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Measuring filter-cake cohesive strength and flowability

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ABSTRACT

The filter-cake has a critical role in temporarily reducing the permeability of the wellbore to prevent issues such as lost circulation, formation damage, wellbore collapse and differential sticking. The filter-cake's ability to perform these functions may be impaired by its deterioration caused by the circulation of fluid, swabbing or mechanical interaction. Therefore, being able to measure the strength of the filter-cake, and hence its ability to withstand disturbances, is important to ensure optimal drilling fluid design.Two water-based reservoir drilling fluids were used to produce filter-cakes under high differential pressures. The filter-cakes were thereafter analysed using a rheometer with a specially designed cell for accurate powder shear rheology. This enabled measurement of the cohesive strength and flowability of the filter-cakes.It was found that filter-cakes composed of a conventional reservoir drilling fluid with $CaCO_3$ and polymers, showed low cohesive strength and high flowability. The other fluid, which contained cellulose-based fibres in addition to $CaCO_3$ and polymers, showed much higher cohesion and lower flowability.It was concluded that the test methodology could be very useful in relation to optimising drilling fluid design, particularly for wells were lost circulation, wellbore stability and differential sticking may be relevant problems. It was also concluded that the addition of cellulose-based fibres may significantly increase the filter-cake strength in a water-based drilling fluid.

1. Introduction

During testing of drilling fluids, the fluid's ability to seal the formation is tested using API fluid loss tests or HTHP filtration tests. The properties of the filter-cake are typically described in terms of thickness and surface texture, whereas measurements of the filter-cakes' strength and flowability are not normally studied. During an over-balance drilling operation, the filter-cake is the primary barrier that isolate the higher wellbore fluid pressure from the formation pore-pressure, and thereby prevents fluid loss and pressure communication. Ideally, the filter-cake should have very low permeability and high cohesive strength. This would enable low fluid loss, a thin filter-cake and prevent differential sticking.

Differential sticking may appear when the drill-pipe comes in contact with the filter-cake. At the time of first contact, there is no suction pressure on the pipe. If the pipe is allowed to remain in contact with the filter-cake, the fluid pressure on the filter-cake side will start to fall and gradually move towards the formation pore pressure. Therefore, in a long-term static condition, the suction pressure on the pipe will move asymptotically towards being equal to the difference between the fluid pressure in the wellbore and the pore pressure in the formation. By multiplying the suction pressure with the contact area and the coefficient of friction between the drill-pipe and the filter-cake, the frictional force on the pipe is calculated.

The rate at which the suction pressure builds up is governed by the permeability of the filter-cake and the ease of disturbing or eroding the filter-cake in a dynamic setting, or alternatively seen as the cohesive strength and flowability of the filter-cake. Studies were conducted by Sheerwood and Meeten, 1997 with water-based fluids containing bentonite on the ratio of volume of liquid to volume of solids within the filter-cake. They found that lower void ratio was correlated with lower filter-cake permeability. In earlier studies, Sherwood et al. (1991) used a squeeze-film rheometry approach to study filter-cake yield stress, σ_0. They concluded that with a solids volume fraction, φ, between 0.09 and 0.6, the yield stress could be expressed as function of φ for the fluid studied. Also, they showed that the bentonite filter-cakes compacted over time, and that φ reached an equilibrium value for a given applied pressure.

An intact and low-permeability filter-cake will substantially prevent the build-up of suction pressure on the drill-pipe leading to differential

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sticking. In contrast, a high-permeability filter-cake will lead to higher fluid loss and a faster growth of the filter-cake thickness. As the filter-cake thickness grows, the potential area of contact with the drill-pipe increases. Further, if the cohesion of the filter-cake is low it becomes easier for the pipe to become « tucked-in» so that the contact area increases further, and the pressure barrier is damaged. Therefore, to prevent differential sticking, a filter-cake with very low permeability and high cohesive strength is ideal.

Studies of static fluid loss tests shown that after the initial spurt loss, the fluid loss follows a linear function when plotted against the square root of time. Klungtvedt and Saasen, 2023 used such regression models to calculate the permeabilities of filter-cakes for water-based drilling fluids. In a dynamic condition, the filter-cake will reach a state where the rate of erosion equals the rate of filter-cake build-up, such that the fluid loss follows a linear function against time. By measuring the cohesive strength and flowability of the filter-cake, the differences between static and dynamic fluid loss may be better understood.

The study of powder rheology can be done by measuring the dynamic flow and the shear properties of the powders, where the powder itself may be a combination of liquids, solids and gases. Pedrosa et al. (2021) applied the methodology of measuring wet-granular rheology to calculate the internal friction coefficient of cuttings bed, which provides an insight into the particle cohesion properties. The test methodology used in the study by Pedrosa was also selected for the present study. The primary function is to use a powder shear cell to measure the resistance to flow at low shear rates.

The findings that Pedrosa made when studying cuttings beds may also have some relevance to drilling fluid filter-cakes. He concluded that water-based fluids made with KCl and polymers packed cuttings in a dense manner, where the particles moved in clusters. In contrast, the particles were packed in a loose configuration when submerged in an oil-based fluid, and hence single particles could be moved more freely. These data may indicate that an external filter-cake formed by oil-based drilling fluids may erode more readily than that of a water-based drilling fluid.

The main objectives of the study were:

- To determine if a powder shear cell could be used to effectively analyse the cohesive strength and flowability of filter-cakes, and
- To determine if different drilling fluid compositions would lead to significantly different values of cohesiveness and flowability

2. Methods

The flow behaviour of powders is mostly non-Newtonian, where the resistance to flow falls with higher shear rates. Typically filter-cakes have moisture levels in the range of 15–50% by weight, primarily depending on the solids content of the fluids. Therefore, in order to study the rheology of the filter-cakes, it is important that they are kept in original condition, without being dried. The filter-cakes were made in HTHP tests using ceramic discs.

The test is conducted using a 4.5 mL Anton Paar powder shear cell. It is designed for analysis of powders and uses standard test loops with high precision measurements. The methodology uses the Mohs-Coulomb failure envelop theory, which is conventionally used to describe brittle materials or materials where the compressive strength significantly exceeds the tensile strength, by comparing the measured shear stress with the applied normal stress. Labuz et al., 2012 provides a good insight into the mechanisms and governing equations. The Mohr-Coulomb failure is expressed by equation (1).

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

where τ is the shear strength, σ is the normal stress, φ is the angle of internal friction and c is the cohesion or the inherent shear strength. The coefficient of internal friction μ is calculated using equation (2).

$$\mu = \tan(\varphi) \qquad (2)$$

Fig. 1 shows the shear cell and the stem with the blades. The test material is placed into the cell without initial compaction. Excess materials is scraped off to provide an even surface.

After the filter-cake is placed in the test cell, a maximum normal stress is applied, before the sample is sheared at constant rotation until reaching the cake's failure and the shear stress is measured, this procedure is repeated at 30%, 50% and 70% of the maximum initial normal stress. The test cell is designed with a small open area around the top of the test cell, so that it can identify if powders simply overflow when a given normal pressure is applied. For certain free flowing powders, there will hence we a limit to the applied normal pressure. With the three shear-to-failure points is possible to obtain the yield locus of the Mohr-Coulomb failure envelop, and from there calculate the unconfined yield strength and the major principal stress as shown in Fig. 2.

The unconfined yield stress (σ_c) which represents the major principal stress that will cause the cake to in an unconfined state to fail in shear, together with the major principal stress (σ_1) under normal stress, will provide the flowability of the cake in terms of its Flow Function Coefficient (ffc), as described in equation (3). This flowability is divided into five regions, according to the ffc as follows: not flowing (ffc <1), very cohesive (1< ffc <2), cohesive (2< ffc <4), easy flowing (4< ffc <10) and free flowing (ffc>10).

$$ffc = \frac{\sigma_1}{\sigma_c} \qquad (3)$$

Equipment used for testing:

- Hamilton Beach Mixer, for mixing of drilling fluids
- Ohaus Pioneer Precision PX3202, for weighing the drilling fluid ingredients
- Custom built Permeability Plugging Apparatus with hydraulic pump for testing slotted discs or ceramic discs up to 35 MPa (5076 psi)
- AEP Transducers JET Pressure Gauge with Data Logger, for measuring and logging applied pressure
- Ofite Viscometer model 900, for measuring fluid rheological parameters
- Ofite roller-oven #172-00-1-C, for aging the drilling fluid samples
- Apera pH90, pH meter, for pH measurements
- Anton Paar MCR-301 Rheometer with Powder Shear Cell

3. Results

3.1. Drilling fluid composition and fluid loss tests

Four fluid compositions, shown in Table 1, were selected to represent typical water-based reservoir drilling fluids. Xanthan Gum was used to provide viscosity, starch for fluid loss control and $CaCO_3$ (ground marble) and cellulose based fibres to provide bridging. To ensure sufficient filter-cake thickness for conducting the tests in the powder shear cell, the concentration of starch was kept a little lower than what might be ideal from a fluid loss perspective. The filter-cakes were made by testing the fluids under high differential pressures on 50 μm ceramic discs. Fluid 1 and 2 were tested with average pressures of 1500 psi for 30 min, whereas Fluid 3 and 4 were tested with average pressures of 2400 psi for 40 min.

3.2. Filter-cake shear rheology measurements

Fluid 1 was tested with a maximum applied normal pressure of 3 kPa, as the sample disintegrated and overflowed above this pressure. The disintegration of the filter-cake is evidence of low cohesion and high flowability. The Mohr-Coulomb failure envelope is presented in Fig. 3. The obtained cohesion was 495 Pa and the internal friction angle 14°.

For Fluid 2, testing was conducted at 3, 6 and 9 kPa applied normal

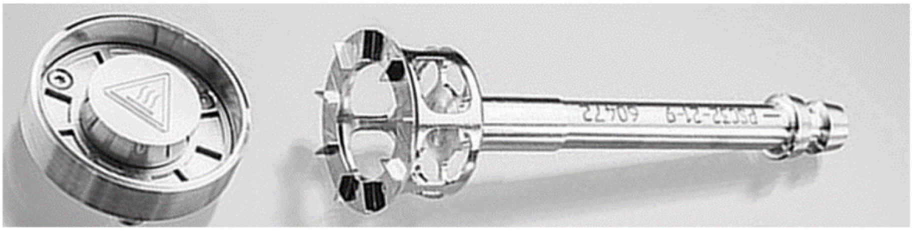

Fig. 1. Anton Paar Powder Shear Cell and stem.

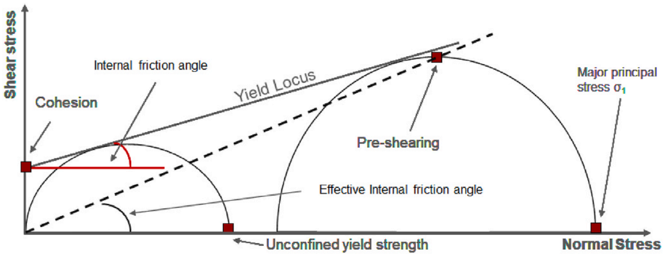

Fig. 2. Mohr-Coulomb failure envelope obtained by rheometry.

Table 1
Drilling fluid recipes 1-4.

Component and mixing sequence	Fluid 1 recipe (kg/m3)	Fluid 2 recipe (kg/m3)	Fluid 3 recipe (kg/m3)	Fluid 4 recipe (kg/m3)
Water	950.6	936	947.6	933
Na2CO3	0.057	0.057	0.057	0.057
NaOH	0.71	0.71	0.71	0.71
Xanthan Gum	4.29	4.29	4.29	4.29
Starch	11.4	11.4	14.25	14.25
MgO	1.43	1.43	1.43	1.43
NaCl	28.57	28.57	28.57	28.57
CaCO3 (<53 μm)	57.14	57.14	57.14	57.14
Cellulose based material with D90 of 75 μm (AURACOAT UF)		14.29		14.29

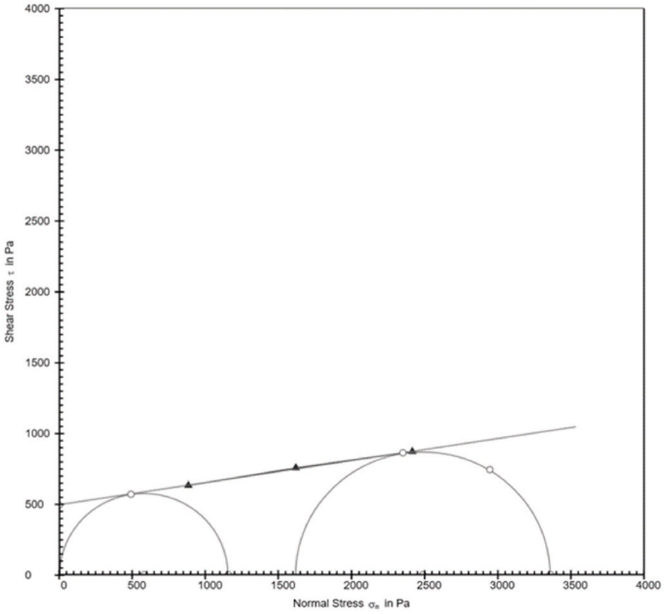

Fig. 3. Mohr-Coulomb failure envelope for Fluid 1 at 3 kPa.

pressures as presented in Fig. 4. The cohesion ranged from 2271 Pa to 3167 Pa, which is around 5 to 6 times that of Fluid 1, and the internal friction angles were from 31° to 44°, indicating lower flowability.

Fluid 4 showed similar characteristics as Fluid 1, and were tested at 1, 2 and 3 kPa normal pressures. Fig. 5 presents these plots, and as for Fluid 1, it can be seen that the Mohr's circles did not overlap for most test conditions. The Cohesion was measured to range from 261 Pa to 361 Pa and the friction angles in the range from 14° to 19°.

Fluid 4 was tested at normal pressures of 1, 2 and 3 kPa, to facilitate a comparison with Fluid 3. The Mohr-Coulomb failure envelopes are presented in Fig. 6. The Cohesion was measured to range from 1032 Pa for the 1 kPa normal pressure test to 1731 Pa for the 3 kPa normal pressure test, and the internal friction angles ranged from 53° to 34°. Relative to Fluid 3, the Cohesion was 4–5 times higher under the same normal pressure conditions, and the friction angle more than double.

The overall unconfined yield strengths were plotted against the major principal stresses for each of the tests. These data are presented in Fig. 7. Using the separation into different flow regimes, it is clear that Fluid 2 and 4 show significantly higher levels of cohesion than Fluid 1 and 3, which appear to be in the range from cohesive to easy flowing. For Fluids 3 and 4, the unconfined yield strength appears to potentially be independent of the major principal stress, within the tested principal stress range. Given that Fluids 2 and 4 are very similar, but tested at different major principal stresses, viewing the two plots together may be relevant. Using this approach it may be interpreted that the unconfined yield strength is constant below a certain major principal stress level, and that when this stress level is exceeded, the unconfined yield strength follows a linear relationship with the major principal stress.

The datapoints for each of the tests are listed in Table 2. Herein, the calculated internal friction angles were lower for higher values of applied normal pressure for all the tests where multiple normal pressures were applied. This also corresponds to higher flowability factors coefficients, for higher applied normal pressures.

4. Discussion

The method of testing filter-cakes using advanced rheometry introduces sources or error and conditions which are unlike those seen in a wellbore. As an example, the filter-cakes were produced under high differential pressures, whereas the rheology studies were conducted without a confining fluid pressure.

The testing using the Anton Paar powder shear cell functioned in a satisfactory manner. The cell required a filter-cake volume of at least 4 mL, and hence the drilling fluid composition and filtration tests need to be conducted in a way that would produce a filter-cake with sufficient thickness. The fluid compositions applied included concentrations of starch ranging from 11.4 to 14.25 kg/m3 to ensure a slightly higher fluid-loss and filter-cake build up. This is somewhat lower than what is conventionally used in wellbore application. Given that the testing was successful, it is natural to conduct future tests with fluid compositions that more closely resemble a field fluid with optimised values of polymers and presence of drilled solids.

The results showed very clear differences between the fluids with and without the cellulose-based fibres. It was clear that the fluid

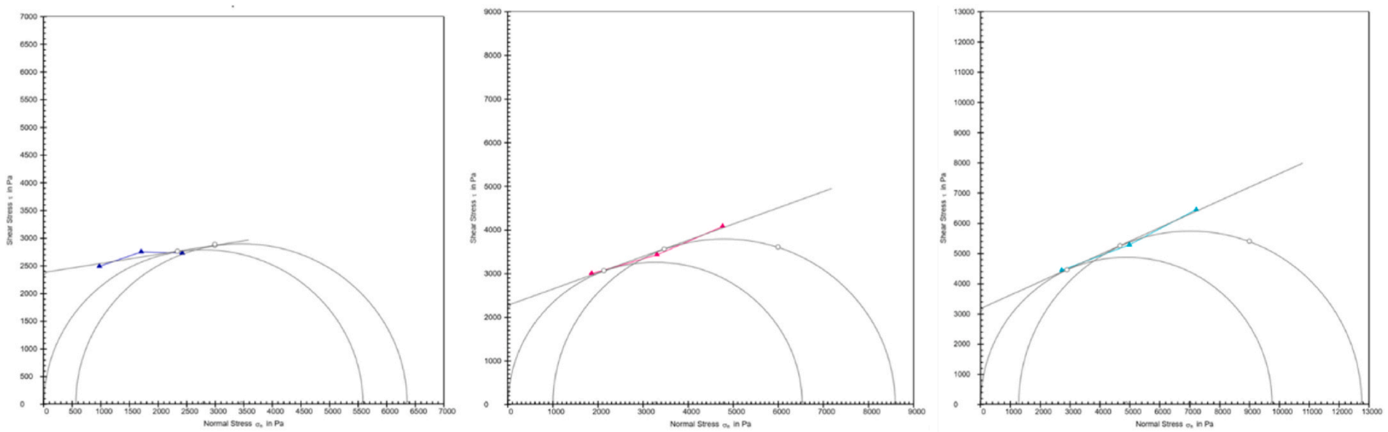

Fig. 4. Mohr-Coulomb failure envelope for Fluid 2 at 3, 6 and 9 kPa.

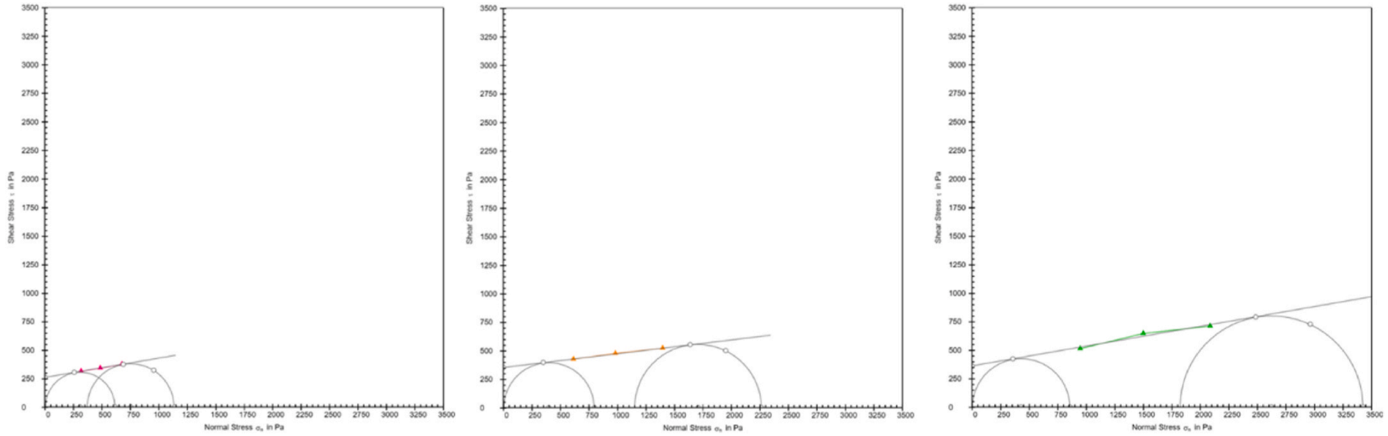

Fig. 5. Mohr-coulomb failure envelope for Fluid 3 at 1, 2 and 3 kPa.

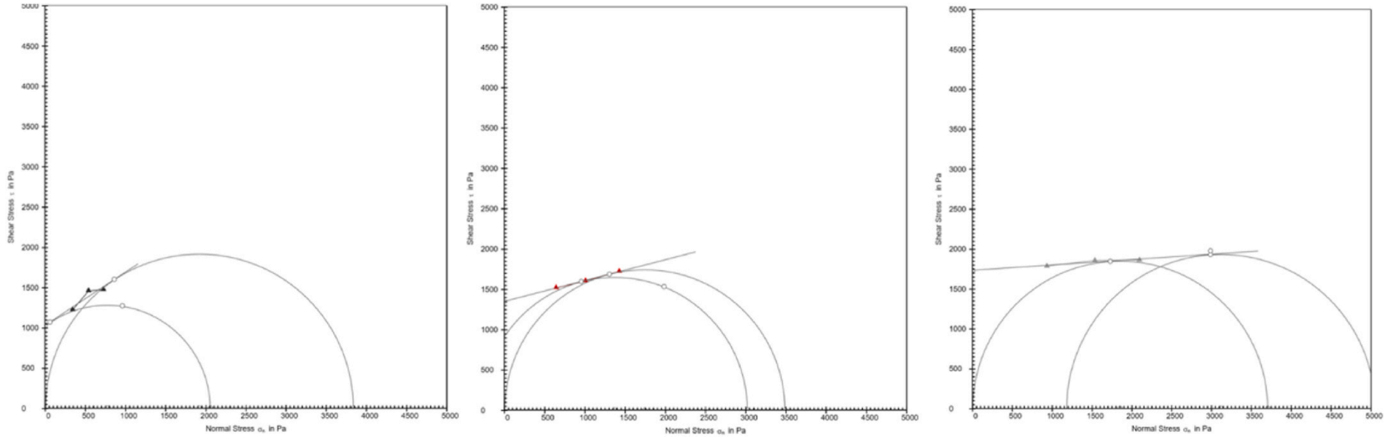

Fig. 6. Mohr-coulomb failure envelope for Fluid 4 at 1, 2 and 3 kPa.

containing $CaCO_3$ as the only solid, created a filter-cake with low cohesive strength and high flowability.

Extending the results to field applications, it may be expected that the fluid without cellulose-based non-invasive fluid additives would be exposed to rapid filter-cake erosion, higher fluid-loss and greater risk of differential sticking, whereas the addition of the tested cellulose-based additives may present a significant reduction of these risk factors.

A cause of the improved filter-cake cohesion for Fluid 2 and 4 may be polar interaction of the cellulose-based fibres and the dispersed polymers in the fluid. Such interaction may take the form of higher adhesive and frictional forces between the particles, and thereby increased shear strength.

Studying the data in further detail, the internal friction angle, or alternatively the coefficient of internal friction, was not constant for either Fluid 2, 3 and 4 as the applied normal stresses varied. For the filter-cakes of each of the three fluids, a higher applied normal pressure led to a lower coefficient of internal friction. For the mentioned filter-cakes, also the highest applied normal pressure led to the largest

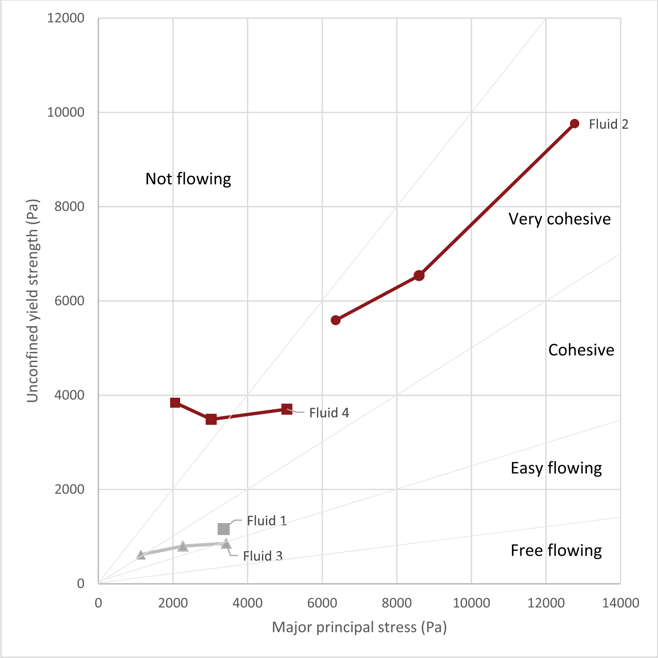

Fig. 7. Flowability of fluid 1–4.

recorded cohesion. The classical Mohr-Coulomb shear strength criterion describes the shear strength as a linear function of the normal stress and the coefficient of internal friction plus the cohesion constant. The observed behaviour indicates that a nonlinear relationship exists when different normal stresses are applied. Shen et al. (2018) presented a nonlinear modified Mohr-Coulomb shear strength criterion for analysing intact rocks. Their model also showed a transition from brittle to ductile behaviour upon reaching a critical level of normal stress, following Barton (1976). At this critical state, the failure envelope becomes horizontal, and the maximum shear strength is half of the normal compressive strength. The tests conducted using the filter-cakes of Fluid 1–4 showed some of the same behaviour as observed by Shen et al. and Barton, however, the testing conducted did not replicate a wide enough range of normal stresses to fully describe the behaviour of the filter-cakes.

5. Conclusions

The conclusions regarding the main objectives of the study are as follows:

- The application of the powder shear cell for measuring the flowability and cohesion of drilling fluid filter-cakes worked well. The test results showed that fluids with relatively similar compositions also yielded similar results.
- A total of four test were conducted successfully and where the primary differences were the addition of an ultra-fine cellulose based non-invasive fluid additive in fluids 2 and 4. The addition of the cellulose-based additive created a significantly higher cohesive strength and lower flowability of the filter-cakes.
- The results from the testing indicate that a Fluid 2 and 4, containing the cellulose-based additive, would provide improved resistance towards erosion of the filter-cake due to fluid circulation and potentially reduced risk of differential sticking.
- Future testing should be attempted across a wider range of pressures to identify if the type of deformation could be identified to change from brittle to ductile at critical normal pressure levels.
- Future testing should be attempted for oil-based filter-cakes to facilitate comparison of the cohesive strength and flowability of filter-cakes made with similar weighting agents and bridging materials, but with different base fluids.

Credit author statement

Karl Ronny Klungtvedt: Conceptualization, Methodology, Validation, Investigation, Writing - Original Draft, Collecting material for experiments, Writing - Review & Editing, Funding acquisition. Camilo Pedrosa; Methodology, Validation, Investigation, Performing experiments, Arild Saasen: Conceptualization, Writing - Original Draft, Writing - Review & Editing, Supervision.

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.

Table 2
Data summary.

	Applied normal pressure (Pa)	Cohesion, c (Pa)	Unconfined yield strength, σ_c (Pa)	Major principal stress, σ_1 (Pa)	Flowability factor coefficient, ffc	Internal fricion angle, φ	Coefficient of internal friction, $\mu = \tan(\varphi)$
Fluid 1	3000	495	1156	3360	2.91	14.14	0.252
Fluid 2	3000	2375	5593	6365	1.14	44	0.966
Fluid 2	6000	2271	6538	8598	1.32	31.07	0.603
Fluid 2	9000	3167	9762	12,770	1.31	30.99	0.601
Fluid 3	1000	261	618	1136	1.84	18.79	0.340
Fluid 3	2000	354	799	2263	2.83	14.39	0.257
Fluid 3	3000	361	858	3425	3.99	13.83	0.246
Fluid 4	1000	1032	3841	2060	0.54	52.92	1.323
Fluid 4	2000	1349	3488	3022	0.87	37.74	0.774
Fluid 4	3000	1731	3704	5054	1.36	33.53	0.663

Data availability

No data was used for the research described in the article.

Acknowledgements

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