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Hole cleaning and wet-granular rheology of rock cutting beds: Impact of drilling fluid composition

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ABSTRACT

Cuttings-beds formation is an issue that must be considered during all wellbore drilling operations. This problem increases at highly deviated or horizontal wells, where cuttings removal efficiency becomes one of the most critical elements for the whole drilling operations. Removal of drilled cuttings is done through circulating the drilling fluid and then separate out the cuttings at the surface. When the wellbore is inclined or horizontal, the cuttings tend to settle and form cuttings-beds. The consolidation strength of these cuttings-beds is normally unknown. Traditional studies on cuttings-bed removal usually focus on the final result: effective cuttings-bed removal. The scope of this study is to analyze the wetted cuttings-bed particle bonding strength and the stress required to break the formed bed, by means of granular rheology methodology. In other words, the strength required to erode a formed cuttings-bed is addressed independently. Wet-granular rheology techniques, complemented by Mohr-Coulomb envelop analysis has shown to be an effective approach to describe the cohesive strength of consolidated cuttings-bed and flowability of the particles within the beds. We have analyzed simulated cuttings-beds' shear strength and flowability using quartz particles saturated with water, water-based drilling fluid and oil-based drilling fluid. The results showed that the interstitial fluid and its composition significantly impact the shear strength of the bed, conveying higher cohesion for water-based drilling fluid in comparison to oil-based drilling fluids.

1. Introduction

With the increasing demand of energy production and optimization of these processes, more complex wellbores are being constructed. In particular, long extended reach horizontal wellbores are required to operate distant resources from existing facilities. Longer areas where drilled cuttings can settle are thus formed and consequently, the cuttings removal efficiency is challenged. For horizontal wells, the main driving force that dominates the transport phenomena is dragging, while lifting plays a minor role (Bizhani and Kuru, 2018). To be able to remove deposited cuttings by dragging or lifting, it is necessary to reach and if possible to exceed the critical flow velocity and shear stress threshold for bed erosion (Li and Luft, 2014). Critical flow velocity is normally calculated based on fluid property models (Okesanya et al., 2020).

The amounts of cuttings transported out has often been obtained from experimental data. Recently it has been showed that further optimization can be done through application of neural network models (Ozbayoglu et al., 2021) and CFD modeling (Naderi and Khamehchi, 2018). Nevertheless, cuttings-bed strength is not taken into consideration for these types of calculations. It is also well known, both from practical applications and from laboratory studies (Sayindla et al., 2017) that hole cleaning is more efficient if oil-based drilling fluids are used compared to if inhibitive water-based drilling fluids are used even if their viscosity profiles are similar.

Different types of drilling fluid compositions with very similar viscous properties can affect the cuttings-bed consolidation and compaction differently. Thus the agglomeration strength of particles-beds will be different and thereby also the required minimum flow rate to mobilize the particles from the bed (Rabenjafimanantsoa et al., 2005). This indicates that fluid viscous properties are not the only drilling fluid properties that should be taken into account for optimized cuttings transport efficiency (Pedrosa et al., 2021a). Also the internal cuttings-bed interaction properties between the fluid and the cuttings granules are important to understand the entire hole cleaning process.

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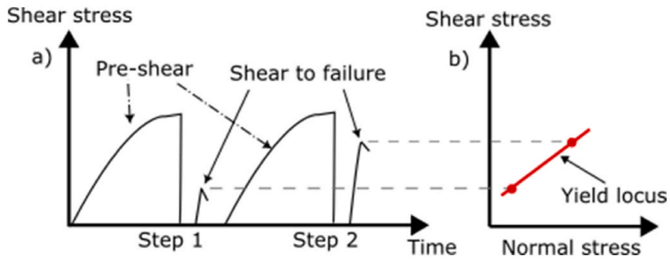

Fig. 1. Yield locus definition from shear to failure measurements.

Bulk properties of granules depend on material characteristics and size of the granulated particles. During transportation processes the material undergoes various modes of deformation and stress conditions, due to compression and shear. Wet granules are grains which size is large enough to make colloidal forces neglectable. Differently from dry particle beds, for wet particle beds the dominating interaction is cohesion due to the interfacial forces.

In the present study, the cuttings-bed internal strength is measured with granular rheology techniques that have been proven to be consistent and reproducible, to analyze the bonding forces imparted by the different fluids, however at this stage of the studies, downhole conditions such as pressure and temperature are not simulated.

These techniques include Jenike shear tester, which has been used to evaluate pneumatic transfer properties of drilled cuttings (Malagalage et al., 2018) and Schulze ring shear tester. The latter has the advantage of being a more automated process minimizing the operator influence (Shi et al., 2018). Nevertheless, it is important to note that with these techniques, as well as it will happen during field operations, prediction accuracy of cuttings transport is fluctuating due to the lack of uniformity in the particle grains (Abbas et al., 2021).

For the internal cuttings bed property measurements with the granular rheometer cell, the samples must be pre-consolidated. This is normally called “pre-shear” and is performed applying a rheometer operator defined maximum normal stress, depending on the particle size, shape and operational conditions. Then at a constant rotational speed, “shear-to-failure” points of reduced normal stress between 30 and 80% of the maximum load are performed, which will result in the bed breaking and starting to flow again. The pre-shear is done to get the sample into a repeatable state, but also at this process already is yielded information on the bed behavior under the pre-compaction stress.

The two measurements stages per cycle, “pre-shear” and “shear-to-failure” are repeated two or more times at varying conditions to record necessary data for the analysis, obtaining the yield locus as an extrapolated line from the failure points. Two measuring cycles are shown in Fig. 1a) is shown the “pre-shear” at a pre-set maximum normal stress and the “shear-to-failure” stresses observed at 30% and 80% of this pre-set maximum normal stress. These “shear-to-failure” stresses are plotted to obtain the yield locus as it is shown in Fig. 1b). The yield locus then, is used to obtain the Mohr-Coulomb failure envelop providing the information of the unconfined yield strength and the maximum principal stress.

Once the yield locus has been obtained, the two semi-circles are calculated in a different manner; one of them is obtain as a semi-circle that has a tangent to the yield locus and crosses over the origin axes, then the second crossing point of the normal stress axe is calculated to be the unconfined yield strength, which is the major principal stress level that will cause bulk material in an unconfined state to fail in shear and the other one is obtain as a semi-circle that has a tangent to the yield locus and crosses over the pre-shear measured stress, where the outset crossing point of the normal stress axe is the major principal stress. A representation of these two semi-circles is shown in Fig. 2.

The measured results are analyzed using the Mohr-Coulomb criterion, in a similar manner as often used for rock mechanics characterization as describe by for example Fjær et al. (2008) which is shown in Eq. (1). To predict the required stress for the cuttings-bed to be disturbed. Hence, to optimally remove the drilled cuttings out of the wellbore.

$$\tau = c + \sigma \tan \varphi \tag{1}$$

where τ is the shear stress, c is the cohesion, σ is the normal stress and φ is the internal friction angle. A graphical representation of the Mohr-Coulomb envelope obtained by using powder rheology is shown in Fig. 2.

Moreover, the yield locus helps to obtain two main stresses, the major principal stress (σ_1) and the unconfined yield stress (σ_c). The unconfined yield stress is calculated as the intersection of the horizontal axis and a Mohr’s-circle that goes through the origin and has as the tangent the yield locus, while the major principal stress is calculated as the higher intersection point between the horizontal axis and a Mohr’s-circle that has the yield locus as a tangent and passes through the pre-shearing point, as shown in Fig. 2.

The relationship between these two stresses provides the Flow Function Coefficient (*ffc*), as described by Jenike (Jenike and Station, 1964) in Equation. 2, which defines the flowability of the cuttings-bed. The Flow Function Coefficient defines the flow in one of the 5 different regions, which can be defined as: not flowing ($ffc < 1$), very cohesive ($1 < ffc < 2$), cohesive ($2 < ffc < 4$), easy flowing ($4 < ffc < 10$) and free flowing ($ffc > 10$).

$$ffc = \frac{\sigma_1}{\sigma_c} \tag{2}$$

Another factor that relates to particle agglomeration is the effective angle of internal friction, which is the angle at which the material will slip on its own surface considering that there is no cohesion, as seen in Fig. 2. This can also be related to the critical angle of repose θc, which is the maximum surface angle built by a piled material before it suffers spontaneous avalanche (Mehta and Barker, 1994). This angle can be analyzed through the failure criterion, where in the case of no cohesion,

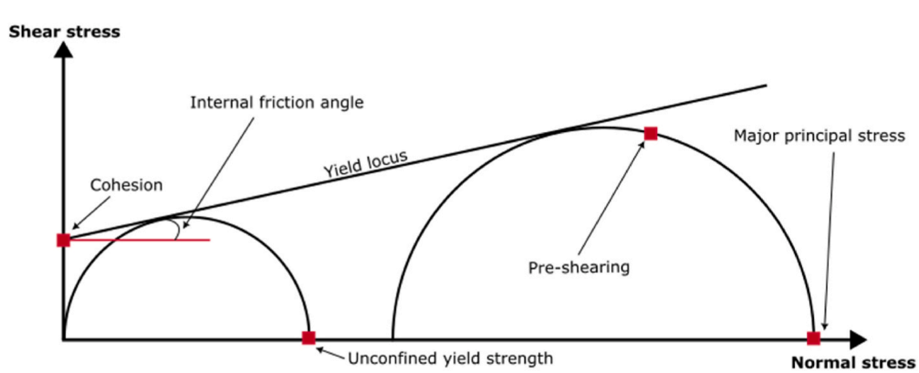

Fig. 2. Schematic diagram of powder yield locus obtained by rheometry.

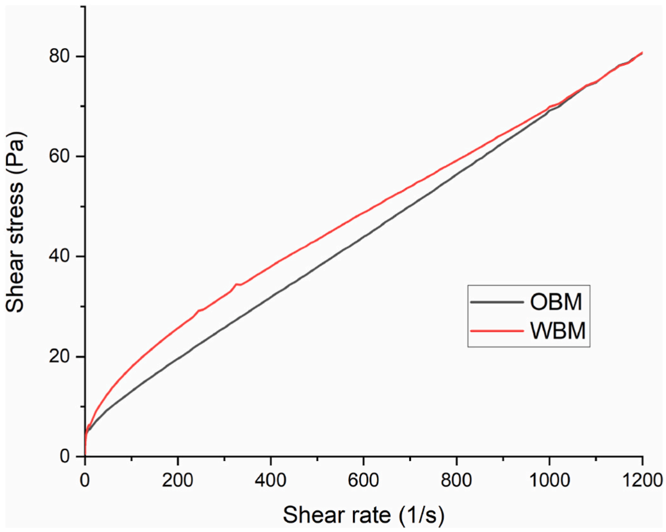

Fig. 3. Water-based (WBM) and oil-based (OBM) drilling fluids shear flow profile.

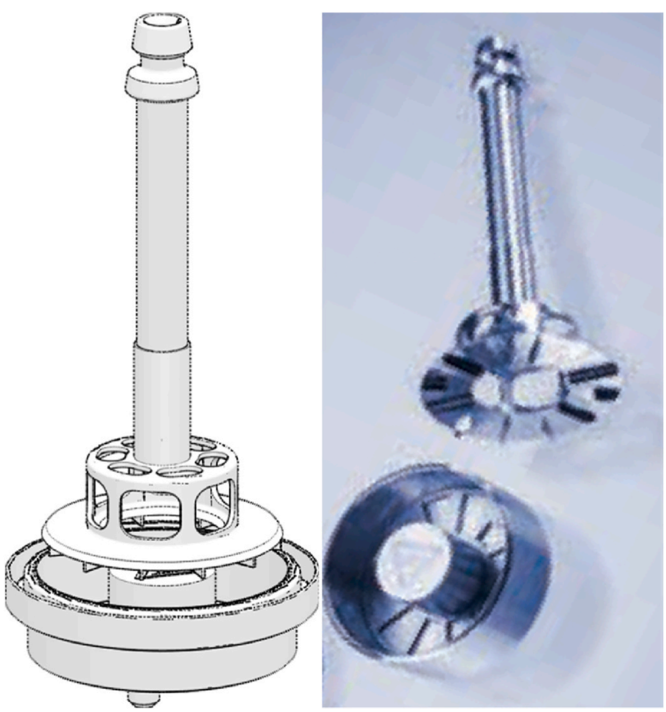

Fig. 4. Ring shear cell and the geometry which is used to consolidate and shear the sample.

the failure criterion depends on a material parameter, the internal friction coefficient μ*, as shown in Eq. (3), which can also be affected by the type of interstitial fluid used to wet the granules (Pedrosa et al., 2021b).

$$\tau > \mu^{*} \tag{3}$$

Comparing Eq. (3) and Eq. (4), the shear stress can be associated to the internal friction coefficient, thus related to the angle if internal friction.

$$\mu^{*} = \tan\varphi \tag{4}$$

In wet particles such as drilled-cuttings, the dominant attractive forces between particles are viscous forces conveyed by the interstitial fluid (Roy et al., 2017) together with capillary attraction forces and

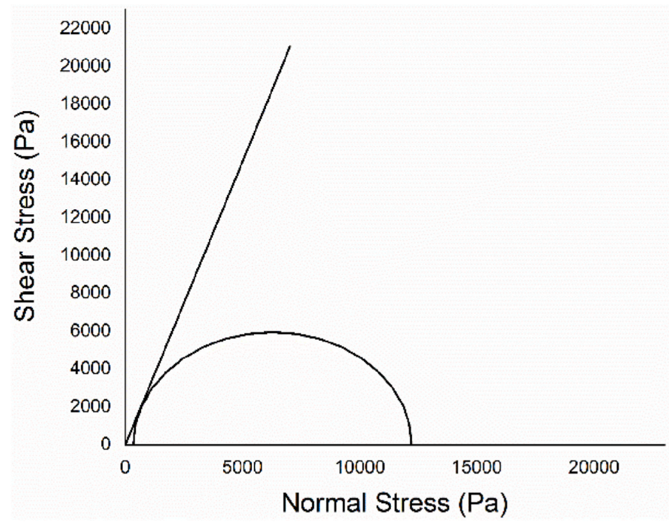

Fig. 5. Mohr-Coulomb failure envelope for dry sand consolidated under normal stress of 6 kPa.

polymer bridging, when saturation is higher than S>70%. If the saturation is lower, the dominant attractive forces are liquid bridges. Adhesive forces caused by different surface chemistry mechanisms such as van der Waals interactions and electrostatic forces are also present. Flowability is used to measure the overall strength of all these attractive forces.

Wet-granulated material such as the drilled cuttings, behave differently depending on the applied stress and particle concentration. It can behave as solid state when it is at rest or under low energy input, while it can flow like a fluid when a certain kinetic energy is reached. In the following, it is studied by using powder rheology how a wetting fluid can modify the motion and properties of the cuttings-bed, in addition to the known contributing factors such as particle size distribution, particle morphology and density (Azar and Sanchez, 1997).

2. Materials and methods

2.1. Materials

In the experiments, sand grains (quartz) of irregular shape, but from the same source with average size of 1.3 mm, sand grains were used to simulate the drilled cuttings as are the simplest type of rock formation down-hole. These particles were saturated in the first test with water. In the second test the particles were saturated with a common field applied inhibitive water-based drilling fluid with specific gravity of 1.5. This fluid contains KCl, soda ash, polyanionic cellulose, starch, xanthan gum, barite. Finally, in the last test a field applied oil-based drilling fluid with specific gravity of 1.5 containing base oil, $CaCl_2$, Clay, lime, fluid loss agents, emulsifiers, and barite was used.

2.2. Drilling fluid flow profile

The drilling fluids' viscosity profile was characterized through a flow curve. The plotted data were derived from analysis performed with a rheometer Anton-Paar MCR102, equipped with a Couette geometry holding the temperature at 25 °C. The samples were initially pre-sheared at 1000 s-1 for 120 s to reach steady-state shear viscosity. After this, a measurement protocol was started ramping down from 1200 s to 1 to 60 s-1 in 100 logarithmic steps, followed by 5 logarithmic steps from 60 s to 1 to 10 s-1, and finally with 100 logarithmic steps from 10 s to 1 to 0.1 s-1. The measuring time per point was set to 2 s. As seen in Fig. 3. The specific gravity and the flow profile of both drilling fluids are quite similar, reaching a maximum difference at a shear rate of 94 1/s of 27%.

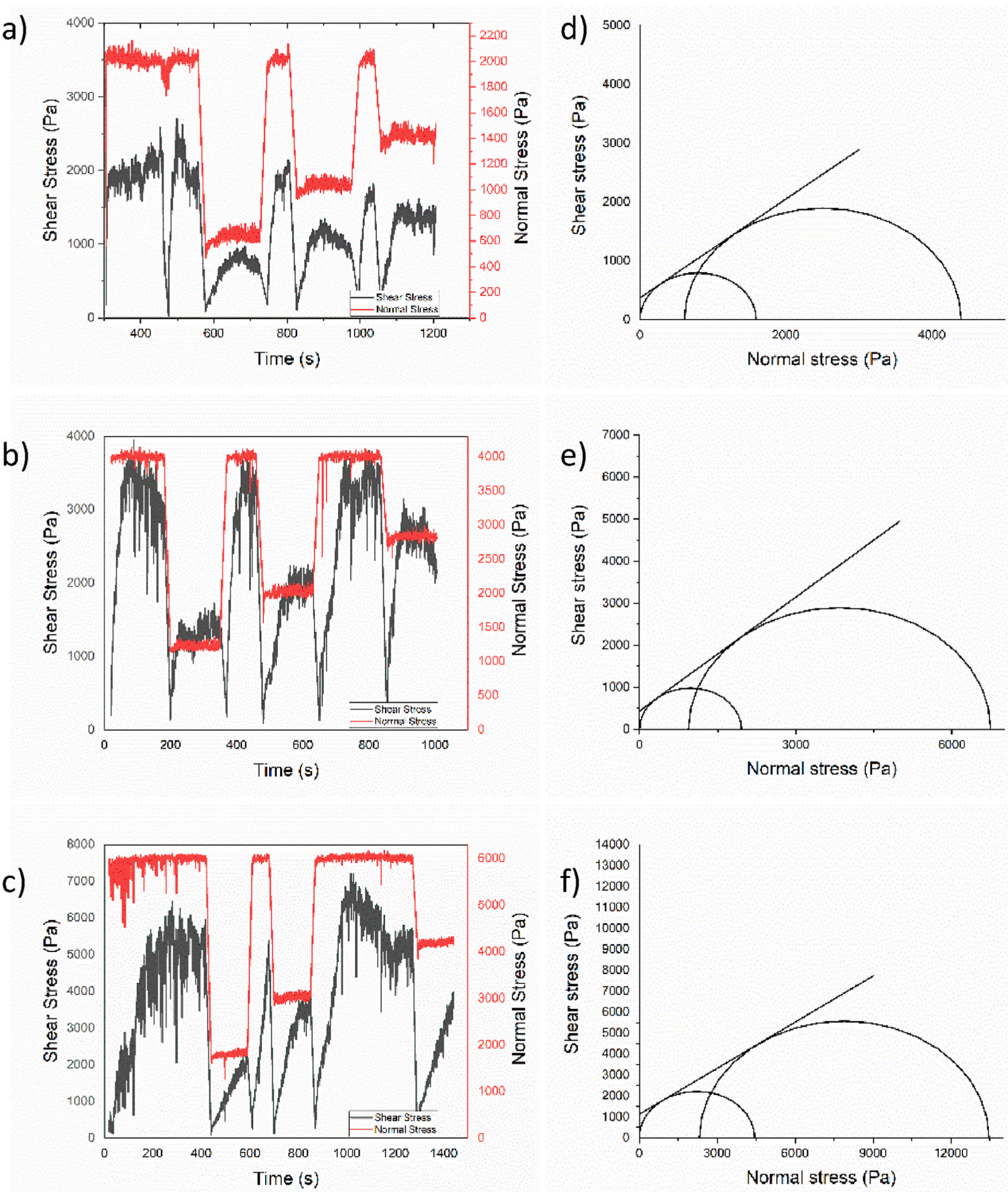

Fig. 6. Shear stress under normal stress confinement for a) 2 kPa, c)4 kPa, e) 6 kPa, and its obtained Mohr-Coulomb envelopes for b) 2 kPa, d) 4 kPa and f) 6 kPa for sand wetted by water.

2.3. Powder rheology procedure

A powder shear cell was used in a rheometer Anton-Paar MCR102 analyzing the shear for granular materials. The measurements were carried out at three different maximum normal force loads per sample. First the granules were filled into a ring shear cell to form the bed, as shown in Fig. 4. Then the bed was pre-consolidated at the maximum load by pre-shearing at a constant rotational speed of 0.005 rpm.

The maximum normal stress for this process was set to 2 kPa, 4 kPa and 6 kPa. After the pre-shear, three shear-to-failure points were performed at each of the maximum normal stresses, being 30%, 50% and 70% of the pre-shear load. At each of the pre-shear loads, the maximum shear stress, namely shear-to-failure is obtained to calculate the yield locus, cohesion, unconfined yield strength, major principal stress and internal friction angle, to perform the Mohr-Coulomb circles analysis.

For the analysis, the sand samples were placed into a centrifuge tube with the wetting fluid with a volumetric ratio of 2/3 of sand and 1/3 of fluid. Then the tube was hand-shaken for 30 s and then centrifuged for 20 min at 3000 rpm, to ensure full contact between the particles and the fluid. After this, the fluid in excess was poured out and the remaining slurry was scraped and placed into the shear cell cup.

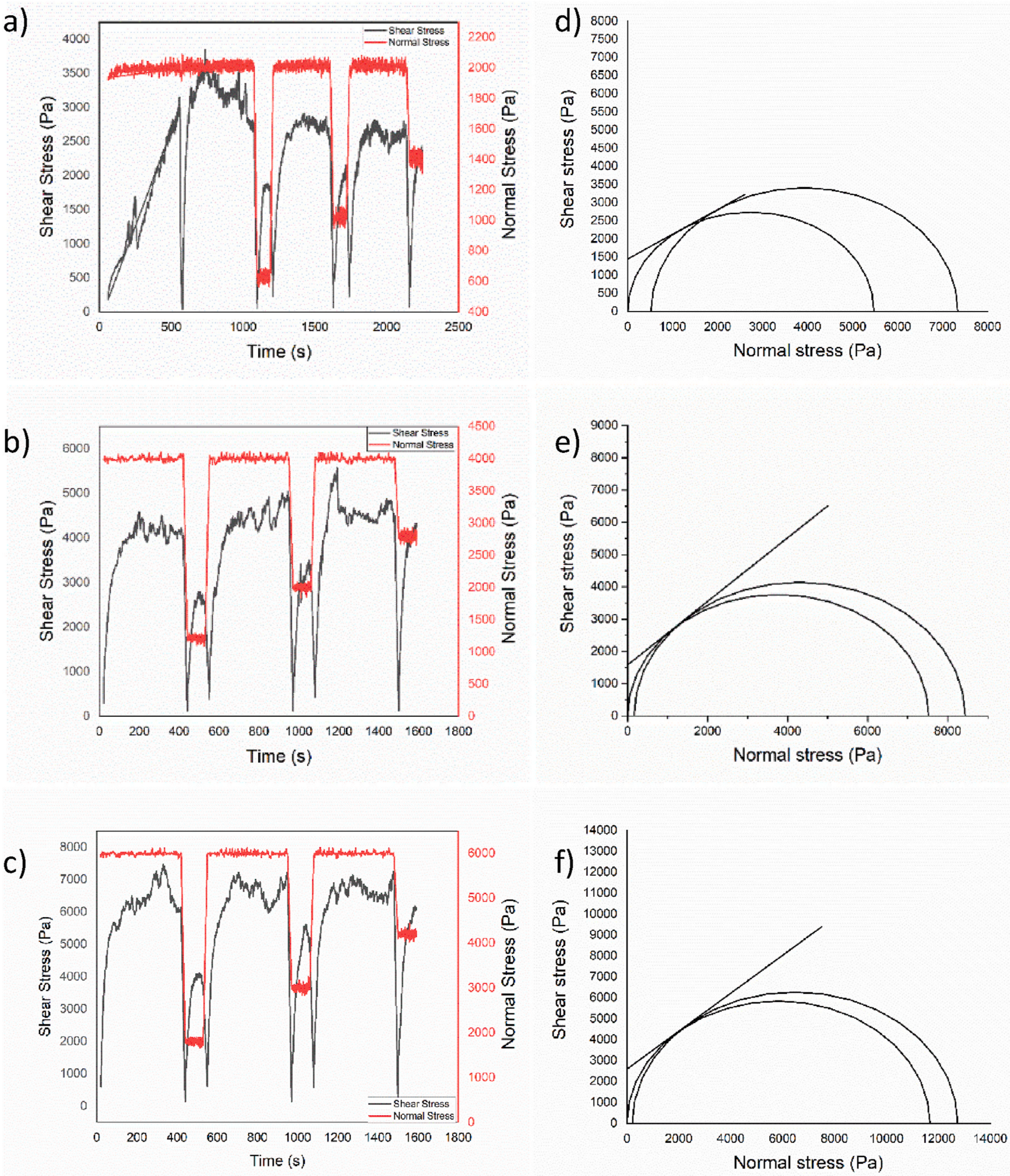

Fig. 7. Shear stress under normal stress confinement for a) 2 kPa, c)4 kPa, e) 6 kPa, and its obtained Mohr-Coulomb envelopes for b) 2 kPa, d) 4 kPa and f) 6 kPa for sand wetted by water-based drilling fluid.

3. Results and discussion

The cuttings-bed configuration strength due to cohesion (c) and tensile strength (Ts) of dry sand and sand wetted by water, water-based and oil-based drilling fluids were analyzed through Mohr-Coulomb failure envelopes, and these are presented here.

The sand grains are non-cohesive when dry (Nedderman, 1992). Nevertheless, the cohesive properties of the dry sand were measured to get a baseline (see Fig. 5) to compare it against the wetted sample results. Showing the Y intercept of the tangent line equal to zero, which indicates a cohesion (c) of 0 Pa and a tensile strength of 0 Pa, thus it can only form one circle, not being possible to obtain the unconfined yield strength therefore flowability cannot be calculated by this method.

Drilled cuttings saturated with water showed a different behavior compared to that of the dry samples. In Fig. 6, a), c) and e) is shown the shear stress during the pre-shear at maximum normal stress, followed by shear-to-failure at 30% of the normal stress. Again, the sample was pre-sheared at maximum stress, followed by shear-to-failure at the normal stress being 50% of the maximum normal stress and finally another pre-shear followed by shear-to-failure at 80% of the maximum normal stress. Where the points to find the yield locus were obtained from the maximum shear stress at the three different shear-to-failure stresses, and in parts b), d) and f) is the yield locus with the and the complete Mohr-Coulomb failure envelope for the three different confining normal

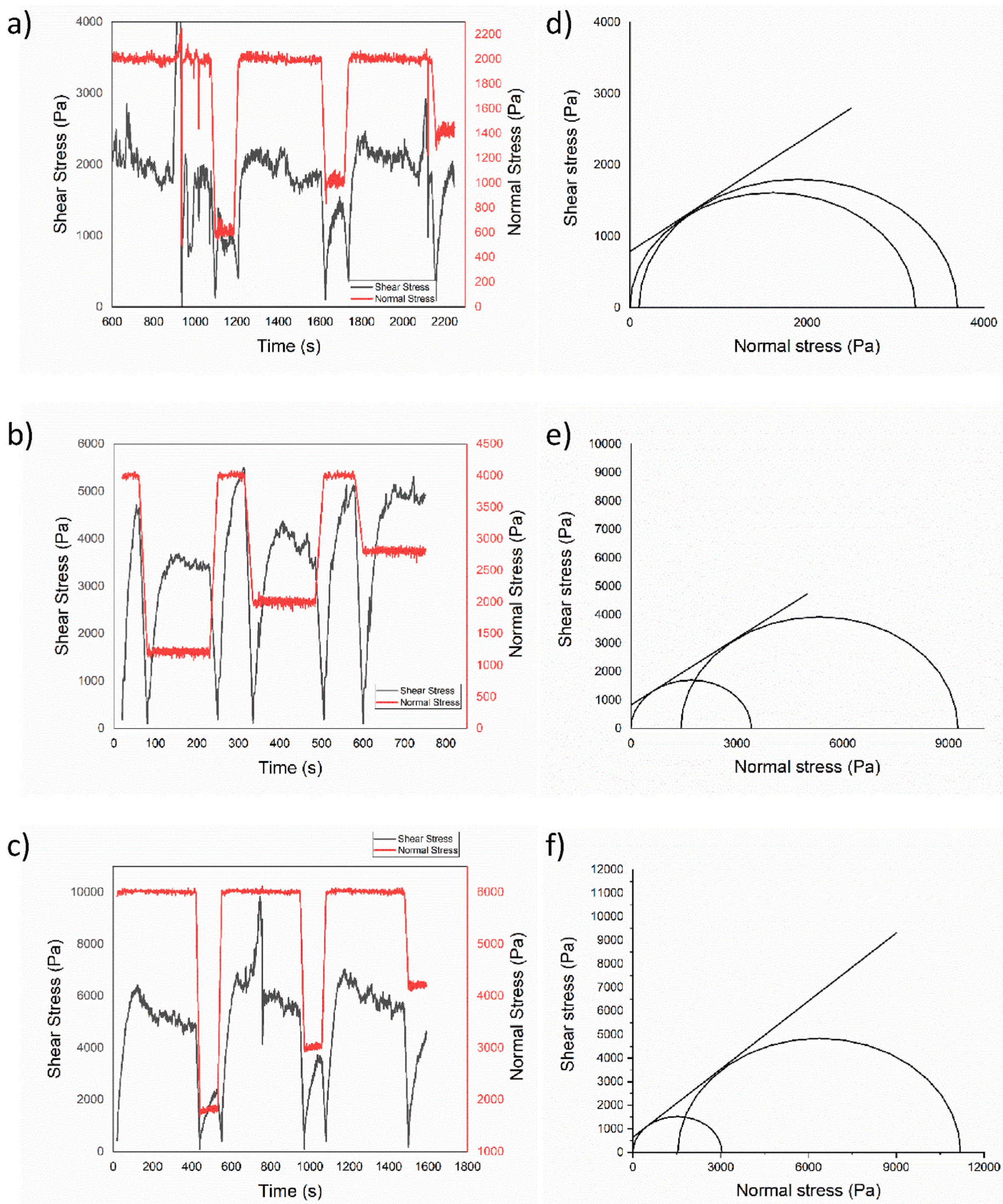

Fig. 8. Shear stress under normal stress confinement for a) 2 kPa, c)4 kPa, e) 6 kPa, and its obtained Mohr-Coulomb envelopes for b) 2 kPa, d) 4 kPa and f) 6 kPa for sand wetted by oil-based drilling fluid.

stresses 2, 4 and 6 kPa.

As shown in Fig. 6, the drilled cuttings wetted by a fluid, in this case water, behave differently as if they were dry, indicating that cohesion forces exist under the different confining normal stresses. The increase in confining pressure resulted in an increase in cohesion force values; being the intercept of the tangent curve with the shear stress axis. The cohesion force value increased from 371 Pa to 434 Pa and then to 1126 Pa as the confining normal stress increases from 2 kPa to first 4 kPa and then to 6 kPa. This means that in a bed formed by these increased confining pressures more force will be required to move the cuttings particles.

The cohesion forces of the grains wetted by the water-based drilling fluid was significantly larger than that of the water wetted grains. A similar increasing tendency was observed, which in this case increased from 1447 Pa to first 1574 Pa and then to 2593 Pa as the confining normal stress increases from 2 kPa to 4 kPa–6 kPa, respectively.

By using more complex fluids such as water-based drilling fluid, the behavioral trend is similar although the cohesion values are higher at each confining normal stress (see Fig. 7), this can be due to the complex formulation of the water-based drilling fluid which might include high molecular weight or branched polymers, such as xanthan gum or polyanionic celluloses. These high molecular weight polymers increase the viscosity of the fluid. Along with charged polymers, the presence of such

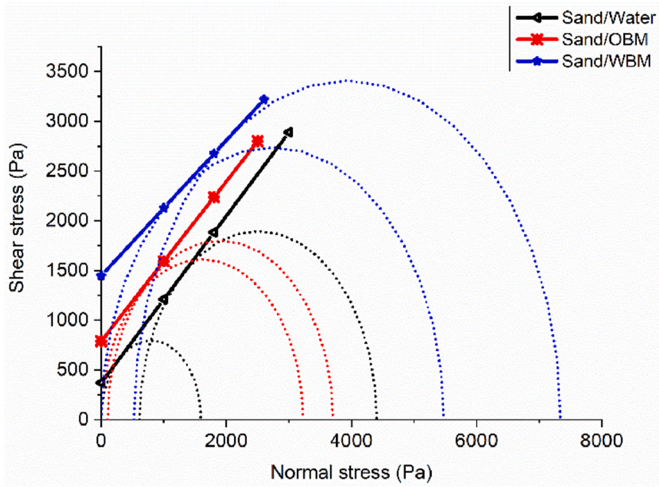

Fig. 9. Mohr-Coulomb envelopes comparison between the different interstitial fluids.

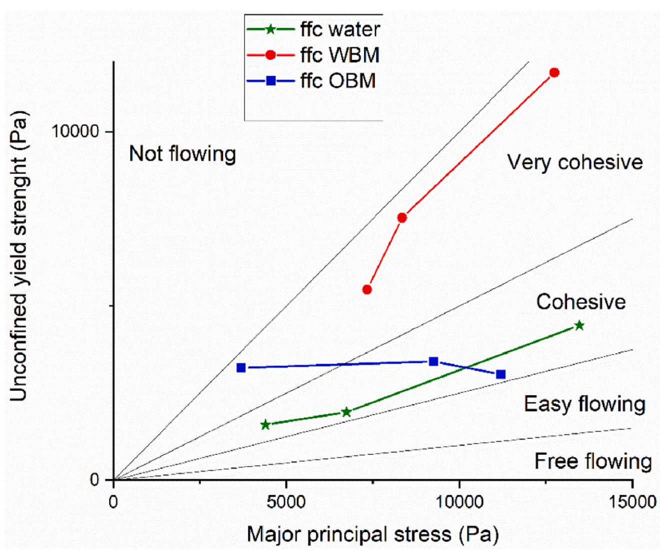

Fig. 10. Flow function coefficient evolution under 2, 4, and 6 kPa normal force confinement for bed situations with the three applied interstitial fluids.

polymers also increases the adhesion (Chaudhury, 1996) and interfacial tensions (Wu, 1974).

In Fig. 8 is shown the shear stress and the Mohr-Coulomb envelopes for the sand grains wetted by oil-based drilling fluid under different confining normal stresses. These cuttings-beds also present cohesion, although its tendency is different from that of the other two fluids. In this case, initially it increases from 789 Pa at a confining normal stress of 2 kPa–832 Pa at confined normal stress of 4 kPa and then it decreases to 646 Pa at a confining normal stress of 6 kPa. This can be due to the lubricant effect caused by the mineral base oil which may provide an average friction coefficient of 0.09 (Syahrullail et al., 2013).

During the shear stress under confining normal stress measurements from all the samples, it was observed that the shear stress was not fully stable, showing some peaks and instabilities during the pre-shear steps. This is most likely caused by morphology effects. The quartz grains are not spherical, thus the effect of shape can be very strong and extremely important (Cleary, 2008). If the cuttings grains were more spherical the charts would be smoother and with less variations.

In Fig. 9, is shown a summary plot to observe the comparison between the different interstitial fluids, showing that the sand particles wetted by water-based drilling fluids present the higher cohesion force. Subsequently, the results obtained are consistent with previous studies (Werner et al., 2017) and indicate that oil-based fluids impart higher drilled-cuttings transport capabilities than KCl/polymer water-based fluids for cases where beds can occur (Sayindla et al., 2017).

Furthermore, this behavior could be different if the cuttings-bed is built by other types of rock formations instead of sand, depending on the reactivity of the material when wetted by the different fluids, thus wet-granular rheology test should be performed to other rock formations to obtain more detailed data on each case.

In addition, with the yield locus, the unconfined yield strength and the maximum principal stress are calculated. The ratio of these indicates the flowability expressed as flow function coefficient (*ffc*) and how it is altered as the confining normal stress increases. In other words, the *ffc* describes the consolidation strength of the material when no external pressure is applied, as a function of the major compaction pressure.

In Fig. 10 the *ffc* for the three different interstitial fluids are plotted. These plots show that cuttings bed with water and water-based drilling fluid as interstitial fluid behave similarly as the confining normal stress increases. These beds remain under the cohesive and very cohesive region respectively through the confining stress increase. The cohesive flow properties with water and the very cohesive flow properties with water-based drilling fluid can be partly attributed to the higher interfacial forces caused by presence of high molecular weight polymers in the water-based drilling fluid.

The cuttings-bed with oil-based drilling fluid as the interstitial fluid, show an initial flowability as very cohesive. As the confining normal stress increase, its flowability improves. The flowability is going through the cohesive region with a final result almost at the easy flowing region. This illustrates how the lubricant effect of the oil improves the cuttings particles' flowability. Another important observation is that for moderate and higher principal stresses, the flowability of cuttings wetted by OBM is significantly more flowable than the investigated WBM wet cuttings.

4. Conclusions

Bonding forces between cuttings-particles wetted by different types of interstitial fluids were investigated experimentally using granular rheology techniques. The major conclusions from this work are summarized as follow:

- Wet-granular rheology techniques can be used to effectively characterize interaction between drilling fluids and cuttings-beds, which can be utilized for cuttings transport optimization.
- Obtained results are in line with what has been seen in the field and by other authors, where oil-based drilling fluids show better performance regarding effective cleaning ability of drilled cuttings particles than water-based drilling fluid.
- As adhesion is a complex phenomenon governed by many processes, interstitial fluid in the cuttings-bed play an important role on the cuttings' movement. Even in a case where rheological profiles are similar between different type of fluids, the chemical composition of the same can greatly modify the bonding forces.
- Water-based KCl/polymer formulated drilling fluid as interstitial fluid of the cuttings-bed presents higher cohesion than oil-based drilling fluid with similar viscous properties. This might be caused by higher attractive forces imparted by the high molecular weight polymers present in the water-based drilling fluid.
- Cuttings-bed's flowability is kept in the same region as the confining normal stress increases when water and the water-based drilling fluid are the interstitial fluids. However, oil-based drilling fluid improves the bed's relative flowability at higher confining stresses. This could be attributable to the lubricant action of the oil present in its composition.

Credit author statement

Camilo Pedrosa: Conceptualization, Methodology, Investigation. **Arild Saasen**: Writing, reviewing and editing, Supervision. **Jan David Ytrehus**: Reviewing and editing, Project administration and Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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APENDIX.

Table 1
Granular rheology data summary

	Water 2 kPa	Water 4 kPa	Water 6 kPa	WBM 2 kPa	WBM 4 kPa	WBM 6 kPa	OBM 2 kPa	OBM 4 kPa	OBM 6 kPa
c (Pa)	371	434	1126	1447	1574	2593	789.4	832.4	646.3
Ts	442.3	479.8	1535	2125	1594	2868	981.9	1067	671.1
Uncon σ_c (Pa)	1593	1956	4445	5474.2	7531.7	11,696	3225	3411	3039
Major σ_1 (Pa)	4403	6740	13,470	7337.6	8437	12,750	3700	9262	11,200
Bulk density	1.68	1.68	1.7	2.43	2.45	2.47	2.03	2.05	2.07
ff_c	2.76	3.45	3.03	1.34	1.12	1.09	1.15	2.72	3.68

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