

Properties of Dense Barite Sediments from Water-Based Drilling Fluids Oscillatory Viscosity Measurements of Wet Barite Powder

Benjamin Werner¹, Camilo Pedrosa², Ragnhild Skorpa¹, Jan David Ytrehus¹,
Torbjørn Vrålstad¹, and Arild Saasen³

¹SINTEF, Trondheim, Norway

²Norwegian University of Science and Technology, Trondheim, Norway

³University of Stavanger, Stavanger, Norway

ABSTRACT

During the lifetime of an oil or gas well, the weighting material, barite, will eventually settle out. Viscoelastic measurements of such laboratory barite sediments from a bentonite mud and a KCl/polymer based drilling fluid is analysed. Despite having non-elastic sediments, the values of the measured G' and G'' is very high. This is a result of analysing dense wet particle sediments. Still, the high G' values indicate a strong yield stress prior to movement in a confined sample.

INTRODUCTION

At the end of the lifetime of an oil or gas well, it is necessary to plug back the well and demolish the surface production equipment^{1,2}. In these processes it is often necessary to remove parts of downhole piping and equipment. Most wells have been drilled with densified drilling fluids. Throughout the lifetime of the production period, most of the weighting agents have been settled out in the different annuli behind the production tubing and following casings. The purpose is to present measurement data helping to describe the consolidation of the weighting material and the force required to mobilise this material. This information relates to the necessary force to pull a casing from a region where the weighting agent barite has settled out behind the casing.

In addition to barite, drilling fluids contain salts, chemicals, polymers and other

particulate materials to control the needed properties. Despite of the usefulness as a weighing material, the sedimentation of heavy barite particles, "barite sag", can lead to problems during drilling operations, and after several years^{3,4}. The barite sag time scale is influenced by the type of drilling fluid and the respective drilling fluid chemistry⁵. It will occur in oil based and water-based drilling fluids, but the effect is more severe in oil-based fluids. This is related to the reason that oil-based drilling fluids do not form real network structures. However, the lack of real network structures may only alter the time scale of the sagging process. When looking at longer time scales, sagging is also observed in water-based drilling fluids. As the drilling fluid is constructed as a mixture of high-density particulate materials dispersed into a liquid, the ultimate fate will always be complete separation.

Barite plugs have also been used to prevent influx from oil or gas wells. In these applications a mixture of barite, dispersant and water has been pumped down into the well, where the barite was left to intentionally separate out quickly^{6,7}. It is important to pull out of the barite plug quickly to avoid being stuck with the drill pipe inside this plug.

Settled material in the annulus outside the casing can also cause problems later in the lifetime of the well, like during well abandonment or slot recovery. When performing casing cut-and-pull operations

the casing may get stuck leading to problematic casing removal^{1,2}. One reason may be that the increased friction and/or bonding between the sediments creates more resistance when pulling the casing. This sedimentation can be observed within a time scale of hours and days. When looking at the lifetime of the well, static sedimentation after several years becomes an issue that is not well understood⁸.

Most research on barite suspension in drilling fluids focused on the mechanisms of sag and measurement of these processes like for example Bern et al.⁹, Dye et al.¹⁰, Maxey¹¹ and Ofei et al.¹². The current article covers measurements of settled barite layers. In oil and gas wells the particles will settle over time and the process is influenced by temperature and pressure. Biodegradation of non-mineral additives may also impact the condition of the sediments. To prepare samples in the laboratory, gravity separation was used and the samples were stored in a heated cabinet for 30 days to simulate a down hole condition. Rheological properties of the resulting sediments were then measured using an Anton Paar MCR 102 rheometer. Fig. 1 shows a photo of a bentonite fluid sample after centrifugation and a schematic illustration of the observed sediment layers. The sedimentation process involves two parallel effects. The first one is called "syneresis". Here dispersion and emulsion particles agglomerate, creating void paths, through which the pure liquid can migrate to the top. The second process is the weight material sagging process. High density particles segregate to the bottom of a lower density fluid. A combination of these processes may be responsible for accelerating sag. As illustrated in the figure, the heaviest particles settle at the bottom and, depending on time, pressure and temperature, may lead to a consolidation of sediments. Above the consolidated sediments, a thin layer of gel-like sediments lay at the interface between the consolidated sediments and the suspension. The suspension made up the

biggest part of the sample. On top of the suspension lay a smaller amount of thinner suspension, followed by some free fluid on the top.



Figure 1. Bentonite/barite fluid sample after centrifugation and a schematic illustration of the sediment layers.

As described in the previous paragraphs, the ultimate fate for solid type weight materials in densified drilling fluids is to end up as a dense sediment on the bottom independent of barite being placed intentionally or as a result of lack of long term stability of the drilling fluid. The time scale of the sedimentation process varies and is not known. However, after a few years production it is likely that there is a sedimentation layer on the bottom that has a different degree of consolidation. In the following sections some rheological measurement of concentrated sediments from two laboratory samples of simple water-based drilling fluid examples are shown. The scope of these initial experiments is to describe a method to measure the bonding strength of wet powders in general and barite sediments in special. Hopefully, such measurements can be used to evaluate the strength and cohesive bonding potential of sediments in the future. Mezger¹³ claims that

Table 1. Composition of the Bentonite based and KCl based drilling fluids..

Components	Bentonite fluid		KCl fluid	
	Weight [g]	Weight [%]	Weight [g]	Weight [%]
Bentonite	12,6	1,83	-	-
OCMA				
KCl	-	-	33,0	4,49
Soda Ash	6,0	0,87	1,0	0,13
Xanthan Gum	0,9	0,13	2,0	0,26
Water	439,0	63,81	465,0	63,3
Barite	229,5	33,36	233,5	31,79
Sum	688,0	100	734,5	100

the upper strain end of the linear viscoelastic range can be defined as a yield stress. When exceeding this stress, significant changes in the internal structure of the material starts to occur. He also defined the point at cross over ($G' = G''$) as a flow point where solid-like state changes to liquid-like state. Thus, it is also possible to denominate the point at cross over as the yield stress which is the nomenclature used in most studies on soil rheometry¹⁴. A conventional device for measuring the strength of powders is the Jenike tester¹⁵. This device has been tested for complex wet powders like drill cuttings in the assessment of drilling waste handling in the oil industry¹⁶. Both the currently applied method and the Jenike tester apply strain to permanently deform the internal structure of the wet powder. Hence, the results from using these two devices should in principle be related. A similar approach as using a rheometer in a parallel method as applied in the Jenike tester has been used by Fall et al.¹⁷ who introduced the friction factor in rheometer tests, a method that has been applied on drill cuttings by Pedrosa et al.¹⁸. This latter method is discussed in more detail elsewhere¹⁹.

MATERIALS AND METHODS

Two laboratory water-based drilling fluids were prepared, one with bentonite and one with KCl. The fluids were prepared

following the standard procedure for laboratory testing of drilling fluids, specified in API 13I/ISO 10416. The procedure described for KCl fluids in paragraph 12.6 was used for both fluids. The chemicals were mixed with water at the high setting of the waring blender (11500 rpm) for a duration of 5 min. Unsuspended material adhering to the walls of the container was scraped off and added to the solution. Blending was continued for an additional 10 min at high shear rate. The procedure was repeated for adding the barite to the solution.

To qualitatively simulate gravity separation in a controlled manner but in an accelerated time frame in a laboratory setting, centrifugation was used to create the samples. To achieve this the fluids were filled into smaller bottles and centrifuged for 20 min at 40°C at 1000 rpm, 2000 rpm, or 3000 rpm. Half of the samples were then stored into the heating cabinet and exposed to 50°C for 30 days. The bottles containing the samples for heat exposure were sealed with Teflon tape to counteract possible evaporation. The sediment particle fraction is anticipated to increase with the centrifuge rotation rate.

The natural process developing sediments in an actual well differs significantly to the centrifugation method. Similarly, differences in temperature, pressure, and time will have an important impact on the separation and

biodegradation processes may take place during a long time period. However, to accelerate the sedimentation process to be able to create reasonable representative sediments that can be used in measurement systems, a centrifuge separation was selected. Still, with the restrictions given by the applied method, the use of this method will provide an initial knowledge about the consistency of the settled barite.

The different fluid sediment phases were analyzed in an Anton Paar MCR 102 rheometer. The fluid like phases were tested with the concentric cylinder geometry, and the more solid like phases were tested with the smooth plate-on-plate geometry. When using the plate-on-plate geometry it is recommended to not exceed a maximum particle size of 10% of the gap height. The API specification stated the particle sizes should include maximum 1.5% of the barite larger than 74 μm . Since there would be several particles slightly larger than 70 μm , the gap height was set to 1 mm to be much larger than the particle size.

After centrifuging the bottles containing the samples, these were taken out of the centrifuge. The free water on top, and the thin suspension were discarded. The suspension phase was poured into the measurement cup for flow curve analysis. The gel-like phase was removed from the bottle to reach the consolidated sediments. These were taken out with a small spatula and placed evenly on the lower plate of the rheometer. After moving the upper plate into place, the sample was trimmed, the temperature adjusted, and the measurement started.

RESULTS AND DISCUSSION

The sediments consist of barite particles embedded in a water-polymer solution with or without any clay platelets. Within the sediments some particles are in contact, while others have a lubricated layer of liquid and polymers. These sediments cannot be considered as a fluid, neither as a solid. It is basically a wet powder being constrained to

stay within its set boundaries defined by the rheometer plate – plate system. Hence, a high G' value does not necessary mean that the material is viscoelastic. The G' value shows the elastic response in a brittle material at lower shear stresses than the yield stress of the material. An idealized drawing of the sediment is shown in Fig. 2. The powder consists of barite particles of different sizes.

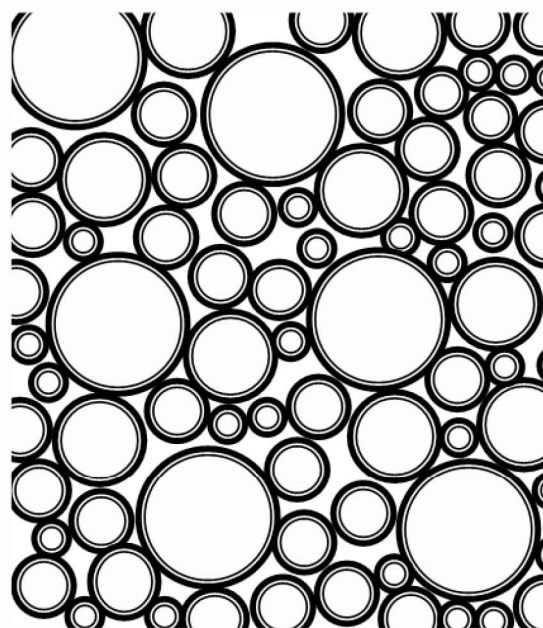


Figure 2. Model of the barite sediment, illustrated by the different circular bodies.

When applying an oscillatory strain, as being shown for sediments in a bentonite mud in Fig. 3, a high G' value is measured. Figure 3 shows the results of the amplitude sweep tests of the barite sediments from the bentonite mud for centrifugal speeds of 1000 rpm to 3000 rpm. The right-side graph contains the results of the heat exposed samples. In this case the internal structure is produced also by addition of the bentonite clay platelets. This sediment is looser than the other sediments, meaning that there is more liquid between the particles. Hence, at low strains the smaller particles can move small distances within the samples, giving room for the larger particles to re-position as

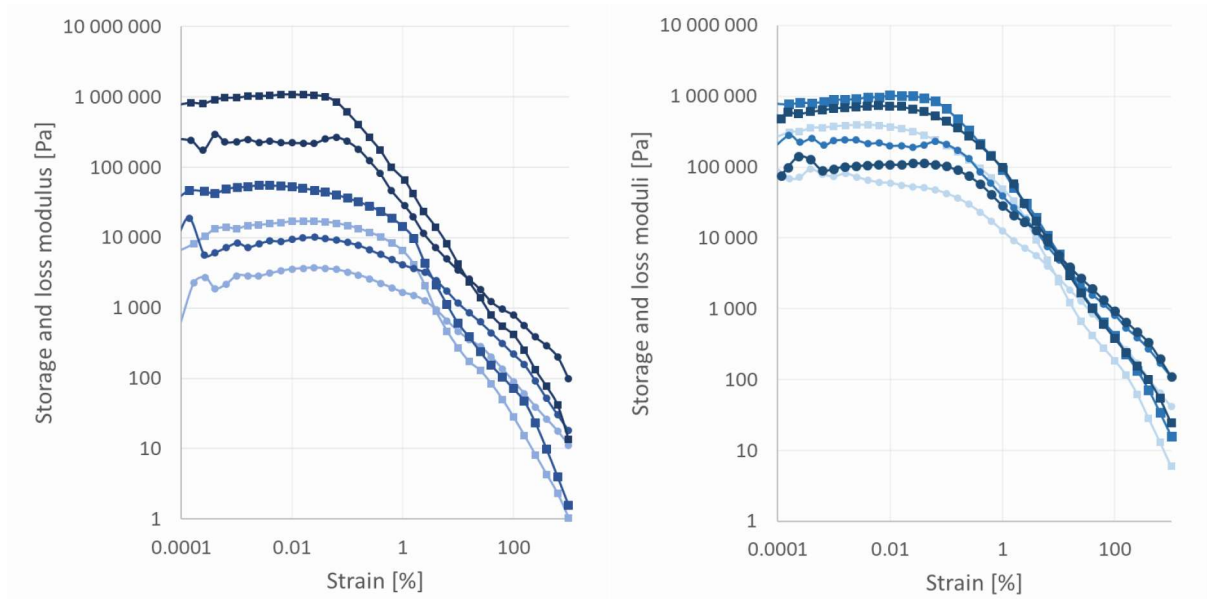


Figure 3. Measurements of the storage and loss moduli of barite sediments in bentonite mud.

Square symbols represent the storage moduli and round symbols the loss moduli. The sediments were centrifuged at 1000, 2000 and 3000 rpm. The darker the colour the higher the centrifuge speed. The left figure is prior to 30 days storage and the right figure after storage.

illustrated in Fig. 2. The “elastic” response is because the particles tend to be moved back into their original position to minimise the energy. When the strain increases, the larger particles will have to start climbing onto neighbouring particles. The bentonite platelets are “forced” to slide and rotate in between the barite particles. This requires application of larger forces. Therefore, the G' value will remain high until the particles start to leapfrog and the G' value starts to be reduced with strain amplitude. Note that the linear viscoelastic range is very small for these samples.

The left side of Fig.3 shows the amplitude sweep test results of the barite sediments from the bentonite fluid for centrifugal speeds of 1000 rpm to 3000 rpm. These clay platelets have a huge surface area like 40-100 m^2/g , according to van Olphen²⁰. Any fluid motion from sedimentation will create a vorticity in the material. Vorticity with platelets will create a significant resistance to rapid motion. However, the separation will continue with seepage flow around the platelets until a sedimentation layer with

particle-particle contact is obtained. The platelet vorticity will prevent the ability of the smaller barite particles to migrate as independently as they would in a liquid solution. Therefore, we expect relatively constant G' and G'' values when varying amplitude during measurements measure inside what we normally would consider as the linear viscoelastic range for a fluid.

30 days aging of the bentonite material made the material denser by seepage flow of water through the sediments. Hence, all the sediments became denser and more equal. This is shown in the right-hand figure of Fig. 3. All the curves are essentially equal with nearly the same G' and G'' values. The size of the linear viscoelastic range remains fairly constant, indicating an equal brittleness of the material prior to reaching the yield stress.

The G' and G'' values of both the initial and the aged sample of the KCl/polymer drilling fluid sediments centrifuged at 3 000 were reasonably constant when the strain amplitude varied as shown in Fig. 4. However, the G' values are lower for the stored sample, a result that is somewhat

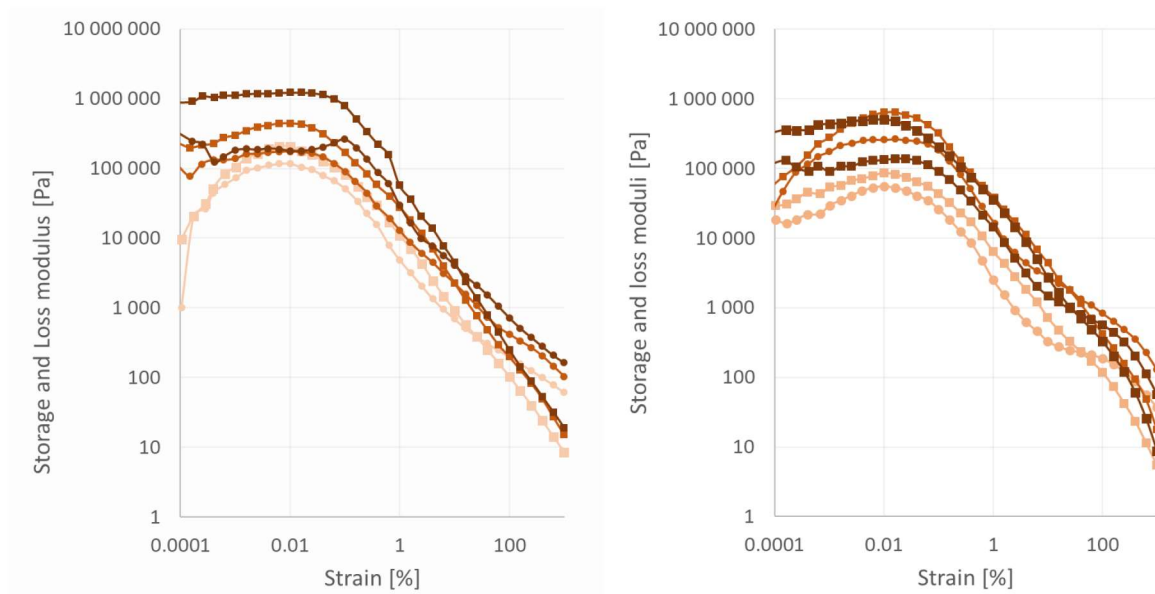


Figure 4. Measurements of the storage and loss moduli of barite sediments in KCl/polymer based drilling fluid. Square symbols represent the storage moduli and round symbols the loss moduli. The sediments were centrifuged at 1000, 2000 and 3000 rpm. The darker the colour the higher the centrifuge speed. The left figure is prior to 30 days storage and the right figure after storage.

surprising. Since the G' and G'' values measured on the sediments from the un-stored KCl – polymer-based drilling fluid obtained using 3 000 rpm centrifuge speed were equal to the values of the bentonite mud sediments as shown in Fig. 3, it is anticipated that the separation is nearly complete. The reduced values at the aged KCl/polymer based sediment samples are likely to have been caused by a less proper loading of the sediment sample to the rheometer's measurement cell. Hence, the particles may have had other internal directions to unload the particle-particle collision forces.

The storage modulus is a representation of the elastic energy stored in the sample during the oscillatory shearing. On the opposite, the loss modulus describes the deformation energy which is lost during shearing¹³. The relationship between the storage modulus and loss modulus characterizes the stiffness of a material and its internal friction. The linear viscoelastic range (LVER) represents the strain range in

which the storage modulus displays a constant plateau. When the curve deviates from linear the structure of the sample is broken. The cross-over point, also called flow point, is where the storage and loss modulus intersect. It indicates the point from where on the sample shows viscous behaviour. An uncertainty that should be taken into consideration is the possibility of deforming the sediment since the measurement cell is not a closed system. Thus, the normal force may decrease if the sediments “loosen” the contact with the upper plate¹⁸. This may introduce unexpected behaviour. For the sample centrifuged at 1 000 rpm and to some degree also for the one centrifuged at 2 000 rpm a peculiar behaviour is observed: G' and G'' are both increasing with increasing strain. For this KCl/polymer based drilling fluid, the viscosity is produced by addition of polymers like Xanthan gum and PolyAnionic Cellulose (PAC). Most likely, these polymers enter the sediments and lubricate the internal motion

of the smaller particles. Hence the maximum values are obtained by strains primarily affecting the internal structure of the larger barite particles. The movement of the larger particles may create a confining normal stress that is not created for the smaller strains.

The presence of a very high G' value of wet powder type sediments under shear strains introduces high normal force values and thus, high resistance against the movement. Since movement of a casing in a region where the barite behind the casing has settled completely out, this indicates that a high force is needed to pull the casing out of this region. In this respect, viscoelastic measurements seem to have a potential to be used to describe the consolidation and binding properties of wet powders.

CONCLUSIONS

A set of dynamic viscosity experiments has shown that viscoelastic parameters can be used to describe consolidation parameters of wet powders. High G' and G'' values of wet powders do not automatically indicate presence of an elastic material.

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REFERENCES

1. Khalifeh, M. and Saasen, A., 2020, *Introduction to Permanent Plug and Abandonment of Wells*, Spinger Open. doi.org/10.1007/978-3-030-39970-2
2. Vrålstad, T., Saasen, A., Fjær, E., Øia, T., Ytrehus, J.D. and Khalifeh, M. "Plug and Abandonment of Offshore Wells: Ensuring Long-Term Well Integrity and Cost-Efficiency", *J. of Petroleum Sci. and Engn.*, vol. 173, pp. 478-491, 2019. doi.org/10.1016/j.petrol.2018.10.049
3. Scott, P.D.; Zamora, M.; Aldea, C. Barite-Sag Management: Challenges, Strategies, Opportunities. IADC/SPE Drilling Conference, Dallas, TX, USA, 2-4 March 2004. Paper SPE-87136-MS, doi.org/10.2118/87136-MS
4. Zamora, M. Mechanisms, Measurement and Mitigation of Barite Sag. Offshore Mediterranean Conf. and Exhibition, Ravenna, Italy, 25-27 March 2009. Paper OMC-2009-105.
5. Omland, T. H. Particle Settling in Non-Newtonian Drilling Fluids. PhD Thesis, University of Stavanger, Norway, 2009.
6. Messenger, J.U. Barite Plugs can Effectively Seal Active Zones, *Oil Gas J.*, 1969, April 28, pf. 66.
7. Messenger, J.U. Barite Plugs Simplify Well Control, *World Oil.*, June 1969, pf. 83.
8. Vrålstad, T.; Skorpa, R.; Saasen, A. Rheological Properties of Barite Sediments in Water-Based Drilling Fluids. ASME 37th International Conference on Ocean, Offshore and Arctic Engineering, 17-22 June 2018, Madrid, Spain. Paper OMAE2018-78695
9. Bern, P.A.; van Oort, E.; Neusstadt, B.; Ebeltoft, H.; Zurdo, C.; Zamora, M.; Slater, K. Barite Sag: Measurement, Modelling and Management. *SPE Drilling and Completion*, 2000, **15** (1), SPE-62051-PA. doi.org/10.2118/62051-PA
10. Dye, W., Hemphill, T.; Gusier, W.; Mullen, G. Correlation of Ultralow-Shear-Rate Viscosity and Dynamic Barite Sag. *SPE Drilling and Completion*, 2001, **16**, 1, SPE-70128-PA. doi.org/10.2118/70128-PA
11. Maxey, J. Rheological Analysis of Static and Dynamic Sag in Drilling Fluids. *Ann. Trans. Nordic Rheol. Soc.*, 2007, **15**,
12. Ofei, T.N., Lund, B., Kalaga, D.V., Saasen, A., Linga, H., Sangesland, S., Gyland, K.R. and Kawaji, M, "Laboratory Evaluation of Static and Dynamic Sag in Oil-Based Drilling Fluids", *SPE Journal*, SPE-199567-PA, 2020, doi.org/10.2118/199567-PA

13. Mezger, T.G. 2014. The Rheology Handbook. 4ed. Vincentz Network, Hannover, Germany
14. Pértile, P.; Holthusen, D.; Gubiani, P.I.; Reichert, J.M. Microstructural Strength of Four Subtropical Soils Evaluated by Rheometry: Properties, Difficulties and Opportunities. *Scientia Agricola*, 2018, **75** (2), 154-162.
15. Malagalage, A., Ratnayake, C., Saasen, A., Thomassen, T. and von Hafenbradl, F.O. “Flow Properties of Drill Cuttings with Varying Drilling Fluid Content Using Jenike Shear Testing”, *Chemical Engn. & Techn.*, **41** (8), pp. 1544-1550, 2018. DOI: 10.102/ceat.201700554
16. Malagalage, A.; Ratnayake, C.; Ariyaratne, W.K.H.; Melaaen, M.; Aas, N. “Pneumatic Conveying of Model Drill Cuttings – Pilot Scale Experiments and Simulations”, SPE Bergen One Day Seminar, 5th April, 2017, Bergen, Norway, Paper SPE-185899-MS.
17. Fall, A., Ovarlez, G., Hautemayou, D., Mézière, C., Roux, J.-N. and Chevoir, F., 2015 “Dry granular flows: Rheological measurements of the $m(I)$ -rheology”, *Journal of Rheology*, **59** (4), 1065-1080.
18. Pedrosa, C., Saasen, A., Lund, B. and Ytrehus, J.D., “Wet drilled cuttings bed rheology”, *Energies*, **14**(6), 1644. 2021. <https://doi.org/10.3390/en14061644>
19. Pedrosa, C., Ytrehus, J.D., Aschl, T., Lund, B. and Saasen, A., “Wet-granular rheology to measure cuttings-bed strength”. *Ann. Trans. Nordic Rheol. Soc.*, 2021.
20. van Olphen, H. *An Introduction to Clay Colloid Chemistry*, 1977. 2nd ed., Wiley Interscience, New York