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FLOWABILITY OF DRY AND WATER WET BARITE POWDER

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ABSTRACT

Barite is added to drilling fluids as weight material to increase its density. Over time, when the drilling fluids are left static in the annulus, gravitational forces will make the barite settle out. This settled barite is today the main reason for casing cut and removal process, which accounts for up to 50% of time related to P&A operations. Knowledge of settled barite on top of cement behind casing is also essential for perf, wash & cement procedures.

The most compact barite sediment can be characterized as a non-elastic dense wet particle sediment where the packing of the particles and the particle size of the grains varies. To fully understand the packing mechanism of the consolidated barite sediments characterization of barite powder (both dry and wet) is important.

In this study we have done comparable measurements with a Jenike shear test, which measures direct shear strength under different loading conditions, and compared these to rheological measurements using an Anton Paar powder module under the same loading conditions. Experiments were performed on both dry and wet (by 2.5 wt% and 5 wt% water) barite and with 1, 3, 6 and 9 kPa loading.

The results from the Jenike test and the powder module were found to be complimentary. At a low water content, the sample showed an increase in flowability, while with a high-water content a decrease the flowability was observed compared to that of dry barite.

Keywords: barite, wet powder compaction, rheology, shear strength

1. INTRODUCTION

There is an inevitable upcoming "Plug and Abandonment (P&A) wave" of oil-, CCS (Carbon Capture and Storage)- and geothermal wells. In the North Sea alone, approximately two thousand wells need to be permanently plugged and abandoned the next three decades.

During P&A operations, the casing is cut and pulled out and removed from the wellbore to set a proper gas tight plug. During P&A operations, settled barite in the annulus, as it per today is not defined as an annular barrier, is the main reason for having to cut and remove the casing to place a new well barrier according to regulations [1]. Settled barite behind casing will greatly complicate, and sometimes also make it impossible to pull the casing out of the annulus [2, 3]. This might result in several cut and pull operations which will greatly increase the cost. Settled barite is a consolidated sediment phase formed during gravity separation when the drilling fluid is left static in the annulus for several years [4]. A rule-of-thumb from the industry is that over time, a 1/3 of the mud column above the

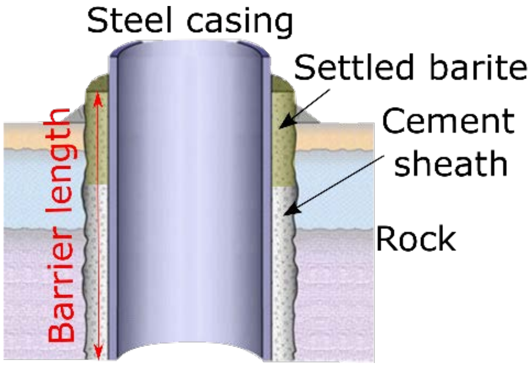

FIGURE 1: SCHEMATIC ILLUSTRATION OF A SECTION OF A WELL, ILLUSTRATING THE CEMENT BARRIER WITH SETTLED BARITE

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cement in the annuli consists of settled barite. The flowability of these sediments will be dependent on the amount of fluid present in the barite powder. Previous studies in the literature shows a decrease in the flowability of powders with increasing water content due to the formation of capillary bridges between the grains [5–7].

We have previously used a rheometer with a plate-plate geometry to characterize barite sediments from water-based drilling fluids [4, 8]. Additionally, we have used Jenike Shear tester to investigate flow properties of drill cuttings with varying fluid content [9]. The following paper is a continuation of this. In this paper we have investigated the flowability of both dry and wet barite, both using the standard Jenike shear test cell and using Anton Paar Powder module. Understanding the flowability of wet barite powder will be of importance with respect to pipe-pulling operations, where the settled barite behind casing can make it impossible to pull casing.

2. MATERIALS AND METHODS

2.1 Samples

For the experiments performed with the rheometer, mixing of the barite with tap water was performed with a spatula and by shaking a closed bottle.

The Jenike tests were performed with dry barite, and with wet barite at 5% water content by weight. Rheometer tests were carried out on dry barite and wet barite at 1%, 2.5%, 4%, 5%, 6.5% and 8% water contents. A mix containing 10% of water was also prepared but gave a thick paste in which the blades of the top plate could not penetrate. This observation corresponds well with the observed results in described in this paper, and the sample was therefore not further investigated. Pictures of the different barite samples used in this study is given in Fig.2

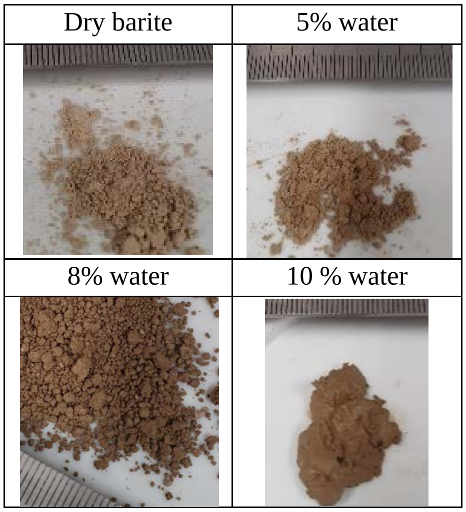
Dry barite
5% water
8% water
10 % water

FIGURE 2: PICTURES OF SOME OF THE BARITE SAMPLES, ILLUSTRATING THE EFFECT OF WATER ON THE ASPECT OF THE POWDERS.

2.2 Anton Paar Powder shear module

A powder shear cell was used in an Anton Paar rheometer MRC102. The cell consists in an annular cup and top annular plate as schematized in Fig. 3. The bottom surface of the cup is profiled, and the top plate is covered by blades, to avoid material slip. The 4,3 mL cup is filled carefully with the barite before each experiment and the surface is equalized with a straight ruler, for all the tests reported in this paper, the mass of material inside the cell is 6 +/- 0.2 g

Then, the barite is tested successively at four increasing consolidation normal loads F_C: 1 kPa, 3 kPa, 6 kPa and 9 kPa. For each value for the consolidation load, the test sequence alternates consolidation phases, when the normal stress F_N is equal to the consolidation load F_C and measuring phases with normal stresses F_N smaller than F_c, as illustrated in Fig. 4. Due to the configuration of the powder cell, the normal force is applied to the particles only, and not the full samples (including the fluid). The results presented in the following are average values obtained from three identical experiments.

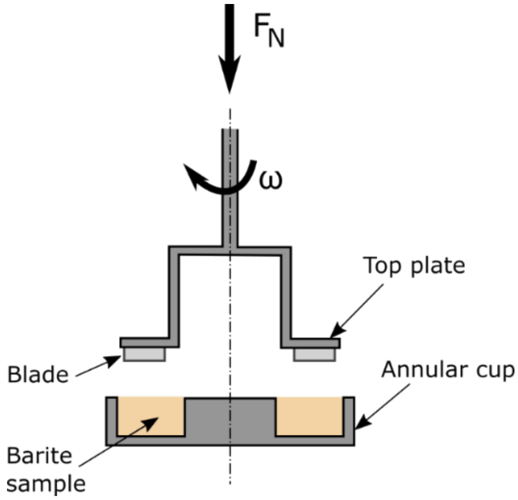

FIGURE 3: SCHEMATIC DIAGRAM OF THE ANTON PAAR POWDER SHEAR CELL

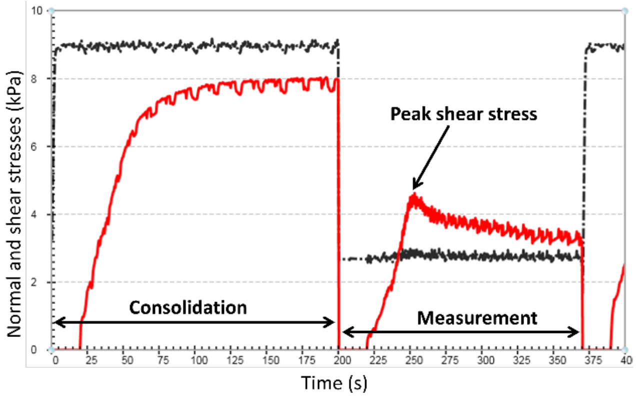

FIGURE 4: EXAMPLE OF STRESS CURVES MEASURED DURING THE CONSOLIDATION AND MEASUREMENT EVENTS: VERTICAL NORMAL STRESS IS BLACK AND SHEAR STRESS ISRED.

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The gap size (i.e., the distance between the top plate and the cup bottom) and the shear stress τ are measured by the rheometer during the consolidation and measurements events. During consolidation phase, the shear stress increases with time and reaches a plateau value. During a measurement phase, the shear stress increases linearly up to a peak value, then decreases to a plateau value. Before the peak, the barite powder behaves like a solid, and after it is reached, the powder deforms.

2.3 Jenike shear tests

The standard Jenike shear tester was used to determine the unconfined yield stress for different barite/water mixtures. The shear cell has two rings and the powder is filled into the rings as shown in Fig 5. Initially a consolidating load is applied to it for pre-consolidation and then it is replaced by a lower load (F_N). Then an increasing shearing force (F_S) is applied to the top ring and when the applied shear force is strong enough to slide the top ring it is considered that the bulk powder specimen has been sheared. This combination of the shear force and the consolidation load gives a data point on the yield locus. The yield locus can be plotted by conducting the same experiment with different normal loads [10, 11].

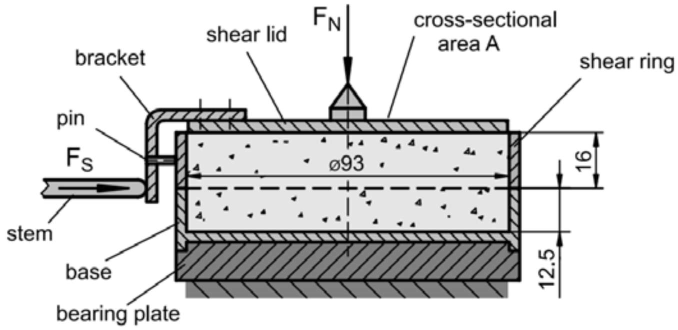

FIGURE 5: SCHEMATIC DIAGRAM OF THE JENIKE SHEAR CELL (DIMENSIONS ARE IN MM) [11]

3. RESULT AND DISCUSSION

3.1 Rheometer results

The yield loci result for the dry barite sediments and with 5% water is shown in Figs. 6 and 7. The yield locus of a material is the curve obtained from the peak shear stress point. For stress conditions below the curve, the material behaves like a solid, and above the curve, it flows.

Three points were used to obtain a yield locus for each measurement. For a given material and consolidation stress, the peak stress increases linearly with the applied normal stress. This is expected as a granular material flows less easily when an increasing confining stress is applied [6, 12]. In addition, the yield loci values increase with the consolidation stress [5, 13]. In our experiments, the gap between the upper plate and the bottom of the cup, measured by the rheometer, decreases when the confining stress increases. Therefore, the barite powders become denser when the consolidation pressure increases.

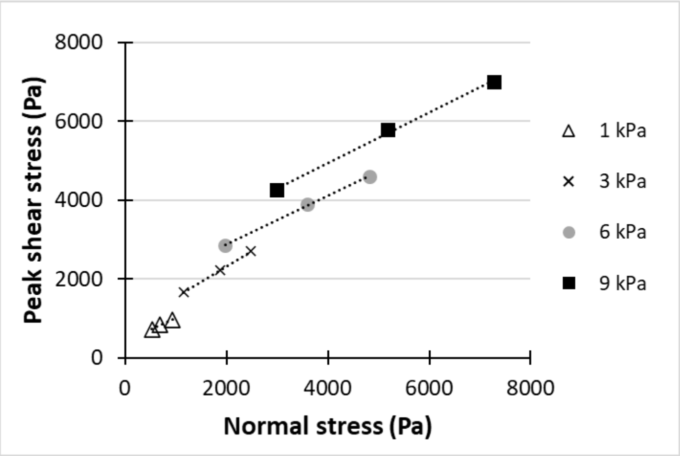

FIGURE 6: YIELD LOCI OF DRY BARITE, MEASURED WITH THE RHEOMETER. THE LEGEND INDICATES THE CONSOLIDATION STRESSES F_C.

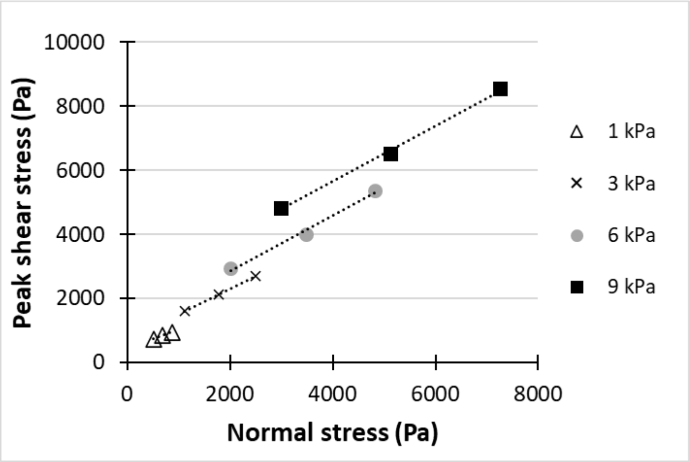

FIGURE 7: YIELD LOCI OF BARITE POWDER WITH 5% WATER BT WEIGHT OF BARITE, MEASURED WITH THE RHEOMETER. THE LEGEND INDICATES THE CONSOLIDATION STRESSES F_C.

The same experiments have been performed on the wet barite powders, and the same effect of the consolidation stress was observed. In Fig. 8, we compare the yield loci of all the samples obtained with the highest consolidation stress (9 kPa). When the water content is low (1%), the water seems to shift the yield locus towards smaller values of the shear stress. On the other hand, for water contents of 4% and above, the yield locus values increase. Therefore, for a given consolidation stress, powder flow more easily if the water content is low than if it is above 4%.

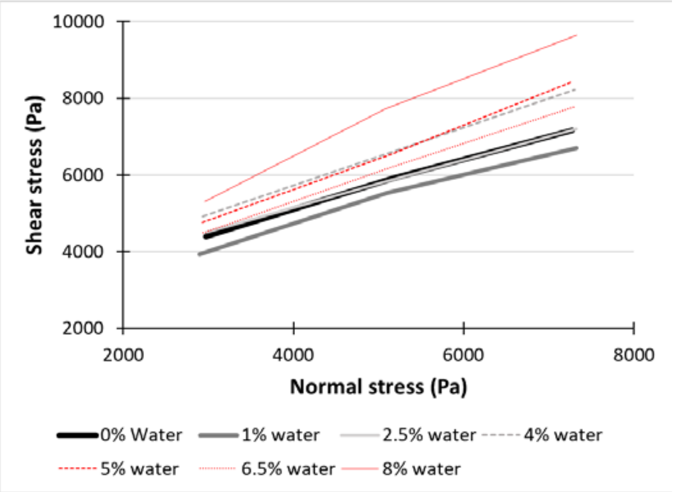

FIGURE 8: YIELD LOCI OF ALL THE BARITE POWDERS AT CONSOLIDATION STRESS 9 kPa. EACH CURVE IS AN AVERAGE OF THREE EXPERIMENTS.

3.2 Effect of water content, and comparison of Jenike and rheometer test

The properties of powders are often characterized by using the flowability curves, where the unconfined yield strength f_C is plotted as a function of the major principle stress σ_1 [14, 15]. The calculation of f_C and σ_1 is illustrated in Fig. 9. f_C is obtained from the Mohr circle tangent to the yield locus, which crosses the origin. σ_1 is the largest principle stress during consolidation.

As mentioned before, the addition of a large amount of water, above 4% by weight, leads to a switch of the yield locus toward larger values of the shear stress. The consequence is illustrated in Fig. 9: both f_C and σ_1 increase [14, 15].

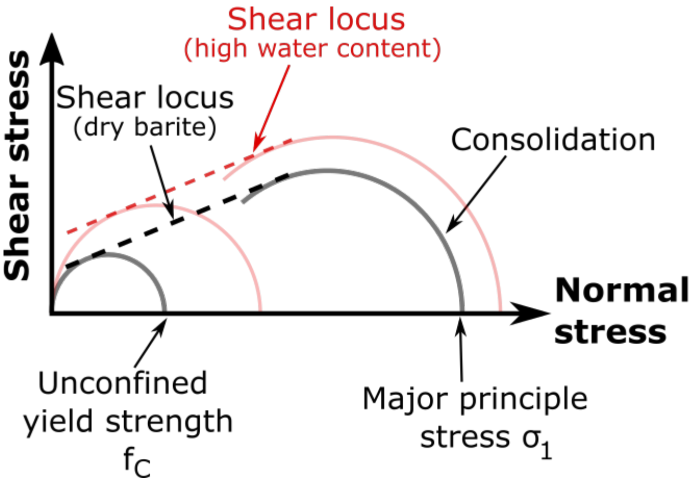

FIGURE9: EXPLICATIVE SCHEMA FOR THE DEFINITION OF THE UNCONFINED YIELD STRENGTH f_C AND THE MAJOR PRINCIPLE STRESS σ_1 (INSPIRED FROM [15]). THE RED LINES ILLUSTRATE THE EFFECT OF WATER ON THE YIELD LOCUS, AND HOW IT AFFECTS f_C AND σ_1.

In Fig. 10 the results obtained in the rheometer with the powder shear cell are compared to those obtained with the Jenike shear tests. The tests methods differ by their geometry, sample volume and by the application of the consolidation load. Indeed, the applied consolidation load is only a normal force in the Jenike test, whereas both a normal and shear force are applied with the rheometer. Despite these differences, we observe that the obtained results are very close, both for dry barite and with 5wt% of water. The powder shear cell in the rheometer can therefore be used to investigate barite sediments, and these results can be compared with measurement performed with a Jenike tester.

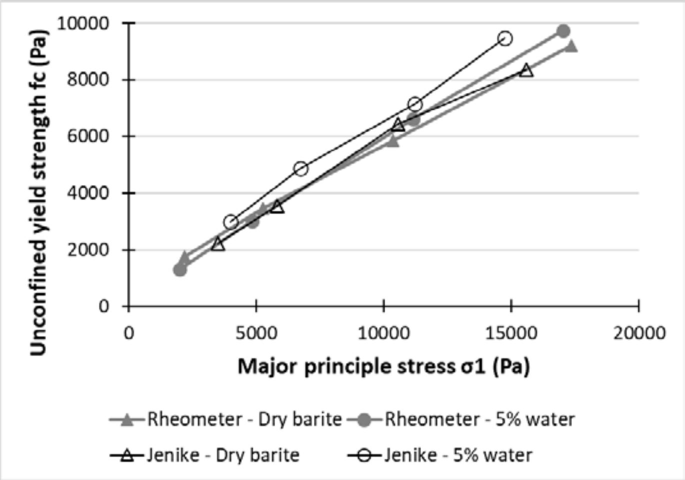

FIGURE10: FLOWABILITY CURVES OF BARITE POWDERS, COMPARISON OF RESULTS OBTAINED WITH THE JENIKE CELL AND THE RHEOMETER.

The flowability results from the rheometer are given in Fig. 11. As can be seen from the figure, it is hard to extract a trend with respect to the effect of water on flowability, indicating that there is little or no effect of increasing water up to 8 %. The sample volume used in the rheometer setup is small (4.3mL) and thus, a slight variation in sample composition could have a large effect, making reproducibility harder compared to the Jenike tests. Additionally, we observed that for the samples with the highest water content, a stationary state was not always reached during the consolidation phase prior to measurements. This could also affect the reproducibility and the result itself.

As can be seen from Fig. 10 and 11, for each sample, the unconfined yield strength f_c is proportional to the major principle stress σ_1. To evaluate the flowability of the samples, we have calculated the flowability ratio $ff_c = \sigma_1/f_c$ for all the samples studied with the rheometer. The results shown in Fig. 12 are the average of all the values obtained for consolidations stresses 3, 6 and 9kPa, for three experiments per water content. In the classification proposed by Jenike, powders where ff_c is between 1 and 2 are said very cohesive, and between 2 and 4, cohesive [14, 15].

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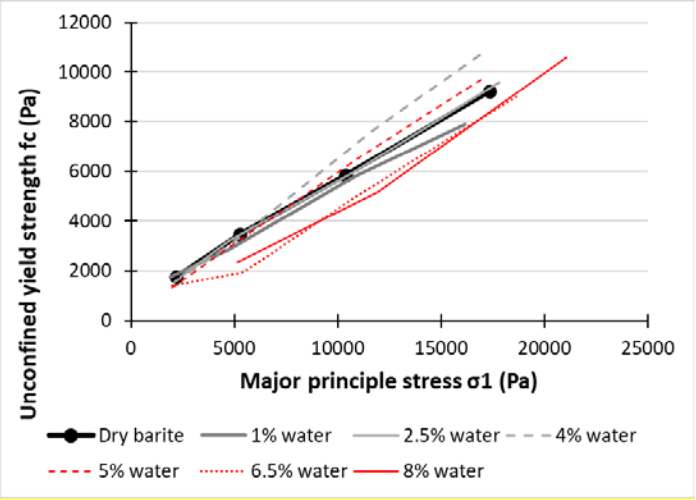

FIGURE 11. FLOWABILITY OF BARITE SEDIMENTS WITH DIFFERENT WATER CONTENTS

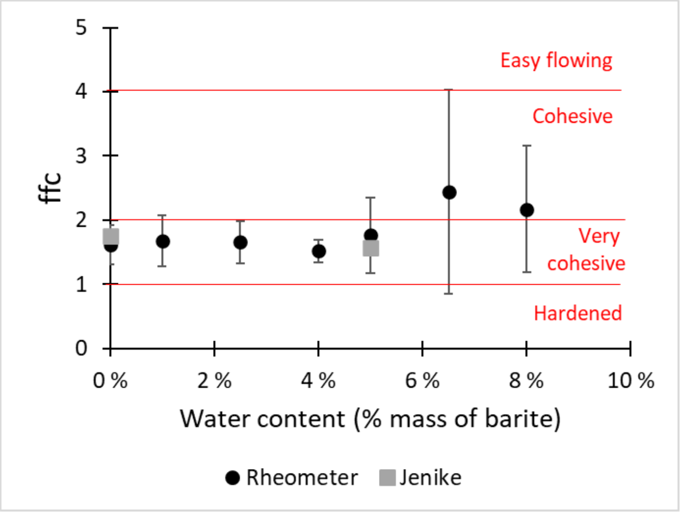

FIGURE 12: FLOWABILITY RATIO FOR ALL THE SAMPLES STUDIED BY THE RHEOMETER AND THE JENIKE TEST. THE POINTS INDICATE THE AVERAGE VALUES OBTAINED FOR CONSOLIDATIONS STRESS 3 kPa, 6 kPa AND 9 kPa, AND THE ERROR BARS INDICATE THE STANDARD DEVIATION.

We first notice in Fig. 12 that the standard deviation is large for the samples containing the largest amount of water. This results probably from the heterogeneous distribution of the water in the powder: the more water is added, the more particle agglomerates can be seen, and the less free barite particles are present in the sample (see Fig. 2).

In addition, the average flowability ratio seems to increase when the amount of water exceeds 6%, which means that the powder is less cohesive. However, given the large error bars for these measurements, the results could just as well be cohesive, and in line with the other measurements.

The sample mass for all four samples of dry and wet barite is around m = 6g and the cell volume is V = 4.3 mL. The volume fraction of the barite powder is given by the relation $\Phi_b = m/(\rho_b V)$, where $\rho_b = 4.5$ g/cm3 is the barite density. We calculate for our experiments: $\Phi_b \approx 30\%$. The porosity between the barite particles is therefore about 70% of the total volume. When we add water to the powders up to 5% by weight of barite (i.e. up to about 20% by volume of barite), the pore space is not filled with water.

In a granular material where both water and air are present, water creates capillary bridges between the particles, which in turn forms heterogeneities such as particle aggregates in the powder. Thus, these capillary bridges decrease the flowability of the powder [5–7]. Flowability of sediments, such as barite, behind casing is an important aspect for pipe-pulling operations, where the barite behind casing can make it nearly impossible to pull casing. The results shown in this paper shows the effect of water on flowability of barite samples and are thus not directly applicable to field scenarios. Addition of additives to the fluids, such as polymers or clay particles would most likely affect the results, but to what extent is not clear.

4. SUMMARY

Our results shows that the results of using the powder module connected to the Anton Paar rheometer are complementary to those obtained with a Jenike Shear tester. Comparing the yield loci of the different wet barite sediments, we observe that for a given consolidation stress, powder flow more easily if the water content is low than if it is above 4%. From the flowability curves from the rheometer, no obvious trend is observed, indicating that there is little or no effect of increasing water up to 8 %. This is in agreement with the observed results for the flowability ratio as a function of water content.

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