Wet-granular rheology to measure cuttings-bed strength

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ABSTRACT

Drilled cuttings-bed formation is a natural process during wellbore drilling operations, although it is not desired. To optimally remove the drilled cuttings out of the wellbore it is important to break the formed beds. Wet-granulated material such as the drilled cuttings behave differently depending on the applied stress and particle concentration, it can behave as solid when is at rest or under low energy input, or it can flow like a fluid when a certain energy is reached. Here it is studied how a wetting fluid can modify the motion and properties of the cuttings-bed by using powder rheology.

INTRODUCTION

Efficient removal of the cuttings is of utmost importance during drilling operations. Cuttings-beds formed while drilling wellbores is a common problematic, especially if they are highly deviated or horizontal. Removal of the drilled-cuttings is done through the circulating drilling fluid. When the wellbore is inclined or horizontal, cuttings tend to settle and form beds at the low side of the annulus. This can cause several problems such as, increased torque and drag, pipe sticking or pipe breakage, among others [1]. The actual consolidation strength of these cuttings-bed is normally unknown, and studies on cuttings-bed removal usually approach the method on the final result: Effective cuttings-bed removal.

Wet-granular rheology can be performed to improve understanding and quantify the consolidation strength of larger particles, such as drilled cuttings [2]. Granular flows analyzed with a powder shear cell, regardless of their solid-wet phase, can be described by the Mohr-Coulomb criterion [3].This method is similar to the one that is often used in rock mechanics characterization, and will be ruled by Eq. 1.

$$\tau = c + \sigma \tan \varphi \quad (1)$$

where τ is the shear stress, σ is the normal stress, φ is the internal friction angle and c is the cohesion. Differently from dry particles, in wet particles the dominating interaction is cohesion due to the surface forces.

Another factor that relates greatly to the cohesion is the critical angle of repose θ_c, which is the maximum surface angle before a piled material suffers spontaneous avalanche [4].

This angle can be analyzed by using the failure criterion, where in the case of no cohesion, the failure criterion is depending on a material parameter, the internal friction coefficient μ^*, as shown in Eq. 2

$$\tau > \mu^* \sigma \quad (2)$$

If there is any plane for which the ratio τ/σ exceeds μ, the material fails at that plane, the critical angle corresponds to the angle of this failure plane. As the stress comes from a weight above the plane, it can be described by Eq. 3 and 4

$$\tau_f = \rho g D \sin\theta_c \quad (3)$$
$$\sigma_f = \rho g\, D \cos\theta_c \quad (4)$$

where τ_f is the shear stress at failure, σ_f is the normal force at failure, ρ is the density and D is the distance of the failure plane from the surface [5]. Although for wet-granular particles, the criterion includes the cohesive stress σ_c imparted by the wetting fluid as described in Eq. 5

$$\tau > \mu^*(\sigma + \sigma_c) \quad (5)$$

Which leads to Eq. 6

$$\mu^* = \tan\theta_c \left(1 + \frac{\sigma_c}{\rho g D \cos\theta_c}\right)^{-1} \quad (6)$$

Besides viscous forces conveyed by the interstitial fluid [6], in wet particles also capillary attraction forces are present, when the saturation is higher than S>70%, if saturation is lower, the dominant attractive forces are liquid bridges.

In this study, the focus is to describe the cuttings-bed strength and the stress required to erode it. Performing granular rheology analysis to the cuttings wetted with different fluids has shown to be an effective approach to describe the bed strength formation [2]. Assuming solid behavior of the cuttings-beds, it is possible to analyze through the Mohr-Coulomb failure envelope the cuttings-beds' shear strength and particle cohesion. The results show that the interstitial fluid significantly impact the shear strength of the bed.

Shear measurements are based on the Mohr-Coulomb theory which measures the failure plane in dependence of the stresses which are applied to the cuttings-bed. The measurement is carried out by filling the granules into a ring shear cell (as displayed in Fig. 1.) and then applying a pre-compaction to the bed and shearing the granules. This is done to get the sample into a repeatable state, but also because this "pre-shear" already yields information on the bed behavior under the pre-compaction stress. The next step is known as "shear-to-failure", here the cuttings-bed is sheared at a reduced normal stress, which will result in the bed "breaking" and starting to flow again. These two measurement steps of pre-shear and shear-to-failure are repeated multiple times at varying conditions in order to record the data which is necessary for the analysis within the Mohr-Coulomb diagram, and the Coulomb failure criterion as described above.

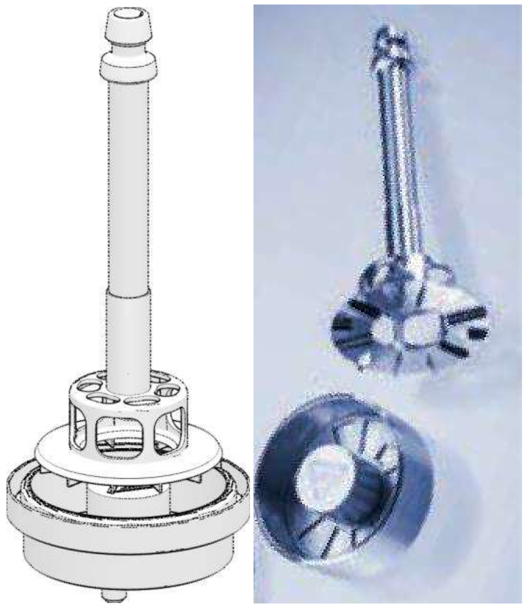

Figure 1. Ring shear cell (lower part) and the geometry which is used to consolidate and shear the sample.

EXPERIMENTAL PROCEDURES

Materials

The materials used in this study were sand grains (quartz) of irregular shape with average size of 1.3 mm, to simulate the cuttings, these were saturated with water and water-based drilling fluids. A standard water-based drilling fluid with density of 1.68 g/cm^3 containing KCl, soda ash, polyanionic cellulose, starch, xanthan gum, barite.

Rheological experimentation

The water-based drilling fluid's viscosity profile is characterized through a flow curve (see Fig. 2). The plotted data are derived from analysis performed with a rheometer Anton-Paar MCR102, equipped with a Couette geometry. The sample was initially pre-sheared at 1000 s^{-1} for 120 s to reach steady-state shear viscosity. After this a measurement protocol was started with a ramp down from 1200 s^{-1} to 60 s^{-1} in 100 linear steps, followed by 5 linear steps from 60 s^{-1} to 10 s^{-1}, and finally with 100 linear steps from 10 s^{-1} to 0.1 s^{-1}. The measuring time per point was set to 2 s.

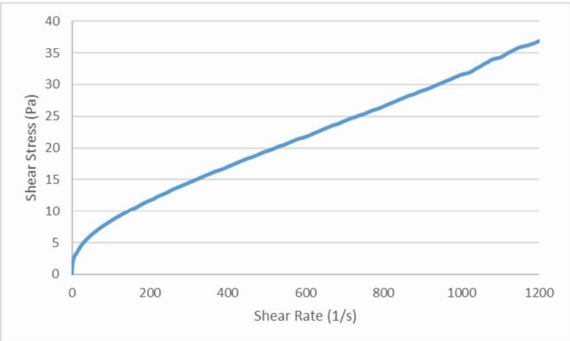

Figure 2. Water-based drilling fluid shear flow profile.

The water-based drilling fluid is a non-Newtonian fluid which presents a shear-thinning behavior, meaning that the viscosity decreases with increasing shear rate. This behavior is different from the Newtonian behavior that water has, therefore it is expected some differences in the particle cohesion and tensile strength of the cuttings-bed.

A powder shear cell was used in a rheometer Anton-Paar MCR102 analyzing the shear for granular materials.

For the analysis the sand samples were placed into a centrifuge tube with the wetting fluid with a volumetric ratio of 1/3 of sand and 2/3 of fluid. Then the tube was hand-shaken for 30 seconds and then centrifuged for 20 minutes 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.

For the shear measurements a maximum normal stress of 2, 4 and 6 kPa was applied to the samples in order to analyze how compaction influences the bed strength. Measurements were done at three pre-shear points at maximum normal stress and three shear-to-failure points at 30, 50 and 70% of the maximum load, and a rotational speed of 0.005 rpm. A schematic of the Mohr-Coulomb envelope obtained by using powder rheology is shown in Fig.3.

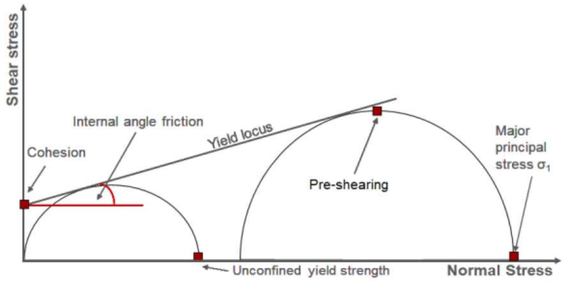

Figure 3. Schematic diagram of powder yield locus obtained by rheometry.

RESULTS AND DISCUSSION

The cuttings-bed configuration strength due to cohesion (C) and tensile strength (Ts) of sand when wetted by water or by water-based drilling fluids was analyzed through Mohr-Coulomb failure envelopes and these are presented here together with results for dry sand.

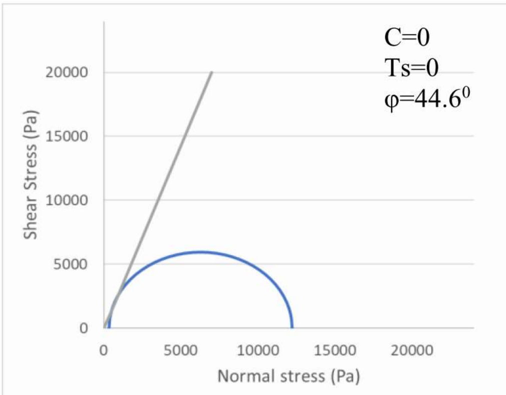

Figure 4. Mohr-Coulomb failure envelope for dry sand consolidated under normal stress of 6kPa.

Sand grains are non-cohesive when dry [7]. This was also seen in the Mohr-Coulomb envelope failure from the shear measurement results, in Fig. 4, where the Y intercept of the tangent line is equal to zero.

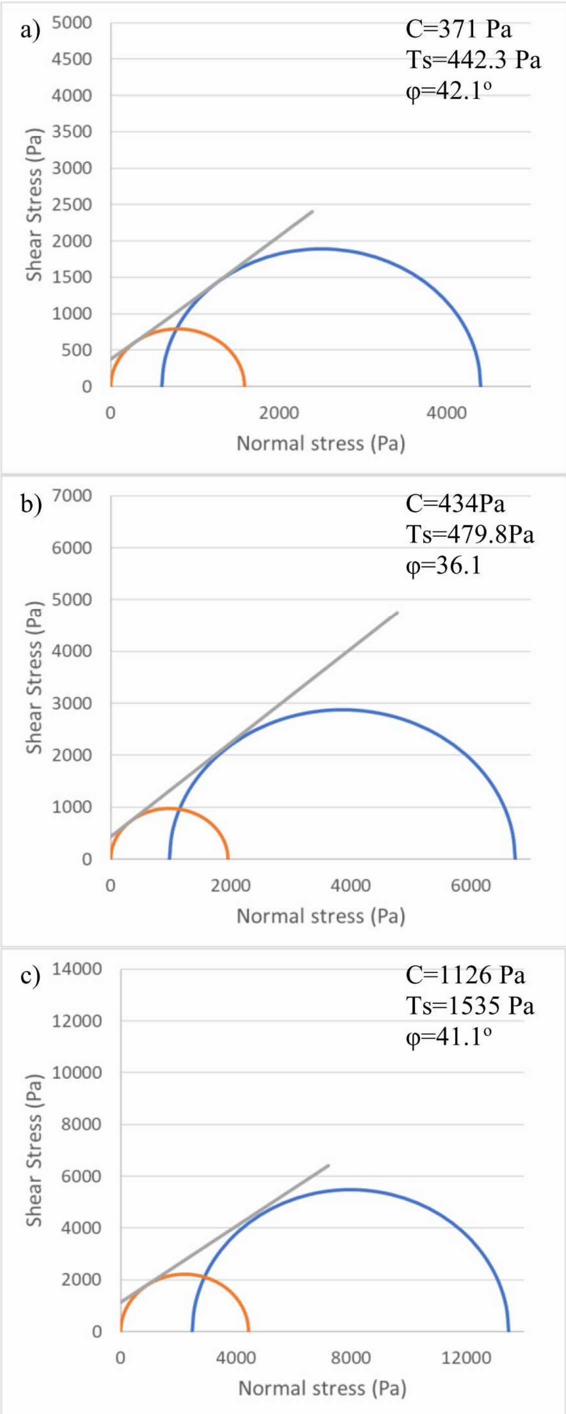

Figure 5. Mohr-Coulomb failure envelope for water saturated sand consolidated under normal stress of a.) 2 kPa, b.) 4 kPa, c.) 6 kPa.

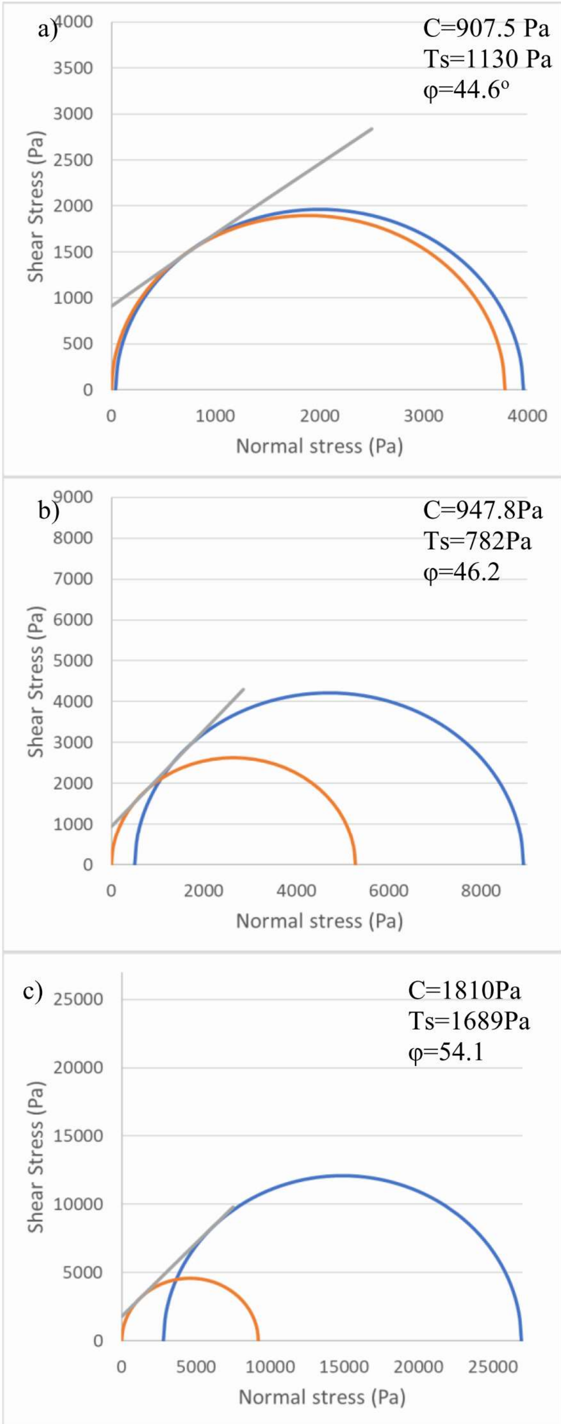

Figure 6. Mohr-Coulomb failure envelope for water-based drilling fluid saturated sand consolidated under normal stress of a.) 2 kPa, b.) 4 kPa, c.) 6 kPa.

On the contrary, when these were saturated with water, the wetted sand undergoes cohesion due to the capillary attraction forces imparted by the water [8], as observed in Fig. 5.

The Y axis intercept of the tangent of the circles is the cohesion, and the tangent to the circles is called the yield locus, which represents the maximum shear stress that the sample can withstand under a certain normal stress without suffering plastic deformation of the cuttings-bed. In the case of combinations of normal and shear stress above the tangent, the cuttings-bed will undergo failure, which can be understood as erosion of the cuttings-bed.

In Fig. 5. The Mohr-Coulomb envelope with pre-compaction normal stress of 2 kPa, 4 kPa and 6 kPa show cohesion of 371 Pa, 434 Pa and 1126 Pa respectively, and tensile strength of 442.3 Pa, 479.8 Pa and 1535 Pa respectively, which is in line with the theory as with more confining force, the sand grains tend to have more contact area and less distance between them provoking more friction [9, 10].

In addition, when using more complex drilling fluids, such as water-based drilling fluids, it is possible to observe higher cohesion between the cuttings-bed (see Fig. 6.), this might be due to capillarity, viscous forces, and electrostatic attraction imparted by the composition and rheological behavior of the interstitial fluid.

The Mohr-Coulomb envelope for the cuttings-bed with water-based drilling fluid as the interstitial fluid, with confining normal force of 2 kPa, 4 kPa and 6 kPa showed cohesion of 907.5 Pa, 947 Pa and 1810 Pa respectively, and tensile strength of 1130 Pa, 782 Pa and 1689 Pa respectively.

CONCLUSION

It has been observed that interstitial fluid composition and its rheological properties can cause the cohesion strength of the cuttings-bed to vary significantly. This information will be important input to models for predicting the required energy to erode a cuttings-bed.

It was seen that fluids with more complex network structure tend to instigate higher cohesion strength between the cuttings' particles. Further tests and analyzes including different type of drilling fluids, including oil-based drilling fluids and different formulations, are required to comprehend how these parameters can influence the particle-particle cohesion.

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REFERENCES

1. Adari, R.B., et al. *Selecting Drilling Fluid Properties and Flow Rates For Effective Hole Cleaning in High-Angle and Horizontal Wells*. in *SPE*. 2000. Dallas, Texas, USA.
2. Pedrosa, C., et al., *Wet Drilled Cuttings Bed Rheology.* Energies, 2021. **14**(6): p. 1644.
3. Pähtz, T., et al., *Local Rheology Relation with Variable Yield Stress Ratio across Dry, Wet, Dense, and Dilute Granular Flows.* Physical Review Letters, 2019. **123**(4): p. 048001.
4. Mehta, A. and G.C. Barker, *The dynamics of sand.* Reports on Progress in Physics, 1994. **57**(4): p. 383-416.
5. Mitarai, N. and F. Nori, *Wet granular materials.* Advances in Physics, 2006. **55**(1-2): p. 1-45.
6. Roy, S., S. Luding, and T. Weinhart, *A general(ized) local rheology for wet granular materials.* New J. Phys., 2017. **19**.
7. *The ideal Coulomb material*, in *Statics and Kinematics of Granular Materials*, R.M. Nedderman, Editor. 1992, Cambridge University Press: Cambridge. p. 21-46.

8. Mason, T.G., et al., *Critical angle of wet sandpiles.* Physical Review E, 1999. **60**(5): p. R5044-R5047.
9. Macaulay, M. and P. Rognon, *Viscosity of cohesive granular flows.* Soft Matter, 2021. **17**(1): p. 165-173.
10. Fjær, E., et al., *Petroleum related rock mechanics*. 2nd ed. Developments in petroleum science. Vol. 53. 2008: Elsiever.