

Supplementary material for ‘Quantifying the yield stress of bentonite muds mixed with other clays during drilling operations’

A. Bougouin*

Aix-Marseille Université, CNRS, IUSTI, Marseille, France

A. Pantet, N.-D. Ahfir

*Laboratoire Ondes et Milieux Complexes (LOMC) - Université Le Havre Normandie,
UMR 6294 CNRS, 76063 Le Havre, France*

1. Limits of the yield stress for binary-clay suspensions

In this paper, a phenomenological model was proposed to quantify the yield stress τ_y of binary-clay suspensions as a function of the bentonite to clay volume ratio R_b and the total clay volume fraction φ_t . For this purpose, it was argued that the yield stress τ_y of binary-clay suspensions was bounded by the upper yield stress τ_y^b of bentonite suspensions (i.e., composed only of bentonite) and the lower yield stress $\tau_y^{k/i}$ of kaolin/illite suspensions (i.e., composed only of kaolin or illite). Figure S1 shows the yield stress τ_y of binary-clay (bentonite 1 - kaolin 1) suspensions as a function of (a) the total clay volume fraction φ_t with $R_b = 0.5$ and (b) the bentonite to clay volume ratio R_b with $\varphi_t = 0.06$. The estimate of the yield stresses $\hat{\tau}_y^b$ and $\hat{\tau}_y^{k/i}$ by the Spearman’s model (Eq. 1 of the paper, with $\varphi_m = 0.64$) for mono-clay suspensions made of bentonite (- - -) and kaolin/illite (—) is also shown for comparison. As expected, the yield stress τ_y increased with both φ_t and R_b independently. Moreover, the yield stress τ_y of binary-clay suspensions was well bounded by the upper and lower values of the yield stress for mono-clay suspensions made of bentonite and kaolin/illite, respectively. Finally, remind that the trend from one to the other was only dependent on R_b .

*Corresponding author

Email address: alexis.bougouin@univ-amu.fr (A. Bougouin)

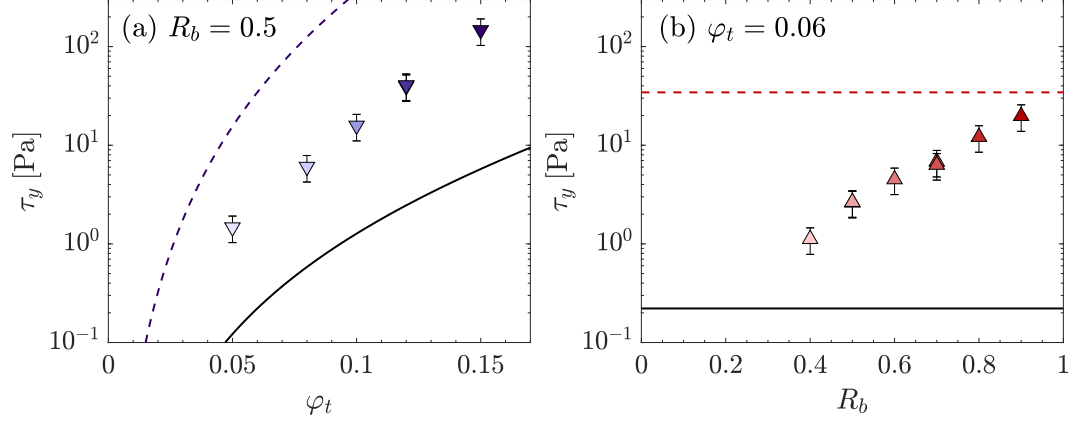


Figure S1: Yield stress τ_y as a function of (a) the total clay volume fraction φ_t with $R_b = 0.5$ and (b) the bentonite to clay volume ratio R_b with $\varphi_t = 0.06$, for binary (bentonite 1 - kaolin 1) clay suspensions. Dashed and solid lines correspond to the Spearman's model (Eq. 1 of the paper, with $\varphi_m = 0.64$) for mono-clay suspensions made of bentonite 1 ($\alpha = 3 \times 10^5$ and $\beta = 4$) and kaolin 1 ($\alpha = 2 \times 10^2$ and $\beta = 3$), respectively.

2. Uncertainties due to thixotropic effects

Bentonite-water mixtures are well known to exhibit thixotropic effects corresponding to a time-dependency of the rheological behaviour under constant stress conditions, which contrasts with the other types of clay materials, i.e., kaolin and illite (Yang and Andersen, 2019). More specifically, it consists in a time-dependent shear thinning property resulting from the long time of bentonite materials to reach the microstructural steady-state compared to the time of measurements (Paumier, 2007). The rheological behaviour of thixotropic suspensions is usually characterized by two distinct flow curves between the up and down shear rate ramps (see Fig. 1(a) of the paper). Thus, such a difference leads to measurement uncertainties on the estimate of rheological properties, and especially on the yield stress.

Figure S2 shows the yield stress τ_y^D as a function of the yield stress τ_y^U estimated from the down and up flow curves fitted by the Herschel-Bulkley model, respectively. Overall, most of data collapse on the slope 1 (solid line), which means that the variation of the yield stress due to thixotropy are much lower than those attributed to the type and the volume fraction of clay materials considered in this study. Moreover, these variations are broadly included in the scatter of results caused by other experimental uncertainties,

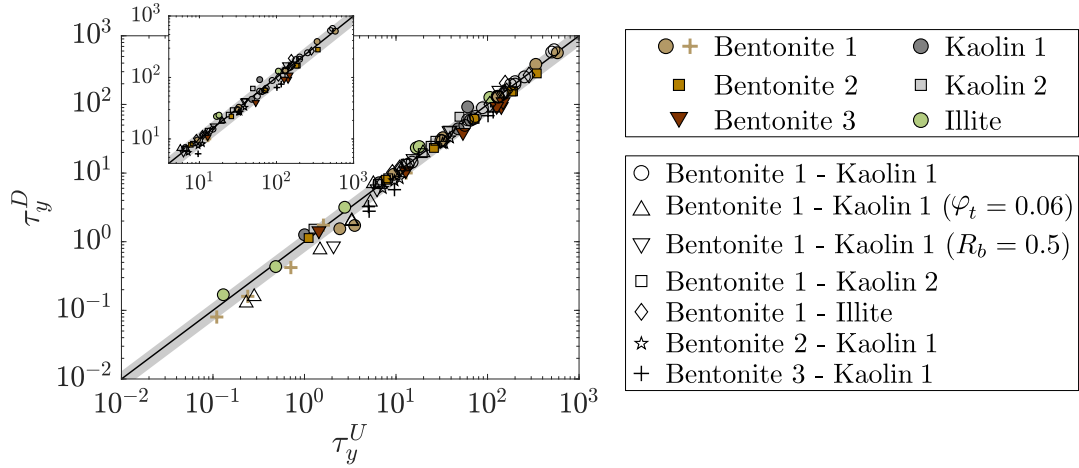


Figure S2: Yield stress τ_y^D as a function of the yield stress τ_y^U estimated from the down and up flow curves fitted by the Herschel-Bulkley model, respectively, for mono- and binary-clay suspensions. The solid line is $\tau_y^D = \tau_y^U$ and the gray area corresponds to the standard deviation of $\pm 30\%$. Inset: Zoom on data of binary-clay suspensions.

such as the accuracy of measurements and models (see symbols above the solid line, i.e. $\tau_y^D > \tau_y^U$, for instance). Quantitatively, the standard deviation leads to a discrepancy of $\pm 30\%$ on the estimate of τ_y (gray area), while the whole of data can be included in a variation of $\pm 50\%$ (not shown here). In the whole of the paper, the yield stress τ_y is therefore estimated as the average value between τ_y^D and τ_y^U and the error bars correspond to the standard deviation of $\pm 30\%$ (not indicated when error bars are similar to the size of symbols). To conclude on, the measurement uncertainties (e.g., due to thixotropy of bentonite materials) do not affect significantly the results in the range of parameters considered here, and they do not change the conclusions drawn in this study.

References

- Paumier, S., 2007. Facteurs déterminant l'organisation et la rhéologie du système argile-eau pour des suspensions de smectites. University of Poitiers (France) PhD thesis.
- Yang, S., Andersen, K.H., 2019. Thixotropy of marine clays. *Geotechn. Test. J.* 39, 331–339.