0.2% (wt/wt) (Na2CO3)	1012	$\tau_w = 0.843184\Upsilon^{0.535}$	18.97	49.4
E Bentonite 5% (wt/wt) + 0.3% (wt/wt) (Na2CO3)	1015	$\tau_w = 0.837366\ \Upsilon^{0.5344}$	18.53	42.29
F Bentonite 5% (wt/wt) + 0.3% (wt/wt) (Na2CO3) + 0.015% (wt/wt)	1016	$\tau_w = 0.828356\ \Upsilon^{0.53384}$	17.96	31.05
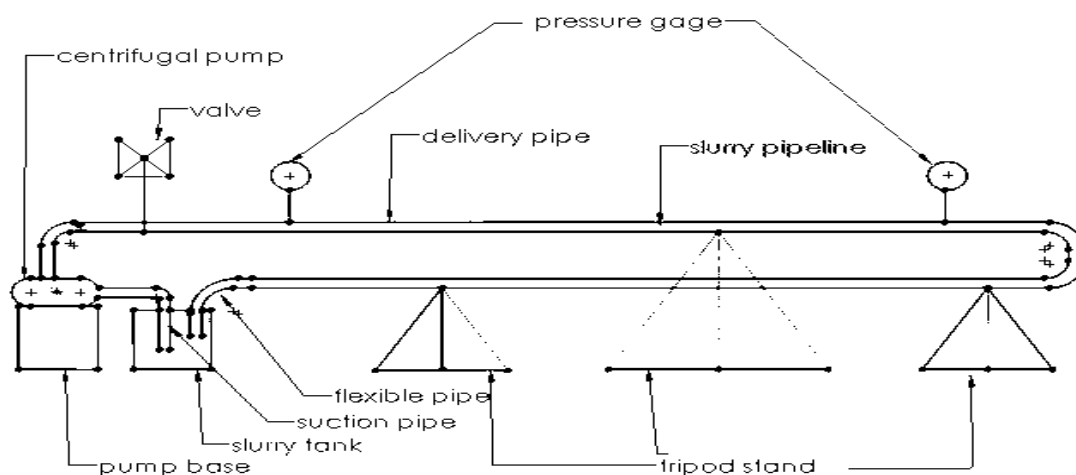
Figure-2: Schematic diagram of pilot plant test loop for experiments.
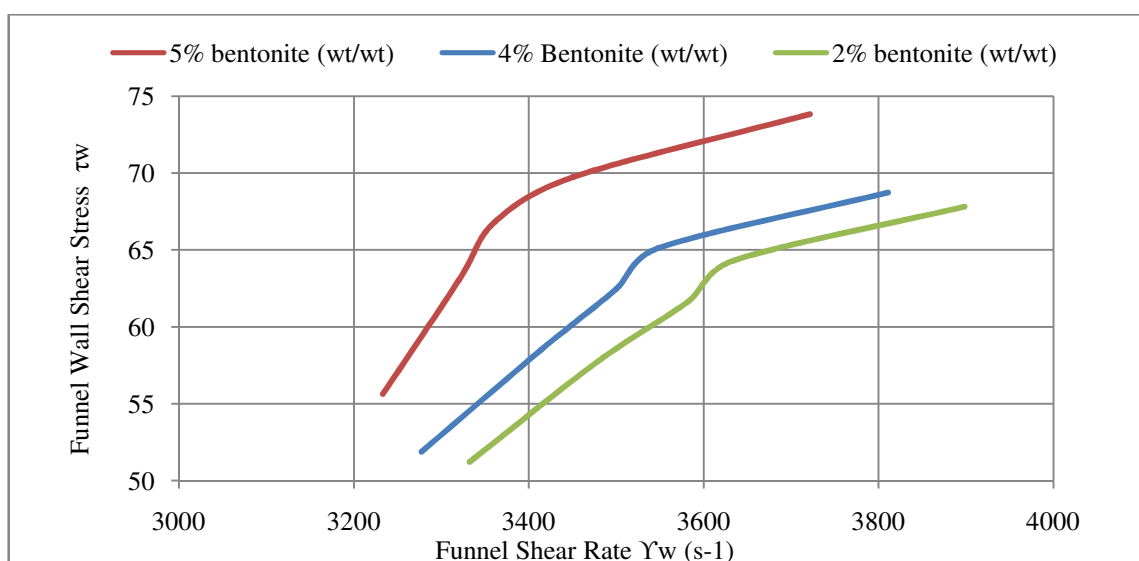

Figure-3: Wall Shear stress vs. wall shear rate for different samples as obtained from the Marsh funnel [without additives].

Experimental determination of flow parameters for water-bentonite slurry: The various flow parameters such as the pressure gradients, wall shear stress, and friction factor have obtained after due experimentations and calculations followed it. These have been experimented for all the samples which were representatives of without additives and with additives cases.

The pipe flow experiments are repeated at different concentration like 0%, 2%, 4% and 5% bentonite (wt/wt). Pressure drop is measured for five different mean velocities is shown in table 4 and table 5. The experiments with bentonite-water slurry with additives are carried out at 0.1%, 0.2% and 0.3% of sodium carbonate (Na_2Co3) and 0.015% of tide detergent.

The time taken to fill the flow measuring is noted down by the help of a stopwatch. Again at each concentration velocity is varied to know how pressure drop reacts with changes in velocity. The pressure drop is measured at each concentration with different velocities in the pressure gauge mounted on the pipe at a distance of 4 m length. From the result it is found that decrease in velocity, pressure drop also decreases. As compared to 2% (wt/wt) bentonite, the pressure drop for Bentonite 4 % (wt/wt) water slurry at any particular velocity is higher is shown in Figure-5. Wall shear stress and Coefficient of friction (f) is also increases by increasing the concentration of bentonite as shown in the Figure-6 and Table-4 and 5.

The analytical result of pressure gradient almost confirms the experimental results for all the cases. At particular velocity of fluid pressure gradient of analytical result is more to experimental results of water 100%, Bentonite 2%, 4%, 5% (wt/wt) and with additives in 5% (wt/wt) Bentonite 0.2%(wt/wt)

Na_2CO_3, 0.3%(wt/wt) Na_2CO_3, 0.3%(wt/wt) Na_2CO_3+ 0.15% Tide as shown Table-4 and table 5.

Conclusion

The experimental procedures have been developed to construct the rheology properties from Marsh Funnel readings for several concentrations of bentonite-water slurry and pressure variation through pipe. At the outset of the experiment the apparent viscosity and plastic viscosity have obtained from consistency plot knowing wall shear stresses at shear rates. At the end a mathematical model is generated in power law form to show the fluid in term of equation for water-bentonite slurry.

The pressure drop for various concentrations (0%, 2%, 4%, 5% and with additives) is measured. Again the velocity is varied between 1.9 to 3.2 m/s for each concentration and pressure drop is measured. The pressure drop for all Bentonite slurry and water is calculated theoretically and compared with the experimental data. Pressure drop increases with increase in velocity for Bentonite slurry flow through pipe. After increasing the concentration of Bentonite to 2% to 4%, 4% to 5% pressure drop increases. By mixing of additives in 5% Bentonite pressure drop deceases with increasing the quantity of additives. Wall shear stress and Coefficient of friction (f) is also increases by increasing the concentration of Bentonite. At the end analytical result of pressure gradient slightly differ for all the cases.

Following are recommended as some of the future works: i. Experiment can be performed for fluid which follow Herschel Bulkley model. ii. Different types of chemical additives can be mixed at higher concentration to save more specific energy consumption. iii. Experiments can be performed for different type's slurry like coal water and sand water slurry.
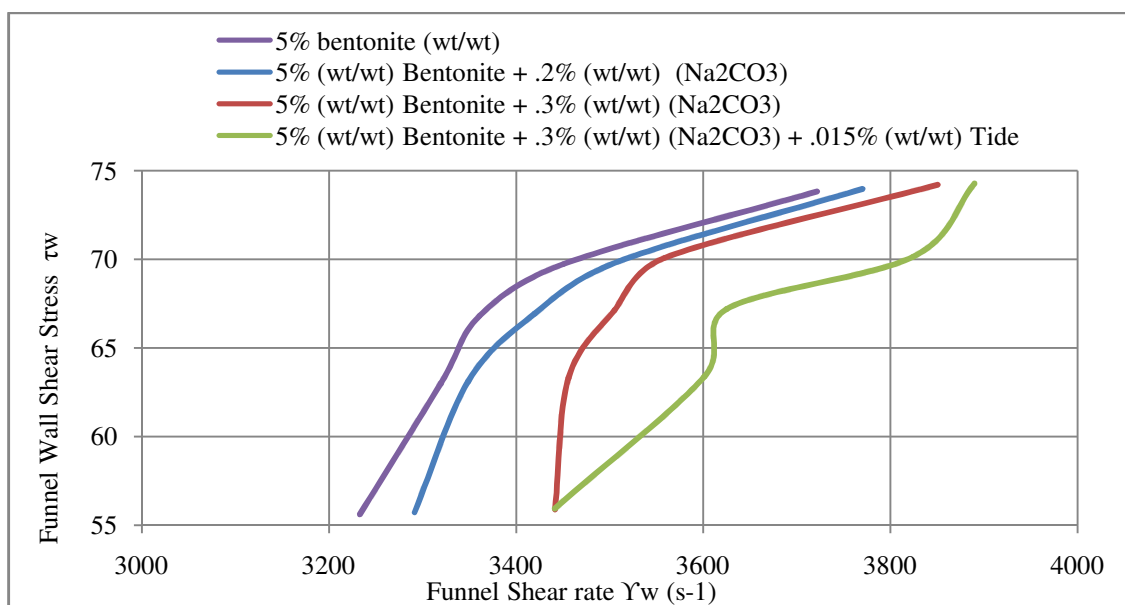

Figure-4: Wall Shear stress vs. wall shear rate for different samples as obtained from the Marsh funnel [with additives].
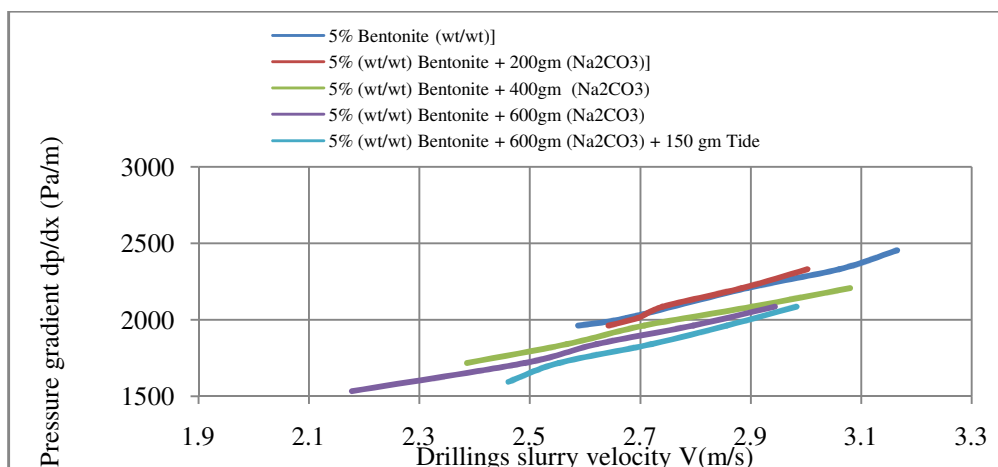
Figure-5: Pressure gradient variation with drilling slurry velocity for different samples [with and without additives].
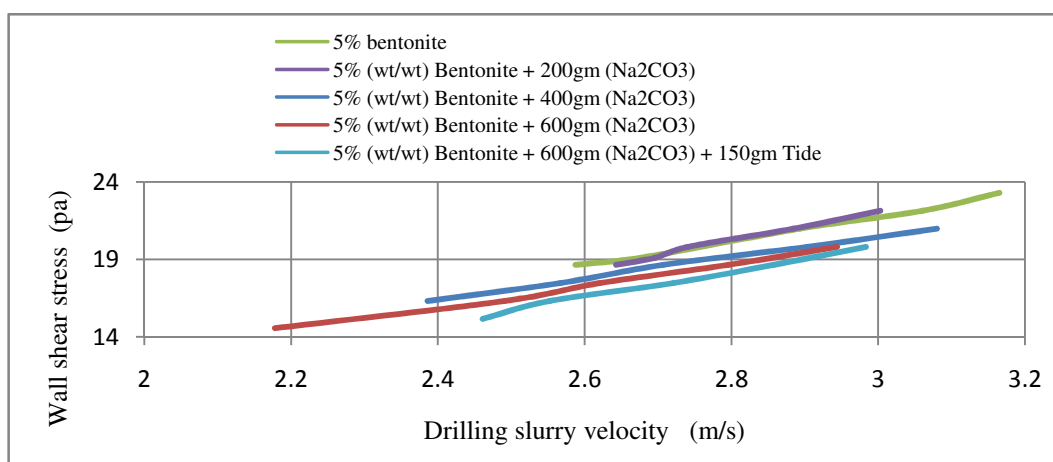

Figure-6: Wall shear stress variation with drilling slurry velocity for different samples [with and without additives].

Table-4: Effect of drilling slurry velocity on τ_w, f and pressure gradient for pipe flow [without additives].

Fluid	V(m/s)	τ_w	f	Experimental dp/dx	Theoretical dp/dx
Water 100%	2.697929	17.47406	0.004449	1661.628	1839.375
	2.56387	16.59413	0.004506	1519.842	1746.75
	2.336129	15.14419	0.004612	1291.516	1594.125
	2.115622	12.81431	0.004727	1085.793	1348.875
	1.9717	10.48444	0.004811	959.8471	1103.625
Bentonite 2% (wt/wt)	2.99	19.807	0.0055	2085	2541.34
	2.81	16.302	0.0057	1716	2326.19
	2.63	14.744	0.0058	1552	2073.46
	2.41	12.806	0.00606	1348	1801.12
	1.98	9.319	0.0064	981	1296.78
Bentonite 4% (wt/wt)	2.93	19.807	0.00578	2085	2598
	2.78	17.467	0.00588	1838.7	2347
	2.54	15.200	0.00606	1600	2027
	2.427	13.660	0.00616	1437.9	1881
	2.099	12.232	0.00646	1287.6	1480
Bentonite 5% (wt/wt)	3.164839	23.29875	0.005903	2452.5	3142.942
	3.060129	22.13381	0.005968	2329.875	2970.818
	2.893093	20.96888	0.006079	2207.25	2704.619
	2.675972	19.10498	0.006237	2011.05	2374.31
	2.587175	18.639	0.006308	1962	2244.408

Table-5: Effect of drilling slurry velocity on τ_w , f and pressure gradient for pipe flow [with additives].

Fluid	V(m/s)	τ_w	f	Experimental *dp/dx*	Theoretical *dp/dx*
5% (wt/wt) Bentonite + 400gm (Na$_2$CO$_3$)	3.080053	20.96888	0.005926	2207.25	2994.418
	2.90283	19.80394	0.006042	2084.625	2711.758
	2.707121	18.639	0.006183	1962	2413.311
	2.566895	17.47406	0.006293	1839.375	2208.412
	2.385923	16.30913	0.006449	1716.75	1955.263
Bentonite 5% (wt/wt) + 600gm Na$_2$CO$_3$	2.943732	19.80394	0.005959	2084.625	2758.448
	2.795629	18.639	0.00606	1962	2530.283
	2.620791	17.47406	0.006191	1839.375	2271.576
	2.490733	16.30913	0.006296	1716.75	2086.708
	2.17767	14.56172	0.006587	1532.813	1668.796
Bentonite 5% (wt/wt) + 600gm Na$_2$CO$_3$+Tide	2.983065	19.80394	0.005867	2084.625	2791.639
	2.856963	18.639	0.00595	1962	2596.879
	2.720468	17.47406	0.006046	1839.375	2392.7
	2.552276	16.30913	0.006175	1716.75	2150.79
	2.460889	15.14419	0.00625	1594.125	2023.861

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