Transport Properties of Offshore Discharged Synthetic Based Drilling Cuttings

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Abstract-The general purpose of the present study was to study the transport properties of offshore discharged drilling cuttings produced with synthetic based drilling fluids (SBFs). The transport mechanisms include flocculation and settling. For this reason, a digital imaging system was developed to observe the time variation of floc size distribution under a variety of combinations of fluid shear, solid concentration, and salinity. The system was also employed to measure the settling velocities of both aggregated flocs and individual drilling cuttings particles of different shapes. The samples used in this study were collected from a production oil well on the east coast of Canada. Thermal treated samples were also used to study the effects of oleophyllic components on the transport properties. From the experiments, it was shown that the untreated cuttings flocculate faster and have much larger steady state median floc diameter than thermal treated cuttings due to the bridge effect of oleophyllic components. For the same cuttings, the steady state median floc diameter and time needed to reach steady state decreased as the fluid shear, solid concentration, and salinity increased. The settling velocity of flocs was found to be a function of both floc diameter and fluid shear. The settling velocity increased as the fluid shear increased. The solid concentration had no distinguishable effects on the settling of flocs in this study. The flocs produced from thermal treated cuttings settled faster than those produced from untreated cuttings. For individual particles with diameters larger than 0.1mm, the equations of settling velocity were derived for both untreated and thermal treated cuttings particles. It was demonstrated by the experiments that the particle shape significantly affects the settling velocity of thermal treated cuttings particles of this size range, while it has no effects on the untreated cuttings particles. For cuttings with the same density, treated cuttings settles faster than untreated cuttings. Experimental results are presented and discussed in the paper.

I. INTRODUCTION

The exploration and extraction of offshore oil and gas from beneath the ocean floor requires the use of drilling fluids to lubricate the drill bit, lift the rock cuttings to the surface, and control the well pressure. Depending on the type of base fluid used, drilling fluids can be generally classified as water-based fluids (WBFs), oil-based fluids (OBFs), and synthetic-based fluids (SBFs).

With the use of WBF, the fluids and drilling cuttings are typically discharged on site. As the US EPA's effluent limitations guidelines (ELGs) prohibit the release of free oil, OBFs and SBFs are recycled, with only drilling cuttings and a small amount of associated drilling fluids being discharged [1].

The transport of discharged drilling wastes in the marine environment is controlled by various transport mechanisms, which may include advection, dispersion, flocculation, settling, deposition, consolidation, and re-suspension.

With the discharge of WBFs, the drilling wastes generally originate as a jet of materials with some initial buoyancy and momentum. As the density of discharged jet is higher than ambient seawater, it descends through the water column, entrains ambient seawater, grows in diameter and bends in the direction of ambient currents. Due to these effects, the particles of various sizes and shapes start to settle out. When the plume encounters the seabed or becomes neutrally buoyant from the loss of solids and water entrainment, it will collapse and spread out into a thin layer. After this point, the plume goes into a stage of passive diffusion [2]. When discharged to the ocean, the OBFs and SBFs cuttings tend to clump together in discrete masses that settle rapidly to the bottom and do not disperse efficiently [3] [4]. The degree of aggregation depends on the amount of fluids retained on cuttings.

Flocculation occurs as a result of particle relative motions due to the turbulence of seawater and different settling velocities.

The settling of drilling cuttings particles in the ocean is a result of gravitational forces, viscous drag on the particles, and inter-particle interactions. The settling velocity usually depends on the size, density, shape, and microstructure of the particle. The time-dependent flocculation and the suspension concentration also affect the settling velocity.

As a result of these effects, most of the discharged materials are deposited to the seafloor near the well site. The distance from the discharge point depends on the depth of water, lateral transport, and cuttings characteristics. The time that the settled material remains at the well site depends on the water depth and energy regimes that govern the re-suspension process [5].

The discharge of these waste materials can result in either physical impacts, such as burial or smothering of benthic fauna and flora, or toxic impacts, such as reduced growth rate and increased mortality [5]. To give operators and regulatory agencies the capability of predicting the fate of drilling discharges under a variety of ocean conditions, a number of drilling waste transport models have been developed. The ultimate accuracy of prediction models is strongly dependent on the transport mechanisms, especially the settling and flocculation as they occur throughout all the transport stages. The sensitivity analysis [6] has shown that the model prediction can be quite different (0.5 – 1.5 km) by using different settling velocity equations. Most of the available models use simplified settling velocity equations that assume cuttings are spherical and of a limited range of size. The physical properties of drilling cuttings, which have a great influence on the settling velocity, have not been incorporated into these available settling velocity equations. The flocculation, which is important as it changes the particle size distribution, density, microstructure, and therefore the settling velocity, was not considered by most models.

Although a considerable amount of work has been conducted concerning the settling velocity of irregularly

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shaped natural particles, very few experimental studies using real drilling cuttings have been reported. Hussaini [7] tested the settling velocity of real drilling cuttings (only two sizes were studied) in various drilling fluids. Delvigne [3] measured the settling velocity of OBFs contaminated drilling cuttings in a sedimentation balance filled with quiescent seawater. It was shown from the experiments that drilling cuttings with the same density but different oil concentrations have different settling behavior. The shape effect on settling was not characterized in Delvigne's [3] study. Carles [8] investigated the settling velocity of drilling cuttings (WBFs and SBFs) in a water tank. Although the shape effect on the settling velocity was assessed in the study, Carles [8] estimated the particle diameter and sphericity that may result in the loss of accuracy. Similar to Hussaini [7], only a very limited number of particles were measured in the study.

The flocculation of WBFs due to both fluid shear and differential settling has been studied by Huang [9] using laboratory flocculators. The settling velocity of flocs was also measured in a settling tube by a double-exposure photographic method. It was shown by Huang's [9] experiments that the settling velocity of flocs is a function of their size and the conditions at which the floc is formed. Curran et al. [10] studied the flocculation of WBFs using a re-circulating flume channel. For OBFs cuttings, Delvigne [3] tested the flocculation of this type of cuttings in a grid column. The settling velocity of cutting particles was also measured using a sediment balance approach.

SBFs are a relatively new generation of drilling fluids that were developed to have the same performance as OBFs, but with less environmental impact. The composition and structure of cuttings produced by SBFs are quite different from those produced by other types of drilling fluids and therefore their transport properties are different. This study focuses on the understanding of flocculation and settling processes of SBFs produced cuttings to provide input to transport models.

II. EXPERIMENT METHODS

The drilling cuttings used in this study were obtained from an exploration well on the east coast of Canada. Cuttings from two different depths (D-1 and D-2) were used. In order to study the effects of oleophyllic components on flocculation and settling, a portion of the cuttings was dried in an oven at 110°C for 24 hours to remove the oleophyllic mass and was then prepared for the experiments.

Fig. 1 shows a schematic diagram of the experimental system. The settling column used in this study was a plexiglas column, 14 cm inner diameter and 250 cm long. Two 500 W halogen lamps reflected off a white wall were used to illuminate the settling particles in the column. A high speed CCD camera (MotionScope PCI 1000s model) was used to capture the settling motion and save the images in a computer. The camera was mounted at 0.5 m above the bottom of the settling column, so that the particles had time enough to reach their terminal settling velocity. The CCD sensor of the camera had a resolution of 656x495 pixels with each pixel occupying 7.4 square microns. As the sizes of cutting particles used in this study ranged from several microns to several millimetres, different combinations of macro-lenses (f=12.5, 26, 75 mm) and extension tubes (10, 20, 40 mm) were used to obtain the best image quality. A scale mounted along the settling column, recorded as part of the image, was used to calibrate the image pixel resolution.

For the particles larger than 100 μm, the combinations of settling velocity tests are listed in Table 1. At the start of the experiment, the column was filled with either freshwater or artificial seawater, depending on the test conditions. The water was allowed to stabilize for 16 hours to release entrapped air bubbles. A small amount of pre-dispersed cuttings samples was then introduced into the column from the top of the settling column. The pre-dispersion of cuttings in water can prevent the entrapment of air bubbles during the introduction, which will affect the settling motion of particles. The settling motion was recorded by the CCD camera at a frame rate of 60 fames per second with a shutter speed of 1/60 second.

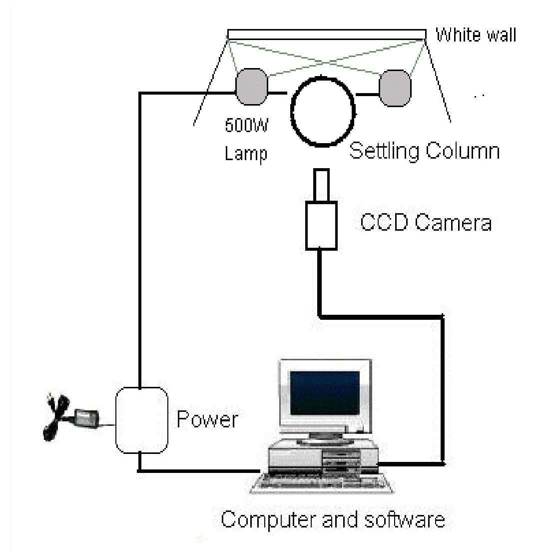

Fig. 1. Schematic diagram of settling column system

TABLE 1
COMBINATIONS FOR SETTLING COLUMN EXPERIMENT

Case	Test Conditions		
	Drill Depth	Treatment	Water
1	D-1	Untreated	Seawater
2	D-2	Untreated	Seawater
3	D-1	Untreated	Freshwater
4	D-1	Treated	Seawater
5	D-2	Treated	Seawater
6	D-1	Treated	Freshwater

The ImageJ software with a user-developed plugin was used to calculate the particle information such as diameter, sphericity, coordinate and so on. The diameter is the projected area equivalent diameter. The sphericity is the ratio of surface area of a sphere of volume equal to that of the particle and surface area of the particle. Due to the difficulty in calculating particle surface area and volume from the 2-D images obtained in this study, Wadell's [11] formula (1.1) was used to approximate the sphericity.

$$\psi = D/D_C \tag{1.1}$$

where ψ is the sphericity, D is the projected area equivalent diameter, and D_C is the diameter of the smallest circle that can circumscribe the particle. Five measurements were conducted to get a mean value for each particle.

Fig. 2 shows the schematic diagram of the flocculation system. A Phipps & Bird six-paddle stirrer was employed in this study to produce fluid shear. The paddle of this stirrer was a 2-blade flat paddle with a length of 76 mm and width of 25 mm. The stirrer had a rotating speed up to 300 RPM that could generate a wide range of fluid shear. The mean velocity gradient for this type of flocculator is given by Camp & Stein [12]

$$G = \sqrt{P/(V \cdot \mu)} \qquad (1.2)$$

where G is the mean velocity gradient, V is the volume of the suspension, μ is the dynamic viscosity, and P is the power dissipated in water, which was calculated using [13]

$$P = K_T n^3 D_a^5 \rho_f / g_C \qquad (1.3)$$

where K_T is an empirical constant, n is the rotation speed, D_a is the paddle diameter, ρ_f is the density of fluid, g_C is the Newton's-Law conversion factor [13].

At the start of the flocculation experiment, 2 L sample in a square test beaker at certain concentrations (25, 50, 100, and 200 mg/L) was loaded with the stirrer at high speed for 90 seconds to disaggregate the sample and to evenly distribute the sample. The initial particle size distribution was recorded using the high speed CCD camera at this time. The stirrer was then run at a constant speed to produce desired fluid shear values (25, 50, 100, 200 G) and a timer was started. As the experiment proceeded, the images were taken after a certain flocculation time (5, 10, 20, 40, 60, 80, 120 minutes). Over 2000 images were captured for each sampling point. The particle size distribution for each sampling point was calculated from the mean of 100 randomly selected images.

At the end of flocculation tests, the stirrer was stopped. The settling velocity of flocs were measured 30 to 120 s (depending on the rotation speed) after the termination of rotation. This length of time allowed decay of the turbulence and permitted accurate measurements of floc settling velocity. The settling velocity of flocs was obtained from the image analysis. The mean value of five measurements was used.

III. RESULTS AND DISSCUSSIONS

A. Settling Velocity of Coarse Particles

As the present experiments on particle settling velocity were conducted in a settling column rather than in an infinite medium, the surrounding boundary must be considered in order to obtain accurate results. The empirical equation [14] was selected to correct the boundary effect

$$u_{corrected} = u_{measured} / \left[1 - (D / D_{tube})^k\right] \qquad (1.4)$$

where $u_{corrected}$ and $u_{measured}$ are the corrected and measured settling velocities respectively, D_{tube} is the diameter of the settling column, the constant k is 2.25 for laminar flow and is 1.50 for turbulent flow.

Fig. 3 and Fig. 4 show the corrected settling velocity data for untreated cuttings (Case 1) and treated cuttings (Case 4) respectively. Case 2 and Case 3 are similar to Case 1 but with different settling rates due to the difference in relative density. Similarly, Case 5 and Case 6 are similar to Case 4, but with different settling rates due to the difference in relative density.

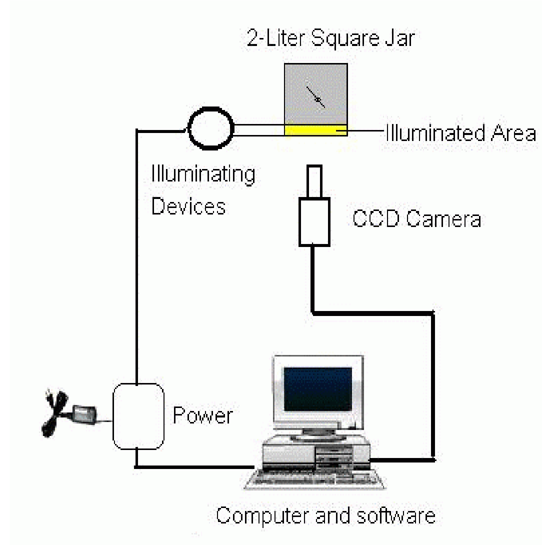

Fig. 2. Schematic diagram flocculation system

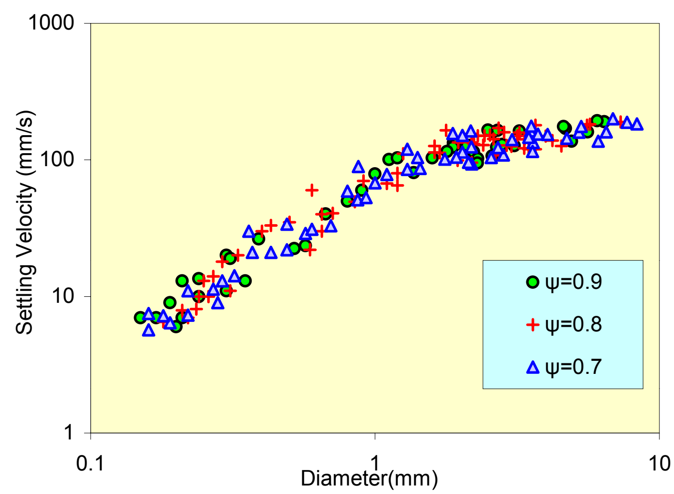

Fig. 3. Settling velocity of untreated cuttings (Case 1).

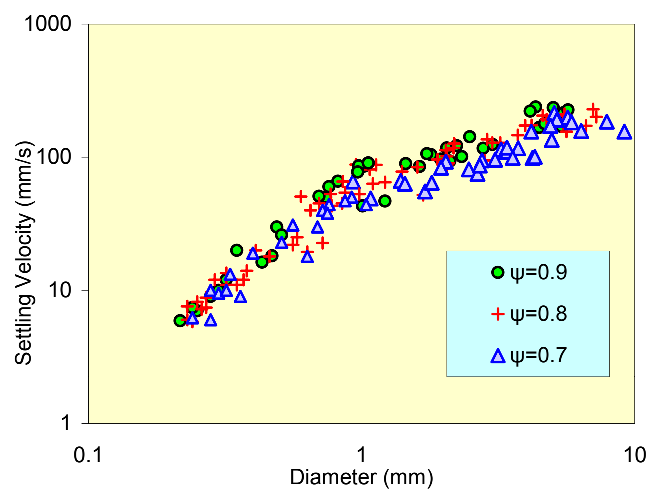

Fig. 4. Settling velocity of treated cuttings (Case 4).

Through a regression analysis of settling velocity data, it was found that the shape effect on the settling of untreated cuttings is insignificant, but it is significant on the settling of treated cuttings. The reason is that settling velocity is not only affected by particle shapes, but also by the microstructure of particles. It was observed that the untreated cuttings settle as lumps while the treated cuttings settle as individual particles. The drag forces on these porous lumps are quite different from that on solid particles, which are relatively uniform. The interaction of the microstructure and shape effect makes it difficult to find a shape effect on the settling of untreated cuttings.

As the shape effect on the settling of untreated cuttings was insignificant, the whole data for untreated cuttings were used to develop a settling velocity correlation:

$$u = \frac{-15.36\ \mu + \sqrt{236.08\ \mu^2 + 0.78\,(\rho_s - \rho_f)\rho_f D^3 g}}{\rho_f D} \qquad (1.5)$$

where u is the settling velocity (m/s), ρ_s is the drilling cutting density (kg/m^3), ρ_f is the fluid density (kg/m^3), μ is the dynamic viscosity (kg/m·s). D is the particle diameter (m), and g is the gravitational acceleration (m/s^2).

For the treated cuttings, the particle sphericity was calculated by (1.1) and the settling velocity was obtained as

$$u = \frac{-3b\mu + \sqrt{9b^2\mu^2 + 48a(\rho_s - \rho_f)\rho_f D^3 g}}{6a\rho_f D} \qquad (1.6)$$

where a, and b are dimensionless parameters which are defined as

$$a = -3.4387 + 13.8462\ \psi - 10.306\ \psi^2 \qquad (1.7)$$

$$b = 225.7155 - 406.5995\ \psi + 223.365\ \psi^2 \qquad (1.8)$$

It should be noted that (1.1) is not accurate for very flat shaped particles, especially circular disk-like particles, as they may have a very high ψ value while their actual sphericity may be very low. Therefore, (1.6) to (1.8) are not applicable for flat shaped particles. Moreover, because most of the particles had a sphericity value between 6.5 to 9.5 in this study, the suggested ψ range for (1.6) to (1.8) is 6.5 to 9.5.

Fig. 5 is a plot of (1.5) and (1.6) compared with OBFs cuttings reported by Delvigne [3]. It can be seen from Fig.5 that the OBFs cuttings have similar settling behavior as SBFs cuttings. The OBFs with higher oil concentrations (15.8% and19.5%) settle as lumps while OBFs with lower oil concentration (0.3%) settle as particles. For the same density, the settling velocity of OBFs cuttings is slightly higher than SBFs cuttings. The reason may due to the different characteristics of cuttings, e.g. fluid type, cutting structure and so on. Another reason for the difference in result is the experimental method. The instrument that used by Delvigne [3] to measure the settling velocity was a sedimentation balance, which is different from the digital imaging system used in this study.

B. Flocculation

The time variation of median floc diameter was obtained under the combination of fluid shear and solid concentration in both seawater and freshwater. It was shown by the experiments that the floc median diameter continued to increase as the flocculation proceeded until it reached steady state (Fig. 6). After this point, the floc median size stayed constant. Table 2 shows the time needed to reach steady state under fluid shear of 25 G. Table 3 gives the steady state floc median diameter under fluid shear of 25 G. Tables 2 and 3 show that increases in concentration resulted in decreases in the time to reach steady state and decreases in steady state median diameter. It was also shown by the experiments that the time to reach steady state and steady state median diameter decrease as the fluid shear increases (Fig. 6).

It can be seen from Tables 2 and 3 that untreated cuttings flocculate faster and have larger steady state median diameter than treated cuttings. The reason is that the oleophyllic components in untreated cuttings act as adhering agents that help to adhere the particles together and enhance the collision efficiency. Table 2 shows that the cuttings flocculate faster in seawater than in freshwater. Table 3 shows that the steady state median floc diameters are larger in seawater than in freshwater. The reason is that most particles in water are charged. The surface charge on a particle and the associated counter-ion charge together form an electrical double-layer. Part of the counter-ion is located close to the particle surface and the remainder is distributed more broadly, which forms a diffuser layer. When two particles approach each other, their diffuse layers overlap and a repulsion force is experienced that will reduce the collision efficiency. If sufficient salt is added (seawater condition), the particles will be destabilized and the flocculation will be enhanced as a result

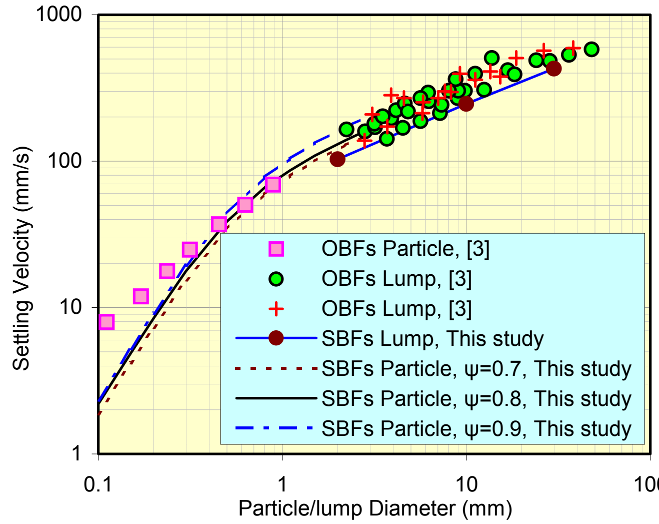

Fig. 5. Settling Velocity of drilling cuttings

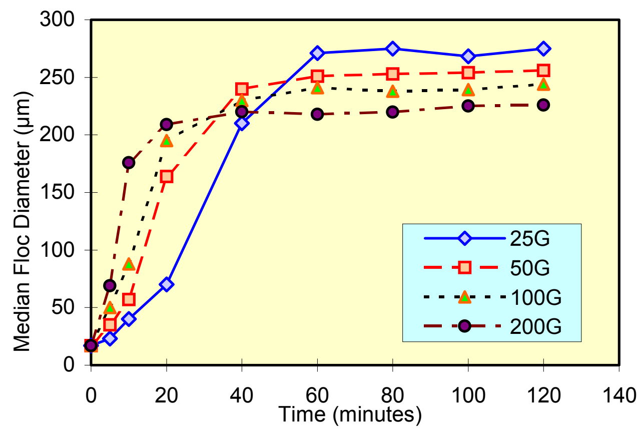

Fig. 6. Time variation of floc median diameter for untreated cuttings at 25 mg/L in seawater

of increased collision efficiency [15]. As a consequence, the time needed to reach steady state is shorter in seawater than in freshwater and the steady state median floc diameter is larger in seawater than in freshwater.

C. Settling Velocity of Flocs

Similarly to the settling column system, the settling velocity of flocs was measured in a square beaker rather than in an infinite medium. Therefore, the obtained floc settling velocity was multiplied by a correction factor of 1.03 to compensate for the wall effect [16]. A total of more than 900 measurements of floc settling velocity and the corresponding floc sizes were made.

Flocs are fragile and their density cannot be measured directly. Therefore, it is difficult to derive a settling velocity equation in the same way as for solid particles. To make the data more quantitative and informative, the power law approximation [16], as shown in (1.9), obtained by least squares regression was made for each data group (same concentration or same fluid shear) to find the effect of concentration and fluid shear.

$$u = AD^m \tag{1.9}$$

where A and m are parameters that depend on the type of particles being investigated and the conditions (e.g. concentration, fluid shear) under which the flocs were produced.

The regression results of settling velocity of flocs produced from untreated and treated cuttings are shown in (1.10) and (1.11) respectively.

$$u = 2.16 \times 10^{-5} G^{1.42} D^{2.22 G^{-0.35}} \tag{1.10}$$

$$u = 2.22 \times 10^{-4} G^{1.07} D^{1.84 G^{-0.32}} \tag{1.11}$$

From the regression result, it was shown that the settling velocity of flocs produced from SBFs cuttings in seawater is a function of both fluid shear and floc diameter. The effect of concentration on settling of flocs in this work is insignificant as the flocs produced from different concentrations have almost the same settling velocity.

The results from (1.10) and (1.11) are plotted in Fig. 7 and 8. The settling velocity of flocs produced from WBFs [9] are also plotted for reference. It can be seen from Fig. 7 and 8 that the settling velocity of flocs in seawater increases as the fluid shear increases. The reason is that the flocs formed at lower shears are fluffier, more fragile, and have lower effective densities than flocs formed at the higher shears [17]. The settling velocity curves of treated SBM flocs are close to the settling velocity curves of WBM flocs and larger than the untreated cuttings. This indicates that the flocs formed by treated cuttings have a higher density. It is also shown by Fig. 7 and 8 that the effect of fluid shear on floc settling velocity is more significant for SBFs flocs than for WBFs flocs.

IV CONCLUSIONS

Experimental investigations of the effects of the shape and oleophyllic components on the settling velocity of drilling cuttings particles with diameters larger than 100 μm were made. From the experimental data, explicit relations between the settling velocity, particle size, sphericity, and relative

TABLE 2
TIME TO REACH STEADY STATE UNDER 25 G

Concentration (mg/L)	Time (minutes)		
	Treated/ Seawater	Untreated/ Seawater	Untreated/ Freshwater
25	80	60	100
50	65	50	90
100	50	40	80
200	40	30	60

TABLE 3
STEADY STATE FLOC MEDIAN DIAMETERUNDER 25 G

Concentration (mg/L)	Diameter (μm)		
	Treated/ Seawater	Untreated/ Seawater	Untreated/ Freshwater
25	129.3	273.1	101.5
50	96.3	254.3	94.7
100	61.8	238.6	89.4
200	52.5	223.1	79.9

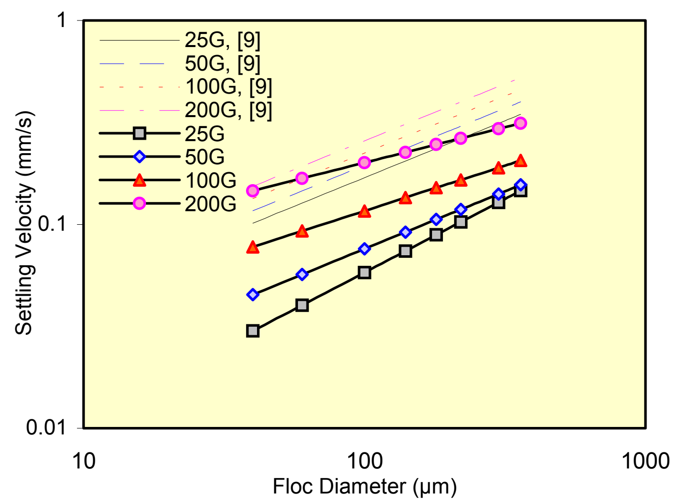

Fig. 7. Settling velocity of flocs produced from untreated cuttings

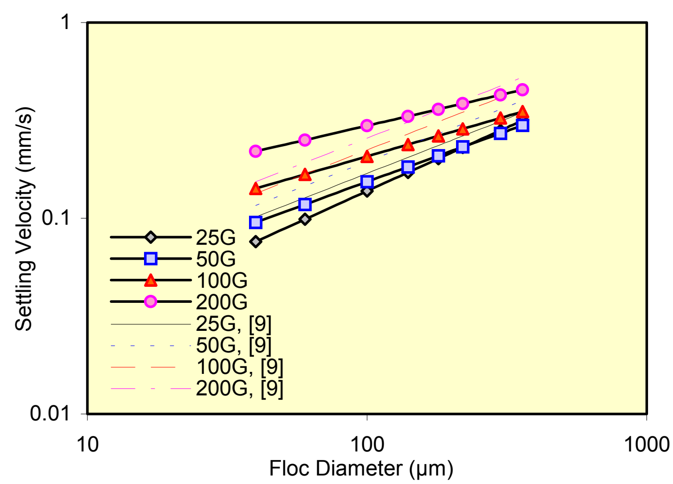

Fig. 8. Settling velocity of flocs produced from treated cuttings

density were developed. The experimental results and the developed explicit formula (1.5) show that the settling velocity of untreated drilling cuttings particles is a function of particle size, bulk density and fluid properties. It was also shown by experimental results and formulas (1.6) to (1.8) that the settling velocity of treated cuttings is a function of particle sphericity as well as size, bulk density, and fluid properties. It was demonstrated that the SBFs cuttings settle in a slightly different way from OBFs cuttings with the same bulk density.

The flocculation experiments were conducted under different combinations of fluid shear, solids concentration, salinity, and quantity of retained oily components. From the experimental results, it was found that the steady state particle size distribution depends on the conditions under which the steady state is approached. The median floc size decreases as the shear stress increases, particles flocculate faster in seawater than in freshwater, flocs are smaller in freshwater than in seawater. Flocs produced from untreated cuttings flocculate faster than treated cuttings. Flocs produced from treated cuttings are smaller than untreated cuttings.

It was shown by the floc settling experiments that the settling velocity of flocs is a function of both their size and fluid shear. The settling velocity increases as fluid shear increases.

Acknowledgments

The authors acknowledge the support from the NSERC Strategic Project entitled *Offshore Environmental Engineering using Autonomous Underwater Vehicles*.

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